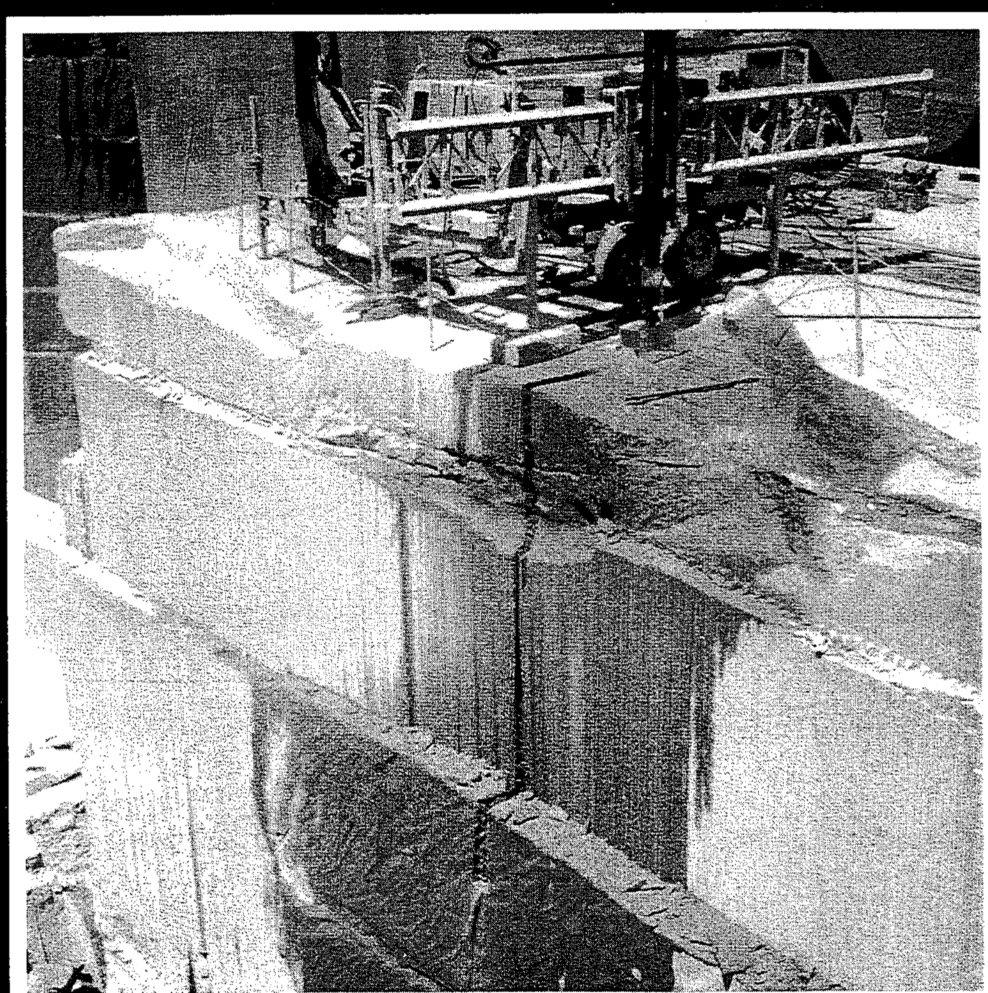
Proceedings
of the
8th American Water Jet Conference

Volume I



August 26-29, 1995

Houston, Texas

Edited by Thomas J. Labus

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Cover photograph: Slot cutting in a granite quarry using a water jet. Photograph reprinted courtesy of Ned Jet Cutting Systems, Inc., Worcester, Massachusetts.

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Forward

Read on if you wish to learn the present state of the art of water jet technology. This volume contains the considered thoughts of some of the leading authorities in the field as expressed at the 8th American Water Jet Conference. These authors assembled in Houston, Texas in August of 1995 to share their thoughts and thereby gain new insights on how water jet technology can be advanced even further.

The Water Jet Technology Association offers this volume, the eighth in a series of *Proceedings of American Water Jet Conferences*, as evidence that water jet technology is contributing significantly to man's ongoing and comprehensive effort to enlarge human power and safeguard human welfare.

George A. Savanick, Ph.D.
President, Water Jet Technology Association

In 1983, when the Water Jet Technology Association (WJTA) was just formed, there were only few charter members. In 1989, when I became the vice president of the Association, the membership was 327 (including corporate members). Now, when I am leaving WJTA as chairman of the board, the membership stands at 535, an indication of truly remarkable growth and interest in the varied applications of ***Fluid Jet Technology***. Similar trends can be noticed in other major associations/societies in the world, for example, the Water Jet Technology Society of Japan. The fact that the International Society of Water Jet Technology (ISWJT) has recently become a Federation of National Associations/Societies in the world confirms that there is a genuine interest for international understanding and collaboration for enhancing the spread of the ***Technology for beneficial uses***.

Yes, we should all be proud. Through our persistent endeavors, we have made noteworthy contributions to advance the ***Technology*** which, in turn, has made the world a somewhat better place to live by increasing productivity and abating pollution that occurs in many industrial processes.

I am certain you will learn a great deal from your participation at this Conference. You will make new acquaintances and friends. You will continue to improve the ***Technology*** to address serious problems (for instance, safe disposal of nuclear waste) of the 21st century. I have friends all over the world and I sincerely thank each and every one of them for giving me the opportunity to serve the ***Fluid Jet Community*** in a modest way. I wish you all the best in your future endeavors.

Mohan M. Vijay, Ph.D.
Chairman of the Board, Water Jet Technology Association

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Preface

Fluid jet technology continues to be a dynamic growth area in the 1990s. The papers in these *Proceedings* provide insight into the areas that are the future of the technology. New types of fluid jets and new uses for the standard jets continue to be developed. Trends identified in the 7th American Water Jet Conference (i.e., nuclear decontamination, hazardous waste removal, and demilitarization) have continued to develop and to achieve commercialization.

The advent of abrasive suspension jets and improvements in standard aspiration-type abrasive jets have moved the technology toward a competitive position versus traditional machining operations. This area continues to evolve as evidenced by the number of papers in these *Proceedings* addressing machining processes, theoretical and experimental investigations of the cutting process, and integration of fluid jets into intelligent machining systems. These trends should continue through the balance of the 1990s. Improvements in abrasive nozzle life, the amount of abrasive used, and cut quality control will drive the adaptation of fluid jets into traditional machining operations. In some fields such as paper processing, fluid jets are the standard against which all other technologies are measured.

Construction and mining applications still have not utilized the potential of fluid jet technology. Several papers in these *Proceedings* address fields such as soil/ground stabilization, hydrodemolition, bore hole mining, and tunnel boring. These areas of application need equipment designed for mobile use that is rugged, has a high reliability, and low capital and operating costs. Some of these issues are addressed in papers in these *Proceedings*.

The evolution of any technology depends heavily on the free exchange of information on research and applications issues. This Conference provides a forum for such an exchange. It is due to the willingness of the authors to share their information and views that this Conference takes place. I would personally like to thank all the authors for their contributions. This Conference continues to be international in nature with 27 of 70 papers submitted for consideration being from international authors. I would like to thank this group of authors for taking time to prepare a paper, and for supporting the conference with their attendance.

Sincere thanks go to Dr. Andy Conn, Dr. Tom Kim, and Mr. Bruce Wood who reviewed all the paper abstracts, which aided in developing the overall technical paper content of the conference. Thanks also goes to Dr. Tom Kim, Mr. Bruce Wood, and Dr. Mohamed Hashish who edited the submitted papers. They executed this time consuming task with diligence and dedication to maintaining a high quality program. Finally, but certainly not the least, the staff at Birenbaum & Associates needs to be recognized.

Mark Birenbaum and Ken Carroll provided guidance and counsel as related to the overall Conference goals. Ms. Jan Tubbs and Rhonda Stevens administered the development of these *Proceedings*. They did an outstanding job. Ms. LeAnn Hampton supported the short course and made it a success. I also wish to express my sincere thanks to all participants for making this Conference a success.

Thomas J. Labus
Editor, *Proceedings of the 8th American Water Jet Conference*
Vice President, Water Jet Technology Association

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8th American Water Jet Conference
August 26-29, 1995: Houston, Texas

Paper **1**

BOREHOLE MINING OF GOLD FROM PERMAFROST

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ABSTRACT

This paper describes the second in a series of two field tests by the U.S. Bureau of Mines designed to determine the feasibility of borehole mining of gold from frozen gravels. This test, conducted at Fox, Alaska in August of 1994, demonstrated that borehole mining operations can be conducted in frozen gravels without causing surface subsidence, that cobbles as large as 12.7-cm (5-in) in diameter can be pumped to the surface, and that blockages can be routinely cleared from the inlet of a downhole slurry pump. In this test, the presence of numerous cobbles/boulders in the 25 to 45 cm (10 to 18 in) size range hampered proper operation of the system. Gold recovery was not sufficient to make borehole mining economically feasible at this stage of development.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

The U.S. Bureau of Mines (USBM) has built and field tested at Fox, Alaska an improved version of a Borehole Placer Miner. This miner is capable of fragmenting frozen gravel and lifting a gravel slurry containing cobbles as large as 12.7 cm (5-in) in cross section 15 m (50 ft) vertically to the surface. The miner incorporates a method for fragmenting and/or dislodging cobbles when they obstruct the downhole slurry inlet. This method entails firing of a projectile inside a delivery tube having its exit at the slurry inlet.

In the 1992 field test of the prototype Borehole Placer Miner, it was not possible to borehole mine coarse gravels without clogging the slurry pumping system. Operations were also hindered by surface subsidence. The purpose of this paper is to describe how these problems were overcome during the 1994 field testing of the improved Borehole Placer Miner.

2. PREVIOUS WORK

Research conducted in 1985 by Hawley Resources Group (Retherford,1985) as well as work done by the USBM in 1990, suggested that gold could not be effectively mined through a single borehole. In 1992 the USBM built a prototype Borehole Placer Miner designed specifically for mining gold in permafrost, and tested it at a mine on Tenderfoot Creek, 43 km (27 mi) northwest of Delta Junction, Alaska. This test (Miller and Savanick, 1993) confirmed that a borehole mining system which uses two borehole mining tools operating in concert in adjacent boreholes is superior to conventional single borehole mining systems when applied to mining gold. Single borehole mining is unsuccessful because much of the gold settles out before the slurry enters the downhole pump. The two-borehole mining system is affected less by the settling problem. After water jets cut a connection between boreholes, the water jet of one miner is operated simultaneously with the slurry pump of the other miner. The slurrified gravel and gold particles are pushed by the jet into the inlet of the pump.

Testing at Tenderfoot Creek revealed two problems which act as impediments to the technical feasibility of borehole gold mining. These were clogging of the borehole miner with cobbles and surface subsidence.

Surface subsidence occurred in the form of a cylinder 1.2 m (4-ft) in diameter and about 1.8-m (6-ft) deep around the casing of the production holes. The subsidence was a process resulting from both the drilling method and the permafrost quality. The permafrost was melted from the surface down to the 7.1-m (23-ft) level. Water used in the drilling process melted the sidewall of the drill hole and caused an annulus to exist between the borehole wall and the casing. This allowed thawed material to fall through the annulus around the casing into the mined cavity at the bottom of the borehole leaving a void at the 7.1-m (23-ft) level. Surface material then subsided into the void. The problem was compounded by borehole wall melting which occurred when the slurry inlet plugged. In this event water rose in the annulus between the borehole wall and the casing because the operator had no way of detecting plugging until water overflowed at the surface through the annulus. When the blocked inlet was cleared by backflushing, further enlarging of the annulus occurred as water rushed down the annulus into the slurry pump.

This problem was avoided in the 1994 test by drilling holes just large enough to accommodate the casing with a tight fit and forcing the casing into the drilled hole. The drilling in 1994 was done using a reverse circulation drill with little or no water. In addition, the permafrost was frozen to within about 0.3 meter (1 ft) of the surface at the 1994 test site.

Clogging of the slurry output line with cobbles was the most serious problem encountered in the 1992 test. It occurred in every trial and was the reason for the termination of the field test. The slurry pumping system was capable of passing a 15.2-cm-diameter (6-inch) cobble and many of these were lifted to the surface. Clogging occurred when large, irregularly-shaped rocks either blocked the slurry inlet or entered the pump and became wedged in the slurry outlet system (figure 1). The problem was compounded when attempts to backflush by closing the slurry exit caused gravel in the vertical column to sink and congregate inside the column. Some of the wedging was caused by the design of the slurry outlet system. The slurry outlet pipe above the jet pump contained an abrupt expansion, the larger volume containing three nested pipes which carried the jet-pump-drive water and the high-pressure water to the cutting nozzle (figure 1). When the inlet was clogged, the flow in this expanded region decelerated to a critical minimum, since the flow through the jet pump nozzle alone was barely enough to maintain the velocity in the slurry outlet required to lift the large rocks. In this situation, large rocks would jostle into pinch points between the nested pipes. Clogging of the outlet conduit would follow, in some cases even if the inlet had been cleared. The problems encountered during the 1992 field test provided a starting point for the redesign of the Borehole Placer Miner.

3. REDESIGN OF THE BOREHOLE PLACER MINER

A improved Borehole Placer Miner was designed and built in 1994 in an attempt to improve the performance that was demonstrated in the 1992 Alaska field test.

The 1994 tool incorporated design changes that avoided clogging of the slurry output lines and allowed for clearing of blockages at the slurry pump inlet. The clogging problem was addressed in the 1994 design by limiting the inlet size of the pump to 12.7-cm (5-in) to reduce the possibility of oversize materials entering the pump, and by redesigning the slurry output conduit downstream of the jet pump. The design of the slurry outlet pipe was changed from the 1992 design which called for nesting three supply pipes inside a 25.4-cm (10-inch) slurry output line. The new design (figure 2) called for a 15.2-cm-diameter (6-in) output line with no pipes inside it. The two jet pump supply pipes were replaced with a single 7.6-cm (3-in) pipe placed alongside the slurry outlet pipe.

A small increase in friction loss resulted from using the smaller outlet conduit and a single jet pump supply pipe. However, these piping changes resulted in a smaller cross sectional area for the slurry outlet pipe with consequent increased vertical velocity. This prevented settling of rocks when the inlet of the jet pump became clogged. The removal of the nested pipes also resulted in a smoother bore inside the slurry line and thereby removed opportunities for rocks to become wedged. These piping changes also decreased the weight of the tool without increasing its overall diameter and made enough space to add a 7.6-cm (3-in) diameter delivery tube. This delivery tube was added to the tool to accommodate a method for clearing blockages at the jet pump inlet.

To address the problem of slurry inlet blockages, a rock breaker was added to the 1994 design in order to fragment and/or dislodge rocks clogging the jet pump inlet. This allowed clearing of the slurry inlet without backflushing. Thus, the full lift power of the jet pump could be maintained to prevent cobbles from sinking inside the vertical section of the borehole miner while clearing inlet clogs.

The 1994 version of the borehole mining tool is sketched in figure 2. Figure 3 is a schematic which shows the layout and operating mode of this miner. The pipe assembly contains four pipes: a 6.3-cm (2.5-in) pipe carrying pressurized water to the cutting nozzle, a 7.6-cm (3-in) feed pipe for the downhole jet pump, a 15.2-cm (6-in) pipe carrying the slurry to the surface, and a 7.6-cm (3-in) delivery tube for the rock breaking device. The jet cutter supply pipe is fed to a horizontally-directed 1.6-cm-diameter (0.62-in) nozzle after passing through a 90 degree elbow. The nozzle and supply pipe can rotate 90 degrees in a horizontal plane and can move 1 m (3 ft) vertically starting just above the jet pump intake. The cutting jet nozzle position is independent of the position of the slurry pump which is stationary at the bottom of the borehole.

Instrumentation to sense when the jet pump inlet was submerged, and to sense the presence of a vacuum just inside the pump inlet (indicating inlet blockage), was built into the 1994 equipment. The vacuum sensor was a tube running from inside the jet pump near the driving nozzle to a vacuum gage at the surface. The water level sensor was a tube with an open end placed just above the level of the jet pump inlet and the other end connected to a manometer at the surface. These sensors were added in response to the results of the 1992 field tests. During these tests, if the slurry inlet was blocked while the jet cutting nozzle was operating, the borehole and subterranean cavern filled with water and overflowing occurred at the surface. In 1992, this contributed to subsidence around the borehole because the backed up water thawed the borehole wall.

The redesigned Borehole Placer Miner works as follows (figures 3 and 4). A 6900 KPa (1,000 psi), 1,325 lpm (350-gpm) jet disaggregates the frozen gravel by melting the matrix. The resultant slurry is drawn into a downhole slurry pump and is pumped to the surface via a 15.2-cm-diameter (6-in) jet pump and slurry line which exits into a 25.4-cm (10-in) transfer line to a holding\recycling tank at the surface.

The mining sequence is as follows: Two identical borehole miners are placed in boreholes approximately 7.6-m (25 ft) apart (figure 4). Each borehole miner is in the form of an assembly of pipes functioning as a water jetting system and a slurry pumping system. Each of the two borehole miners cuts a long, horizontal passage approximately 0.1 m^2 (1 ft^2) in cross section in the direction of the other miner until the two passages meet. The waterjet cutter of one miner is then operated simultaneously with the slurry pump of the other miner.

The cutting jet is directed toward the inlet of the slurry pump of the other miner. Thus the waterjet forces the slurry towards the inlet of the other miner with high velocity and turbulence. This keeps the gold in suspension while the slurry is induced to flow into the inlet of the slurry pump. The nozzle is rotated in the horizontal plane and adjusted vertically to enlarge the cavity. The jetting-pumping sequence is alternated between the two boreholes until the horizon of interest is mined out.

4. LABORATORY TESTING

Several versions of the redesigned miner were tested in the laboratory to ascertain their performance in liberating, slurrifying, and pumping frozen gravels, particularly with respect to the effective vertical transport of slurry, the ability to prevent blockages of the slurry outlet pipe, the degree to which water could be recycled, and the ability to clear blockages of the jet pump inlet.

Three large-scale gravel samples totalling approximately 68 m^3 (90 yd^3) were saturated with water, seeded with gold particles, and cooled to -4 °C to simulate Alaskan permafrost. They were thermally isolated for better temperature control and incorporated multiple cased holes to accommodate the experimental miners. Testing proceeded as follows: Two miners were placed into 35.6-cm (14-in) diameter holes at opposite ends of a 6 m x 2.4 m x 2.4 m (20 ft x 8 ft x 8 ft) block of frozen gravel, and a cavern was excavated between the miners. The excavated cavern was diamond shaped in plan view, with approximate dimensions of 6 x 2.4 x 0.6 m (20 x 8 x 2 ft). Approximately 10,400 kg (11.5 tons) of gravel were slurrified and pumped out of the cavern in approximately 3 hours of running time.

4.1 Water Recycling

Slurry was handled in a closed loop system whereby the water used to drive the jet pump was taken from the tank into which the output slurry discharged. This comprised about 85 percent of the water used. The remaining 15 percent of the water was clear water used to supply the high pressure 6,900 Kpa (1,000 psi) pump, which is susceptible to wear by dirty water.

4.2 Clearing Inlet Blockages

Tests indicated that if the inlet of the jet pump is made smaller to prevent oversized material from entering the slurry pump then there would be a tendency for cobbles larger than 12.7 cm (5 in) to block the inlet of the downhole slurry pump. A laboratory study was performed to determine the most effective method of clearing jet pump inlet blockages. Several mechanisms were built and tested in an attempt to clear blockages. These included jet flushers, rock crushers, drop hammers and demolition guns.

4.2.1 Jet Flushers

Two experimental borehole miners were built which incorporated a secondary jet nozzle of approximately 1.3 cm (0.5 in) in diameter inside the slurry inlet. When the inlet was clogged with cobbles, this jet was operated in the range of 690 to 5,520 KPa (100 to 800 psi) to provide an energetic water jet impact to free the inlet. Although this method worked sometimes, at other times the suction of the jet pump would pull the cobble into the inlet with a greater force than that provided by the blasting jet. In the case where the inlet was submerged and no air could get around the cobble into the jet pump, the suction force on the cobble increased still further, and the blasting jet was even less effective.

4.2.2 Hammers

Several schemes using mechanical means were tested in order to develop a suitable method for breaking cobbles at the inlet of a slurry pump. Rock crushers were found to be generally too large for practical downhole application. A compact rock crusher was built and tested with minimal success.

Various bits were tested for their rock breaking effectiveness using a drop hammer mechanism or with air-hammer drive power. For all bit types tested, percussion air-hammer power had a tendency to create local crushing, grinding or drilling effect without breaking the target cobble. Because an instantaneous shattering of the obstructing cobbles was the goal, the air-hammer approach was abandoned.

To provide high energy impact for shattering cobbles, the various bits were attached to a weighted cylinder and allowed to fall through a drop tube onto the target cobbles. This proved effective, particularly for the wedge bits and for a flat-faced drop hammer bit. Such arrangements precluded a localized crushing effect, and transmitted more energy to the cobbles.

The weighted cylinders with bits tended to stick in the drop tube for two reasons: (1) sand/gravel which splattered up into the tube created a friction lock in the annulus between the tube and the hammer; and (2) occasionally the bit forced an obliquely positioned rock toward the inlet and then glanced off the oblique face, forcing the rock into the inlet hole. In this instance the bit was jammed tightly and could not easily be extracted for continued operation. This problem was more pronounced for the wedge bits.

4.2.3 Boiler Gun

The technique selected for use in the 1994 Alaskan field test involved the use of an industrial demolition tool called the Winchester boiler gun. This tool propels a 57- or 85-gm (2- or 3-oz) slug of lead, zinc or steel at a velocity of approximately 550 m/s (1,800 ft/s). The tool is directed at a cobble obstructing the slurry inlet via a delivery tube (figures 2 and 3). When fired, the slug shatters obstructing rocks up to 25.4 cm (10 in) in diameter in one blow. Steel slugs are deformed by the impact; lead and zinc slugs disintegrate and the fragments are found in the heavy mineral concentrate in the sluice box.

Because of the small size (8 gauge) and high velocity of the slug it tends to lose energy quickly if it encounters water. To remedy this a 3.8-cm (1.5-in) pipe is inserted into the delivery tube, sealed and connected to compressed air. In a water-filled hole this pipe is filled with compressed air, lowered onto the rock, backed off slightly and the slug is then fired through a water-free cylinder. This has allowed excellent cobble fragmentation with standing water at the slurry inlet.

Numerous blockages occurred in the laboratory tests. These were cleared either with a drop hammer or a boiler gun. Both methods were effective but the boiler gun was judged to be a more convenient, efficient, and trouble free method and so was selected for use in the field test.

5. FIELD TESTING

Cooperative Agreements were negotiated with the National Oceanographic and Atmospheric Administration and Goldstream Exploration Inc., in order to set up and run borehole mining test in gold bearing permafrost near Fox, Alaska. Before mining could begin, permits were applied for and received through the Alaska Department of Natural Resources, Division of Mining. Permits included clearance concerning water quality, anadromous fish impact and wetlands impact.

Field testing took place in frozen gravels on the property of the National Oceanographic and Atmospheric Administration - 5.6 km (3.5 miles) northeast of Fox, Alaska. The gold bearing gravel at the test site is about 3-m (10-ft) thick and the gold mainly occurs in a 0.6-m (2-ft) thick layer immediately adjacent to bedrock under 7.6 m (25 ft) of frozen overburden (figure 6). The deposit is on a bench approximately 9-m (30-ft) above the level of Rose Creek. This bench was bypassed when Rose Creek was dredged earlier this century.

5.1 Borehole Drilling

A line of six 20-cm (8-in) diameter sample holes were first drilled to delineate the bedrock profile of the bench and to see where the values were greatest. Next an array of boreholes as shown in figure 5 were drilled and cased. Samples of drill cuttings were taken from each of the holes and panned in order to get an idea of the amount and distribution of the gold present (figure 6 and table 1). Figure 6 gives a columnar section of the production and observation holes showing the lithology and the distribution of gold particles found in the drill cuttings.

The production holes were drilled and cased with 30-cm (12-in) ID steel casing. The casing was driven into place to insure a tight seal to the borehole wall. The observation holes were likewise drilled and cased with 20-cm (8-in) steel casing.

The borehole miners were 28.5 cm (11.3 in) in diameter and hence fit into the 30-cm (12-in) casing. The auxiliary holes (C and B) located midway between the production holes were designed to accommodate cameras to photograph the borehole-mined cavities.

5.2 Field Test Setup

The borehole miners were lowered into the production holes and suspended from the lip of the casing by hanger brackets welded onto the slurry outlet pipe. To guard against subsidence the casings also had hanging brackets welded onto them. These brackets rested on 3-m long (10-ft) wooden poles lying on the ground.

The water to run both the jet cutter and the slurry pumping system was initially obtained from Rose Creek at a temperature of 2 °C and was run through a recycling system composed of a 6 x 2 x 3 m (20 x 7 x 7 ft) steel tank (figures 4 and 7) and a pond 18 m x 7 m x 0.6 m (60 ft x 24 ft x 2 ft). Recycling the water and exposing the water to sunlight and the ambient air increased the water temperature to 13 °C. This enhanced the jet cutting capability because the rate of disaggregation of permafrost is a strong function of the temperature of the jetting water (Miller and Savanick, 1993).

Water for the jet cutter, approximately 1,325 lpm (350 gpm), was drawn from the pond and filtered to protect the boiler-feed pump used to power the cutting jet. This filtration step could have been avoided if a mud pump were available for powering the cutting jet. Water for the jet pump drive, approximately 5,670 lpm (1,500 gpm), was recycled directly from the steel tank.

The jet cutter operating between 180 lpm (50 gpm) at 1,380 KPa (200 psi) and 1,325 lpm (350 gpm) at 6,900 KPa (1000 psi), disaggregated the frozen gravel at the base of the borehole and formed a slurry. The slurry was entrained into a jet pump with a 1,380 KPa (200 psi), 5,677 lpm (1,500 gpm) driving jet. This slurry was lifted to the surface where the solids were deposited in the steel tank and some of the water overflowed back to the pond to be recycled to the cutting jet. Note that figure 4 shows a slightly different system than that used in the field test, i.e., it shows a transfer pump recycling 100% of the water back to the drive pumps, and no settling pond.

5.3 Test Sequences

Two test sequences were completed, the first using boreholes A and E (figure 5) and the second using holes E and F. Further tests were planned but were not conducted because of time constraints.

To start the first test a cavern was excavated relatively easily between holes E and B. A camera was lowered into hole B and a large cavity with the floor covered deep in gravel and cobbles was observed. This suggested local thawing of the permafrost and subsequent roof spalling which may account for the anomalous drill log data for hole B at the 7.3-m (24-ft) level (figure 6).

The next step of this test was to excavate a cavity between holes A and B. Although considerable material was excavated, the cavern did not extend to hole B. Upon extracting the miner and lowering the camera into hole A, numerous 24-45-cm (10-18-in) cobbles/boulders were observed in the cavern. These diverted the jet energy and the diverted water created a large spheroidal cavity instead of the desired horizontal tunnel. As expected, the gold recovery rate (table 2) was relatively low because the test could not advance to the point where material was being forced toward either of the slurry inlets by the opposing jets. Based on the gold recovery rate shown in Table 2 and a cost analysis performed by the USBM (Amaro, 1994), we concluded that borehole gold mining would not be economically feasible at this particular site. The combination of recovery rate and gold values which would allow economic feasibility is discussed in the Amaro paper.

The second test was run similar to the first test but using holes E and F. In this test less gravel was excavated and the recovery rate was even lower than in test 1. Possible explanations are postulated as follows:

1. The miner in hole E was rotated 120 degrees to start test 2. Considerable material, probably the heavier fractions, may have settled in the void behind the miner created during the previous test.
2. Sampling and mining results from holes B and E suggest that the area was not virgin permafrost, but perhaps the edge of old underground workings.
3. Drill data from both holes E and F (figure 6) indicate that a significant portion of the gold was in the bedrock. The excavation was actually above the bedrock.
4. Cobbles and boulders were a problem. They were too large to be moved by the jet and served to dissipate the jet energy.

Clogging of the jet pump inlet and the presence of large rocks interfering with the jet cutter were the main problems encountered. The jet pump clogging was very frequent (100 times during the tests) but all of the clogs were cleared with the Winchester boiler gun. This gun fired an 8 gauge pellet from the surface through the 7.6-cm diameter delivery tube onto a rock caught in the inlet of the pump.

No clogs occurred inside the slurry output line as happened in the 1992 borehole mining tests. Slurry line clogging was avoided by designing the inlet of the pump so that oversized material could not enter the slurry line and by changing the slurry output line from a 25.4-cm (10-in) nested design to a single 15-cm (6-in) pipe. Benefits of this redesighn were: 1) oversize material was caught at the pump inlet where it could be broken and 2) discharge velocity high enough to lift the largest rock pumped was maintained at all times, even when the pump inlet was clogged.

Large rocks impeding the cutting jet were the most serious problem encountered in the 1994 tests. These rocks were too large, 30 to 45 cm (12 to 18 in), to be moved by the cutting jet. This was verified by a video survey and by still photographs taken after the borehole miner was extracted from the hole, using reference objects to estimate the size of the rocks.

It may have been feasible to mine around the large rocks if a downhole inspection camera were used during the mining process. Borehole mining, as presently constituted, suffers because of the lack of real-time visual feedback to the operators. The indicators available to the operator such as output slurry quality are limited and/or indirect. Plans are being made to incorporate a video camera into the borehole mining tool.

6. CONCLUSIONS

1. The Winchester boiler gun is highly effective in clearing blockages at the inlet of the slurry pump.
2. Excellent candidates for this technique are deposits in which most or all of the rocks can be moved with the cutting jet, for this system that would mean minus -25.4-cm (10-in) material.
3. Surface subsidence caused by material funnelling between the casing and the borehole wall can be avoided by driving the casing to create a tight seal to the borehole wall.
4. A method to provide real-time visual data to the borehole miner operator should be developed. This would enable the operator to better direct the cutting jet to control the excavation and avoid obstacles such as large rocks.
5. Borehole mining operations in gravel are profoundly affected by the size of the largest rocks encountered. A deposit that has a significant proportion of rocks which are too large to be moved by the cutting jet probably cannot be mined effectively by borehole mining.
6. In a small borehole mining operation in permafrost a closed loop system can be set up using a relatively small reservoir pond and/or tank. This is an advantage because the water is warmed by passing through the pumps and the rate of disaggregation of the frozen material increases as the temperature of the water increases.
7. A velocity sufficient to lift the largest rock pumped should be maintained at all times in the slurry output line even when the slurry inlet is plugged. Thus, backflushing should not be employed while solids are in the output line.

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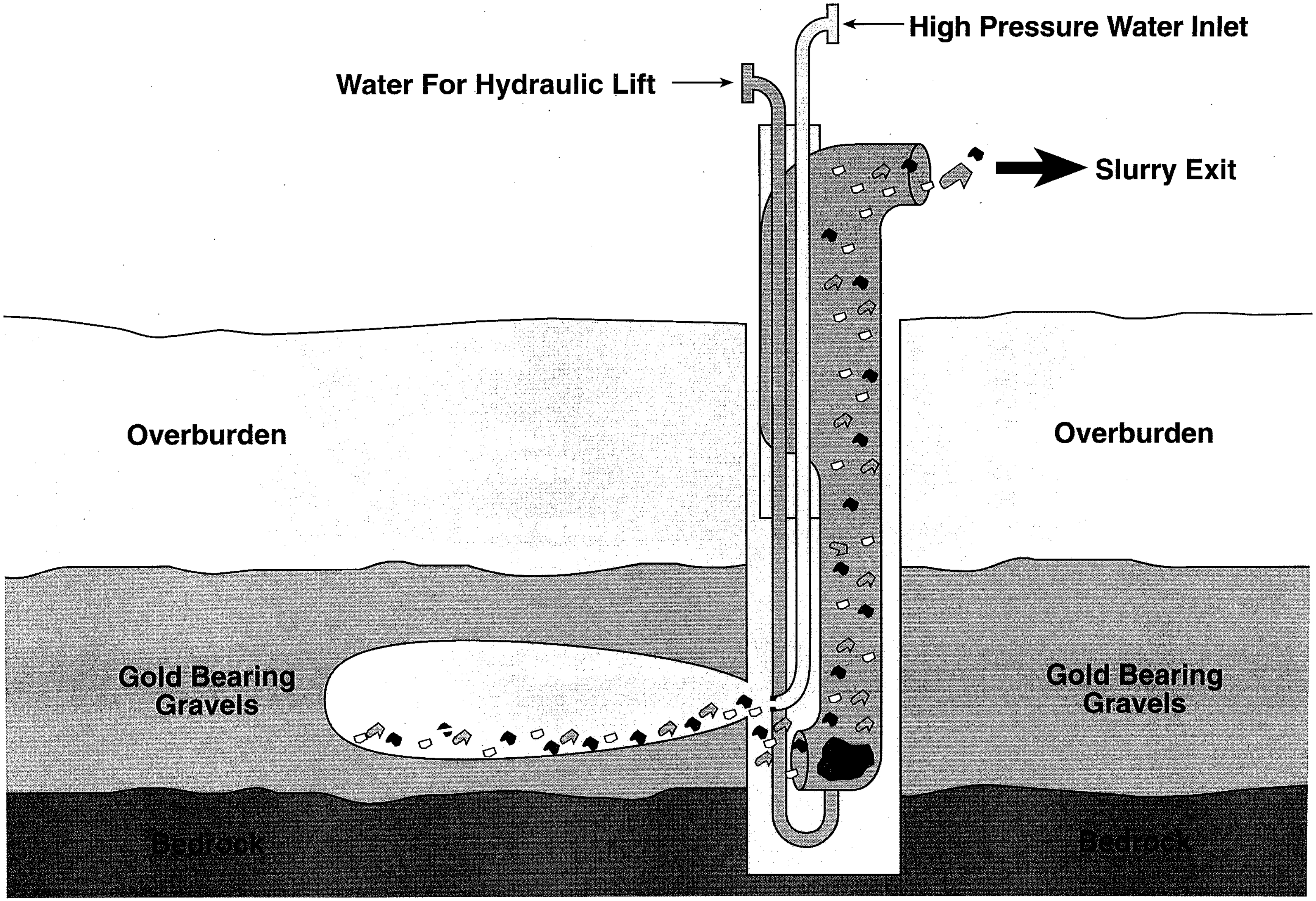

Figure 1. - Schematic diagram of miner used in 1992 tests, with cobble suck in slurry pathway, illustrating clogging.

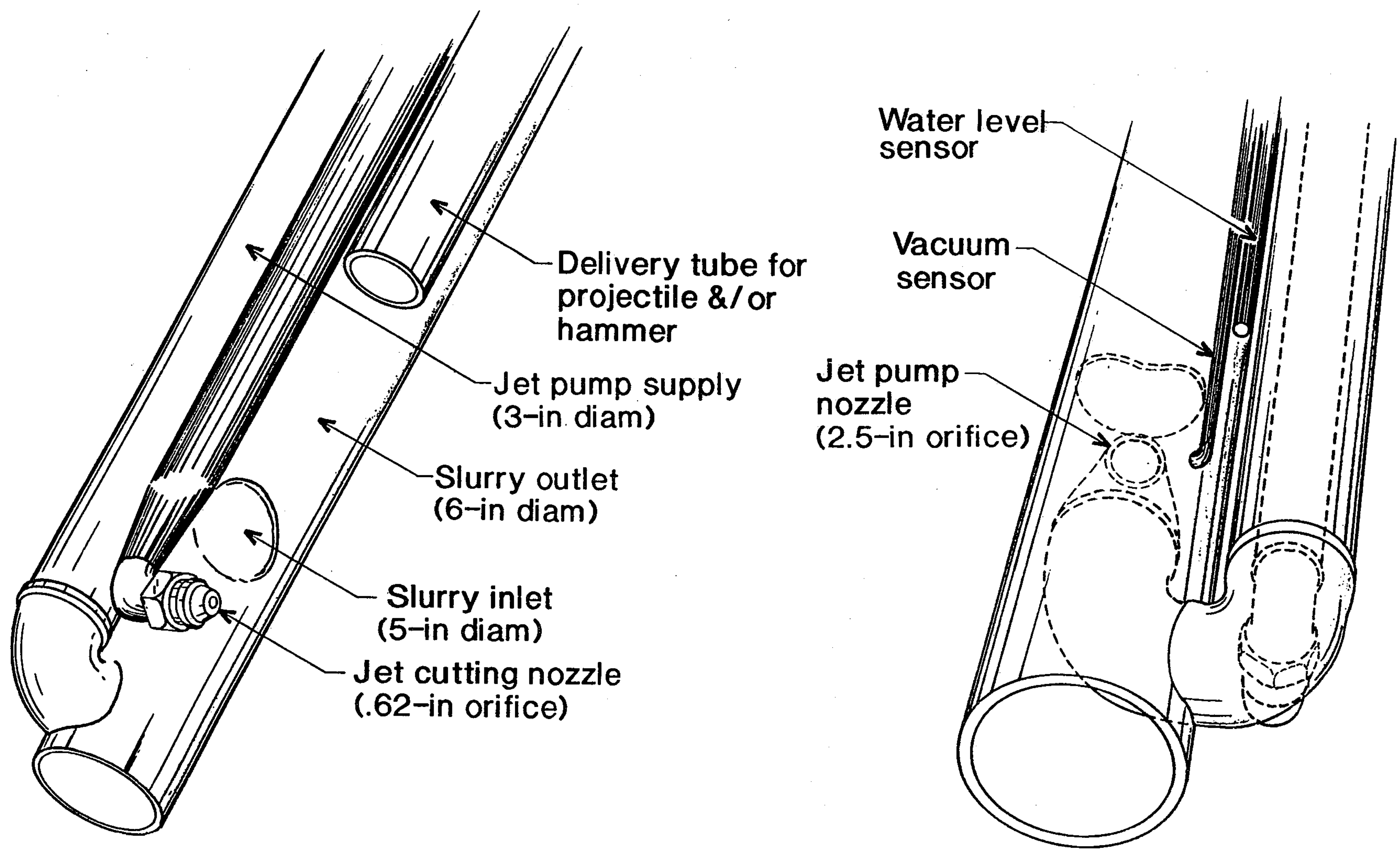

Figure 2. - Base of borehole mining tool used in 1994 test.

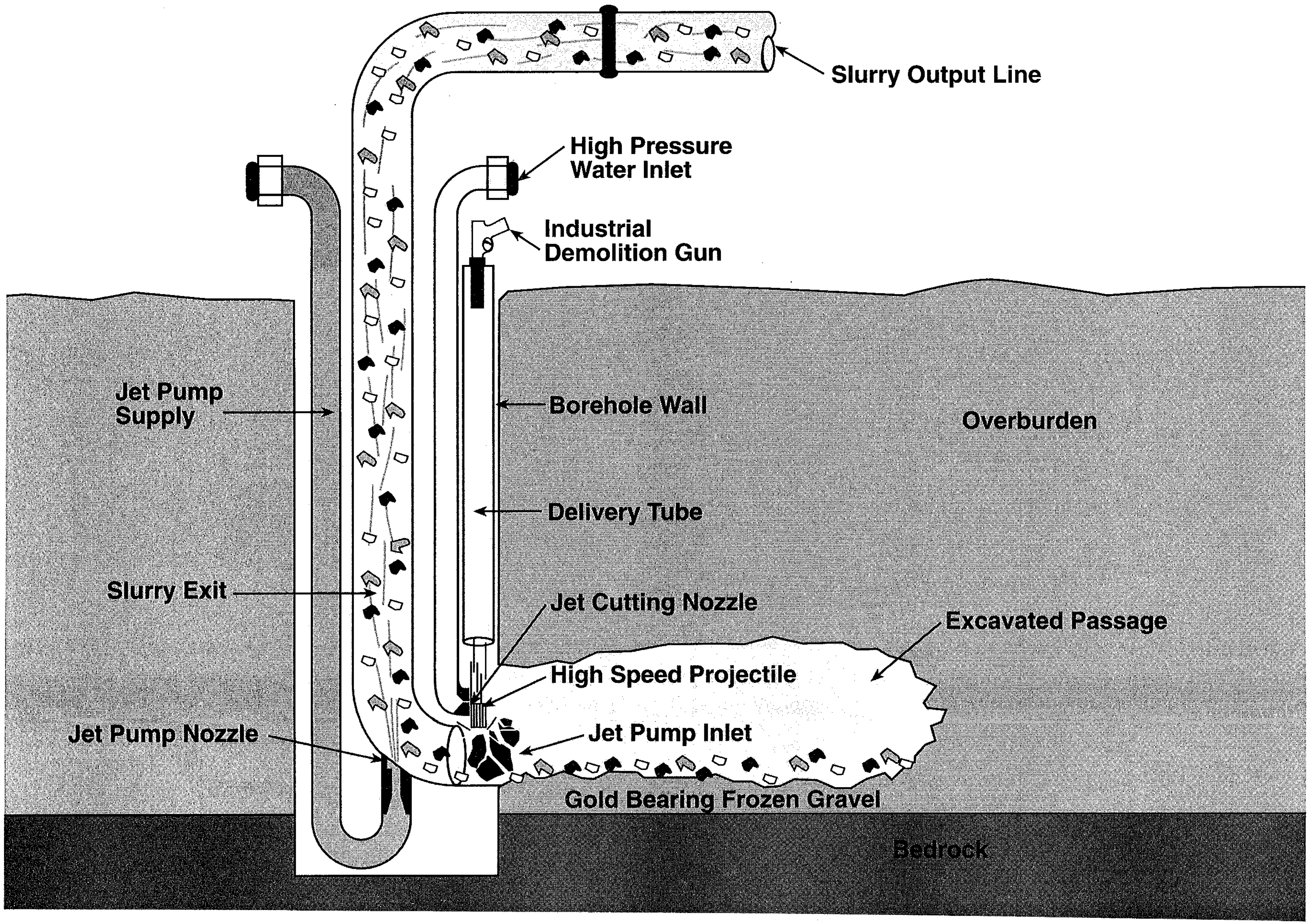

Figure 3. - Schematic diagram of miner used in 1994 test.

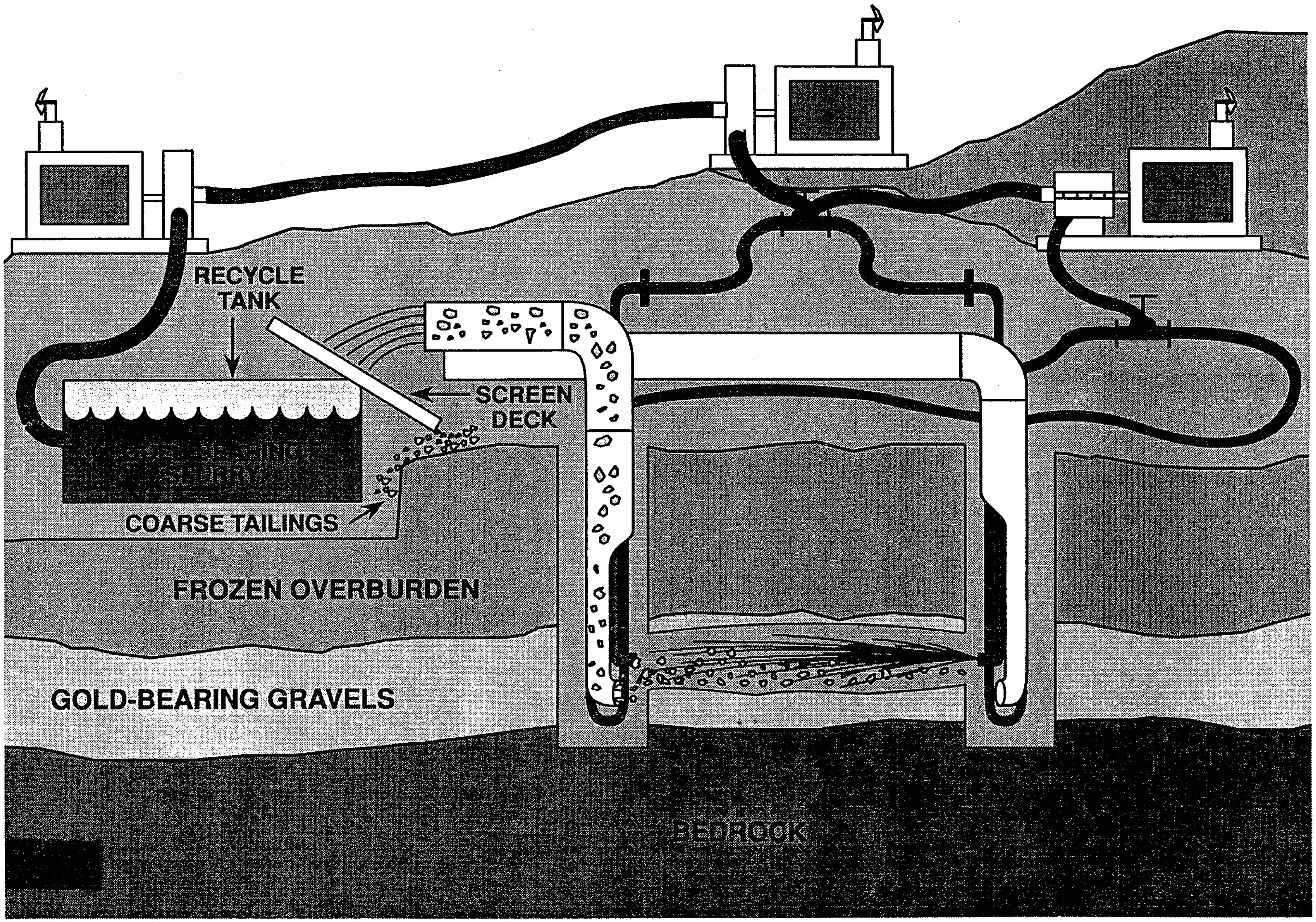

Figure 4. - A closed-loop borehole gold mining system in operation.

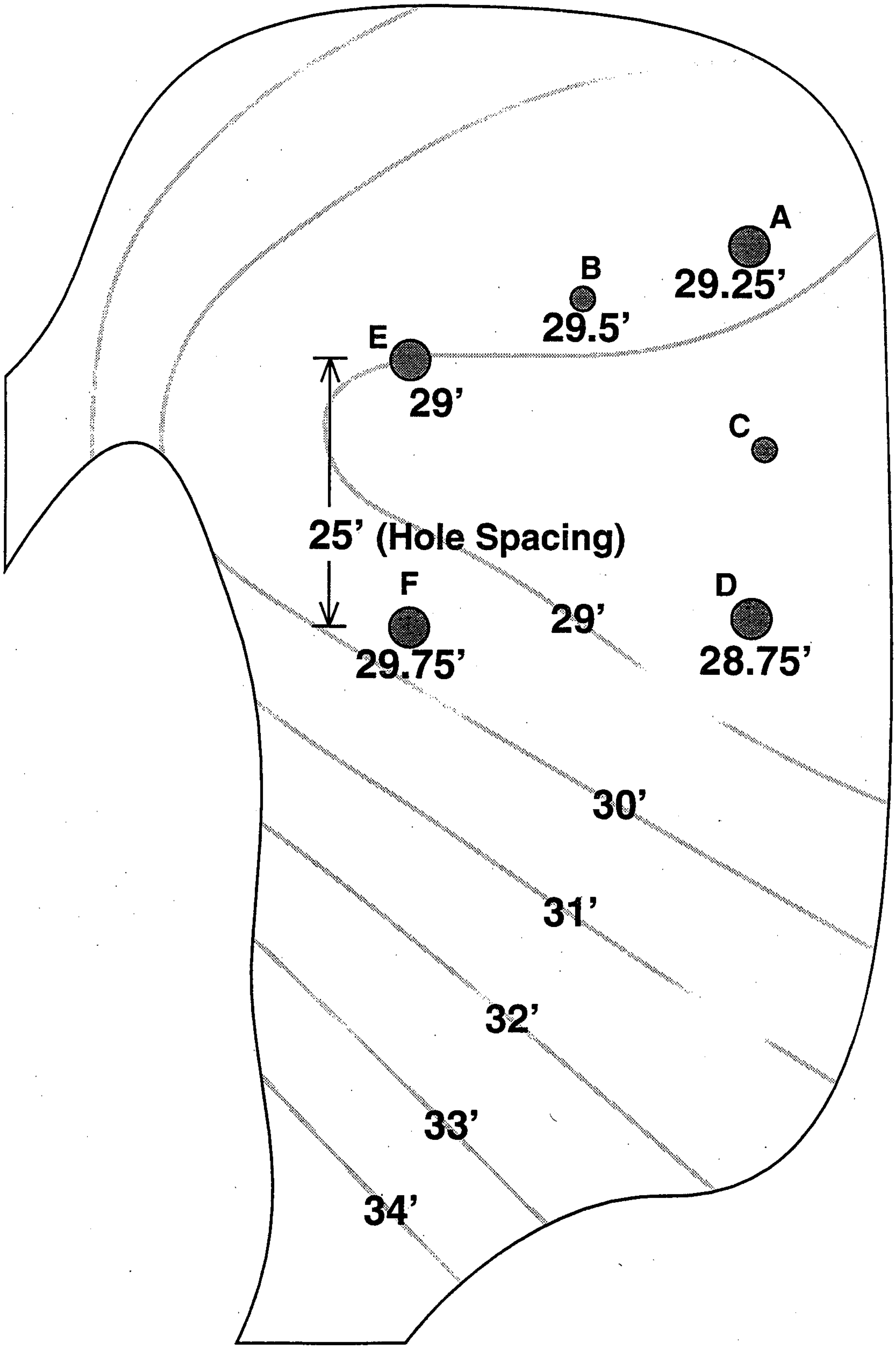

Figure 5. - Plan view of mining area showing distribution of boreholes. Contours indicate bedrock depth from reference point located approximately 4 ft above surface near Hole A.

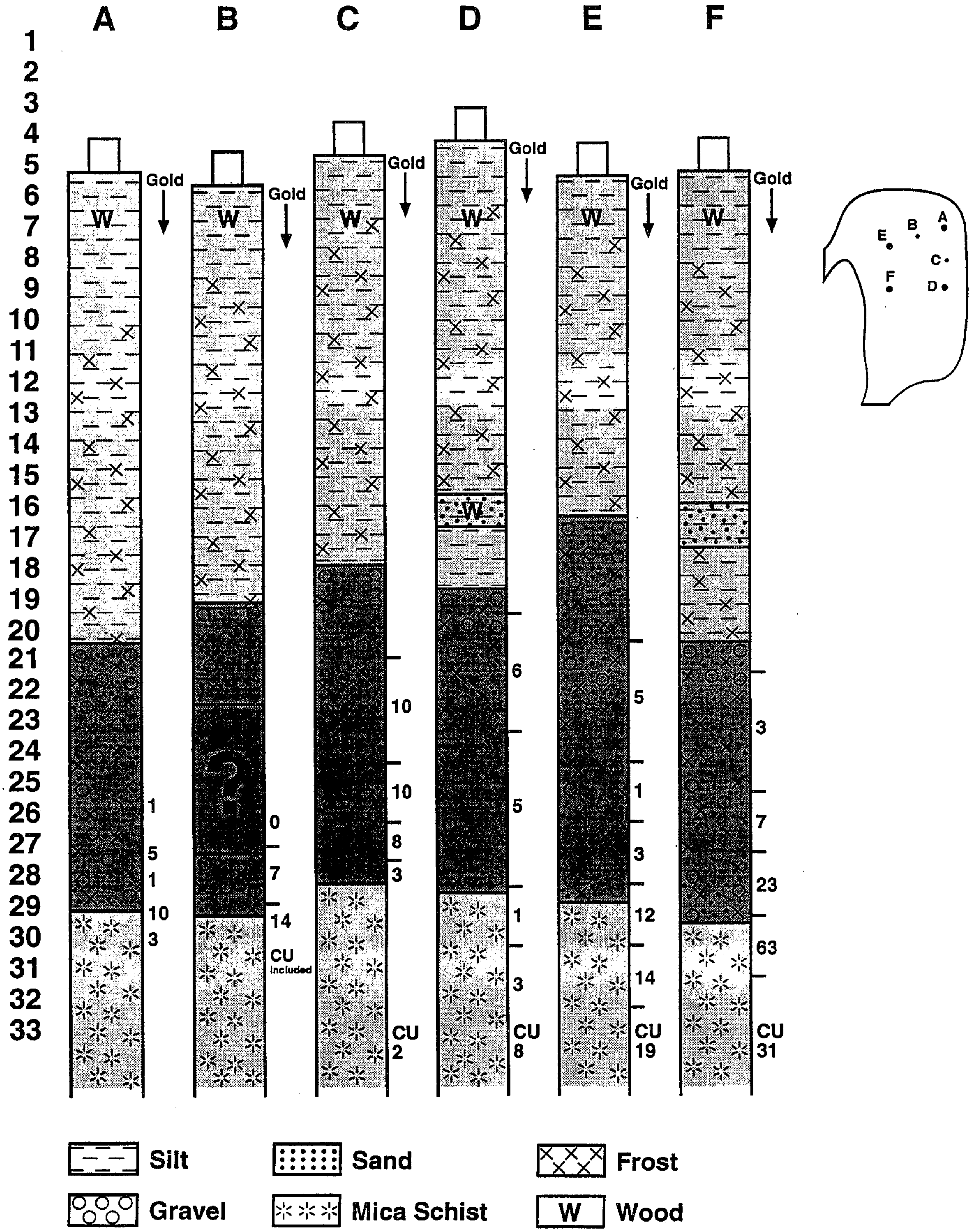

Figure 6. - Cross sections of production holes. Depth in feet from transit level shown on left. The number of gold particles found by panning shown on the right of each column.

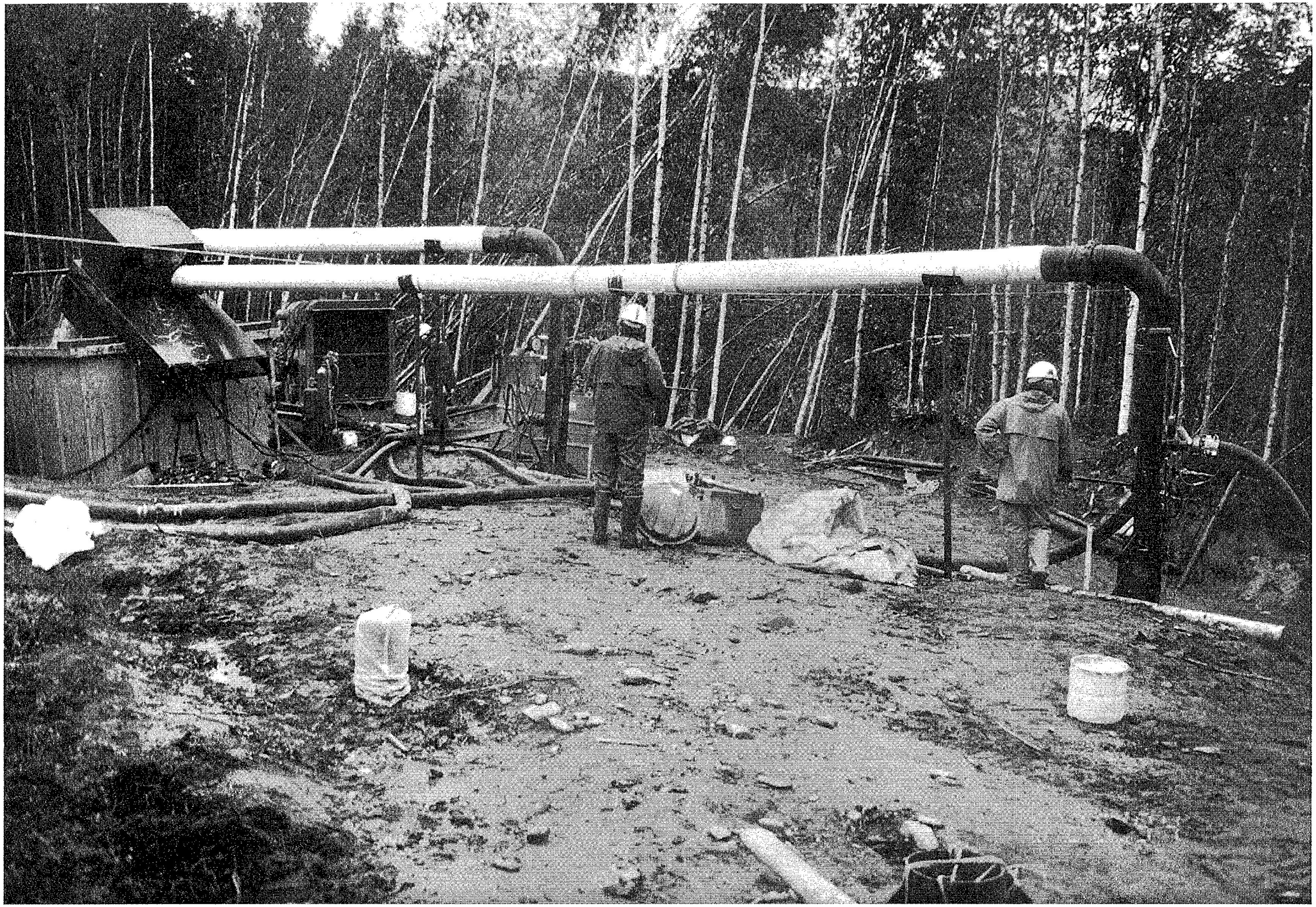

Figure 7. - Borehole miners in place at the test site. Note water discharging into a steel tank.

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Paper 2

HIGH PRESSURE WATER JET ASSISTANCE OF HARD ROCK CUTTING PROCESS

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ABSTRACT

The interaction between hard and abrasive rocks and the cutting tool is the main topic of this paper. Methods for classification of the decisive properties in relation to the cutting process are presented. Research on wearing process of the bit tips and pick consumption is described. Influence of the jet assistance on cutting process based on measurements of cutting and normal forces and energy consumption is discussed.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

Cutting of hard rock requires excessive external energy and therefore still presents a special problem for mining and underground civil engineering. Effective and economical cutting of hard rocks depends on the performance of the cutting tool. An ideal cutting tool should have a high cutting performance and low wear and consumption of specific energy. It should be able to penetrate deeply into the rock and generate neither an excessive quantity of dust nor friction ignition. Furthermore, it should maintain a proper optimum temperature and its cost should be low.

Mining practice has demonstrated that none of available tools can satisfy all the above requirements. The results of long-term and extensive activity in the field of cutting tool development reveal that despite the indisputable progress in the solution of the cutting tool geometry, application of new materials and new production technologies the development of a new cutting tools capable to effectively disintegrate hard abrasive rock has been unsuccessful (Vašek, 1992).

2. CUTTING TOOL–ROCK INTERACTION

The cutting tool–rock interaction has not been completely examined so far and therefore greater attention should be paid to this problem. New possibilities for the application of many physical disintegration principles are coming into existence, allowing creative and constructive opportunities for scientists and technicians.

At present, the conventional approach remains based on the principle that greater rock reactions are overwhelmed with greater actions, using heavier and more powerful and more expensive machines.

Due to the interaction of high action and high reaction, a high level of contact stresses is achieved, with negative consequences. High contact stresses result in quick blunting (Fig. 1.) or even failure of the disintegration tool, which was originally the cause of the

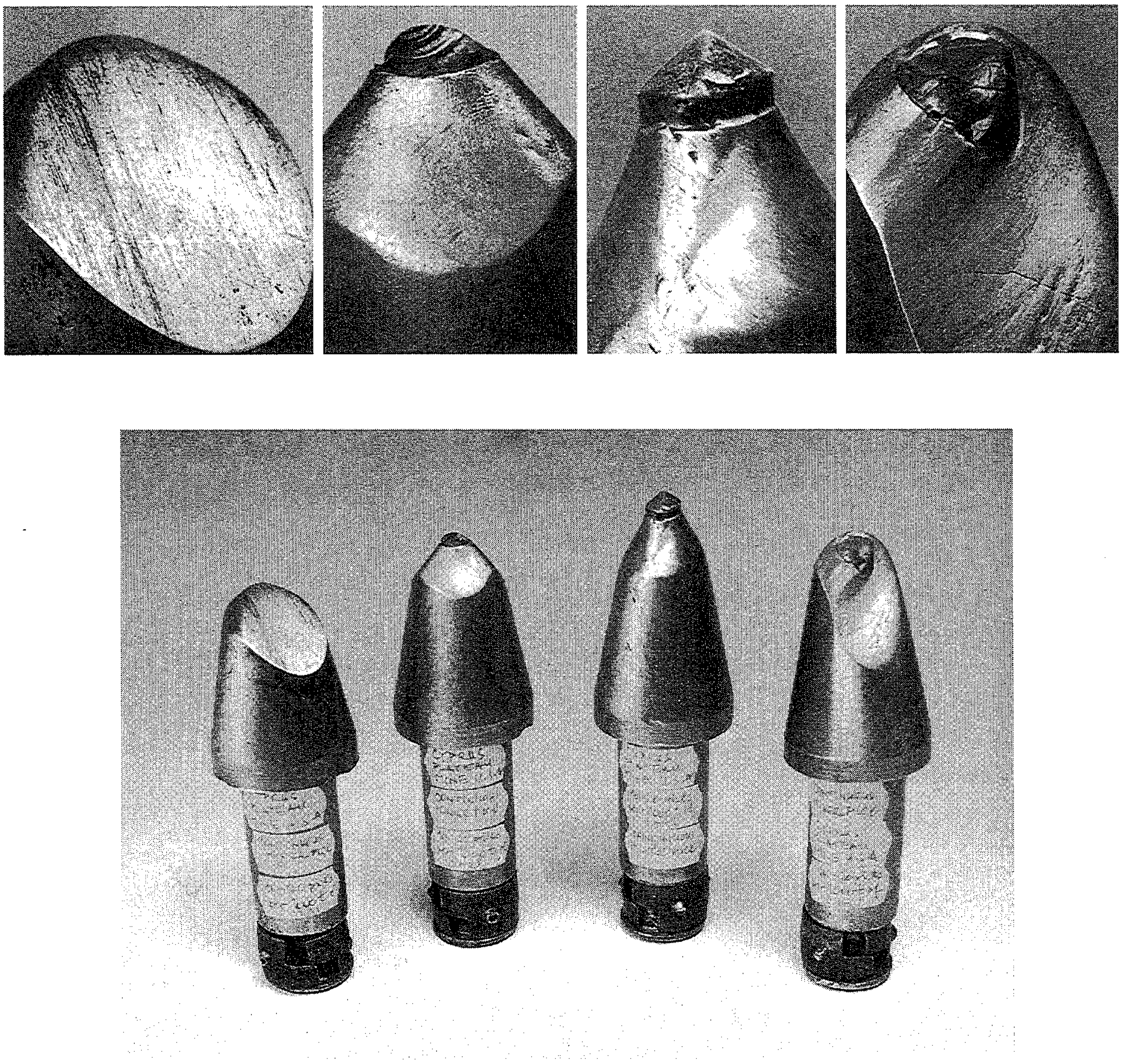


Fig. 1. Worn point attack cutting tools from the cutting head of the Joy 12CM12 continuous miner operated in the Wattis Seam of the Cyprus Mine (Plateau Mining Company, Utah, U.S.A.).

stress (Fig. 2.). This problem is generally resolved by changing the mechanical tools more frequently and by manufacturing the tools from more resistant materials.

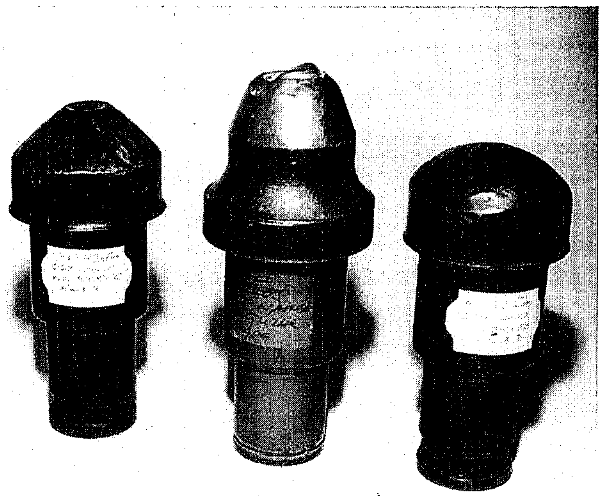


Fig. 2. Point attack cutting tool with damaged cutting bit from the cutting head of the AM–50 roadheader operated in longwall face of the František Mine (Ostrava Coal District, Czech Republic).

3. DECISIVE PROPERTIES OF ROCKS

A method of evaluating the cuttability of rocks using special testing equipment was developed in Czechoslovakia. The evaluated parameters are WORKABILITY, ABRASIVITY, INDENTATION STRENGTH, DEGREE OF FRACTURING and SPECIFIC ENERGY (Fig. 3., Vašek, 1995).

For rough estimation of the consumption of rotating point–attack picks type TN–20 (Czech made), the following empirical relationship was proposed (Vašek 1990):

$$S_p = -\frac{1}{Kk} \ln(1.23 - \frac{(R+200)(Fv+2)}{5410} \qquad [\text{picks}\cdot\text{m}^{-3}]$$

where
Sp – pick consumption (pieces·m^{-1}),
R – workability (kN·m^{-1}),
Fv – abrasivity (mg·m^{-1}),
Kk – coefficient on the quality of picks (for picks TN–20, Kk = 1).

According to this method, rock can be classified as workable or difficult to disintegrate, in relation to the pick consumption. In the case of Ostrava–Karviná coal basin, workable (cuttable) rocks can be classified by following values of decisive parametrs: workability of < 700 kN·m^{-1}, abrasivity < 3.0 mg·m^{-1}, specific energy < 12 MJ·m^{-3} and pick consumption < 0.3 pieces·m^{-3}.

When cutting rocks above the limit extent of cuttable rocks, the pick wears excessively and it involves a lot of adverse consequences such as increase in specific energy consumption, in friction and temperature, increase in cutting resistance, in vibration and in temperature, increase in crushed fraction, in dust generation and many others negative influences that call for higher expenses and deterioration of the working conditions. Their importance requires solutions to be found by research and production development trials (Khair, Vašek, 1995).

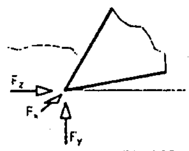
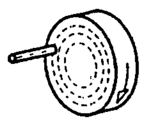
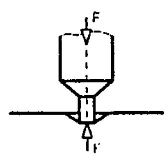
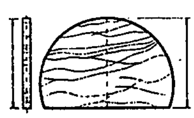
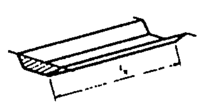
Decisive Properties of Rocks	Symbol	Unit	Schematical Sketch of the Mode of Measurement	Calculation	Standard
Workability	R	kN.m^{-1}	 CUTTING RESISTANCES	$R = \left(3 + \frac{\sum_{i=1}^{n} \frac{\phi F_{zimin}}{h_i}}{\sum_{i=1}^{n} \frac{\phi F_{zi}}{h_i}}\right) \frac{\sum_{i=1}^{n} \frac{\phi F_{zimax}}{h_i}}{4n}$	ON 441120
Abrasivity	F_v	mg.m^{-1}	 EFFECT OF ABRASION	$F_v = \frac{G}{L}$	ON 441121
Indentation Strength	σ_{vt}	MPa	 RESISTANCE OF ROCK AGAINST INDENTATION	$\sigma_{vt} = \frac{\sum_{i=1}^{n} F_{i\,max}}{S_t\, n}$	ON 441121
Degree of Fissuration	SP	-	 LENGTH OF HOMOGENEOUS PARTS OF ROCK	$SP = 1 - \frac{\left[25\sum_{i=1}^{4} f_i + 50\sum_{i=1}^{4} i f_{i-1} + 200(f_k - 100)\right]^2 \xi}{10^4\, l_{max}^2}$	ON 441122
Specific Energy	SE	MJ.m^{-3}	 BREAKING VOLUME	$SE = \frac{F_z\, l_x}{V}$	

Fig. 3. Decisive properties of rocks

4. WEARING PROCESS OF BIT OF PICKS

Wearing process of the cutting tools that changes the geometry of bit picks involves adverse consequences such as finer production, higher cutting resistance, vibration, increased energy consumption, lower disintegration output, higher bit temperature and thus higher rate of bit wear, increased dust generation and higher danger of ignitions of methane and dust.

The results of theoretical and experimental research can lead to the conclusion that it is necessary to try to PRESERVE POINT O (the cutting edge point with the highest stress), (Vašek, 1983).

Besides the oldest but still widely used exchange of worn cutting tools by new ones as well as the more progressive method of application of high materials exhibiting higher wear hardness, rotation of cutting tools and high pressure water jet assistance can considerably contribute to the elimination of the above mentioned negative consequences and thus extend the range of workable rocks.

5. WATER JET ASSISTANCE OF CUTTING PROCESS

The cutting tool with the assistance of high pressure water jet can have two different modes of use depending on their space–time arrangement. In the first case the high pressure water jet acts on the rock at a considerable time and space distance from the cutting tool, whereas in the second case, the high pressure water jet acts immediately on the spot of the interaction ROCK–CUTTING TOOL.

Experimental research in disintegration of hard rocks performed in the Institute of Geonics (formerly Mining Institute) of the Czech Academy of Sciences in Ostrava revealed that use of high pressure water jet (in time and space distance) can considerably diminish cutting forces on the cutting tool, however, without making full use of the advantages of the high pressure water jet such as cooling the cutting tool, decreasing dust generation, reducing the risk of methane–air mixture ignitions, etc. (Vašek 1990).

Therefore, analyses of many scientists were focused on the effect of high pressure water jet at the place of the cutting tool–rock interaction (Fowell, Tecen, 1983, Vijay, 1989, Taylor, Furno, 1988, Hood, Knight, Thimson, 1992).

In cooperation with West Virginia University (Vašek, 1994), six cutting bits (three point attack bits and three drag bits) were prepared and tested in the laboratory using linear cutting device (Fig. 4.) that consists of three component quartz force transducer Kistler type 1683A5 (1) with special pick holders (2) and water jet nozzle (3). Water jets were generated under inclination of 45° (standoff distance 45 mm, water pressure 200 MPa). Rock samples (4) were fixed on the support of the cutting device. Series of tests without and with water jet were performed and evaluated (Khair, Vašek, 1995).

Under given testing conditions, no notable influence of water jet assistance to point attack bits or drag bits on decreasing of mean and peak cutting forces was observed. In many cases, the mean and peak cutting forces were even higher for cutting bits with water jet assistance (Khair, Vašek, 1995). Furthermore, no remarkable differences in character of cutting grooves were observed (see Figs. 5. and 6.).

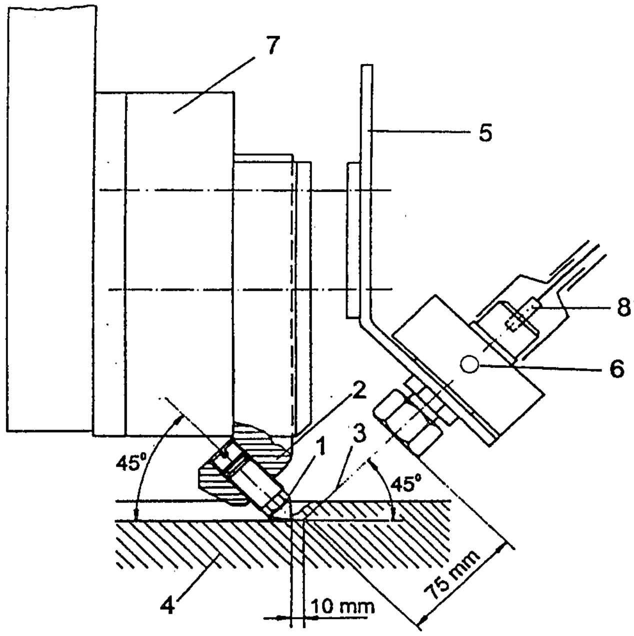
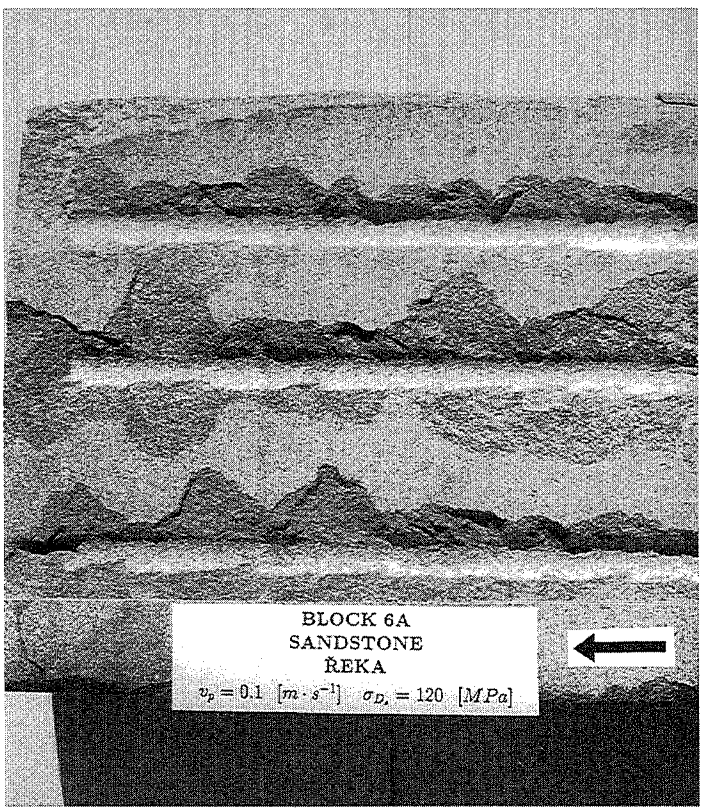


Fig. 4. Water jet assisted cutting bit arrangement 1 – cutting bit, 2 – bit holder, 3 – water jet, 4 – workpiece, 5 – water jet holder, 6 – high pressure water jet inlet, 7 – pressure transducer.



BIT TYPE	JET-NOZZLE POSITION	DEPTH OF CUT [mm]	WATER PRESSURE [MPa]
US3		6	100
US3	–	6	–
US3		6	200

Fig. 5. Cutting grooves made in block of Godula sandstone No. 6A with and without water jet assistance ahead of the drag cutting tool (water pressure 100, 0, 200 MPa, depth of cut 6 mm, compressive strength of the rock 120 MPa)

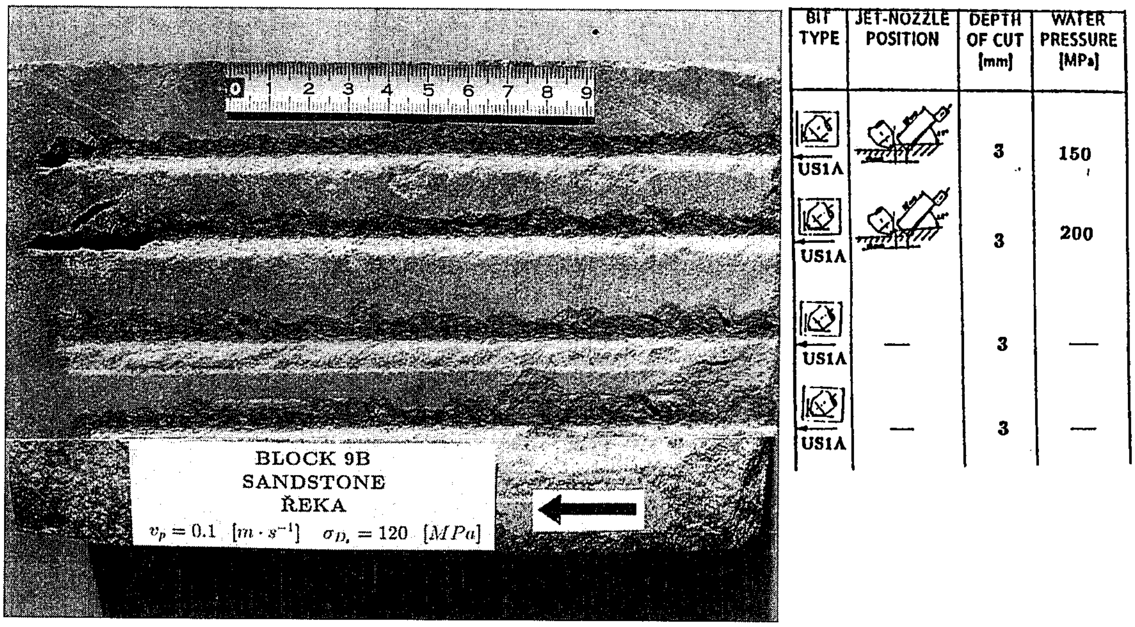


Fig. 6. Cutting grooves made in block of Godula sandstone No. 9B with and without water jet assistance ahead of the point attack cutting tool (water pressure 150, 200, 0, 0 MPa, depth of cut 3 mm, compressive strength of the rock 120 MPa)

Results in this area of research lead the author to the conclusion that further analyses focused on the effect of high pressure water jet assistance have to include also tests with high pressure water jet directed through the cutting bit. Therefore, the design of a new cutting tool was proposed (Fig. 7.).

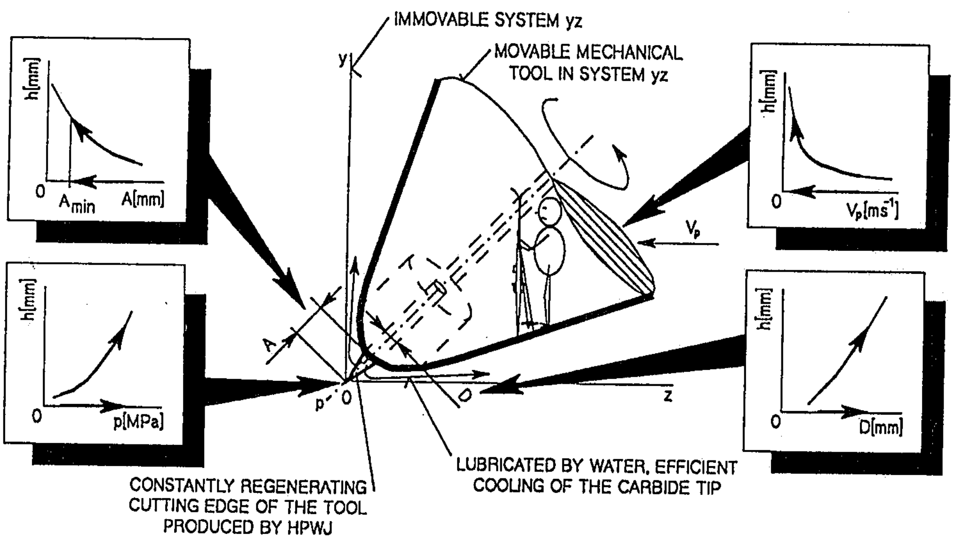


Fig. 7. Sketch of the tool with water jet through cutting bit

First laboratory experimental results obtained with the new cutting tool have indicated remarkable decrease of the cutting forces during the disintegrating process. In some places along the cutting lines the cutting forces dropped even close to zero values. Direct contact between the cutting bit and disintegrated rock was also considerably decreased (Fig. 8., Table. 1.). This phenomenon can lead to more effective cutting process with very low value of friction coefficient between cutting bit and rock. In addition to that, the development of a new generation of the cutting tools preserving the mostly stressed point 0 of the cutting edge by high pressure water jet should be started. New research activity in this area has been already initiated (Sitek et al., 1995).

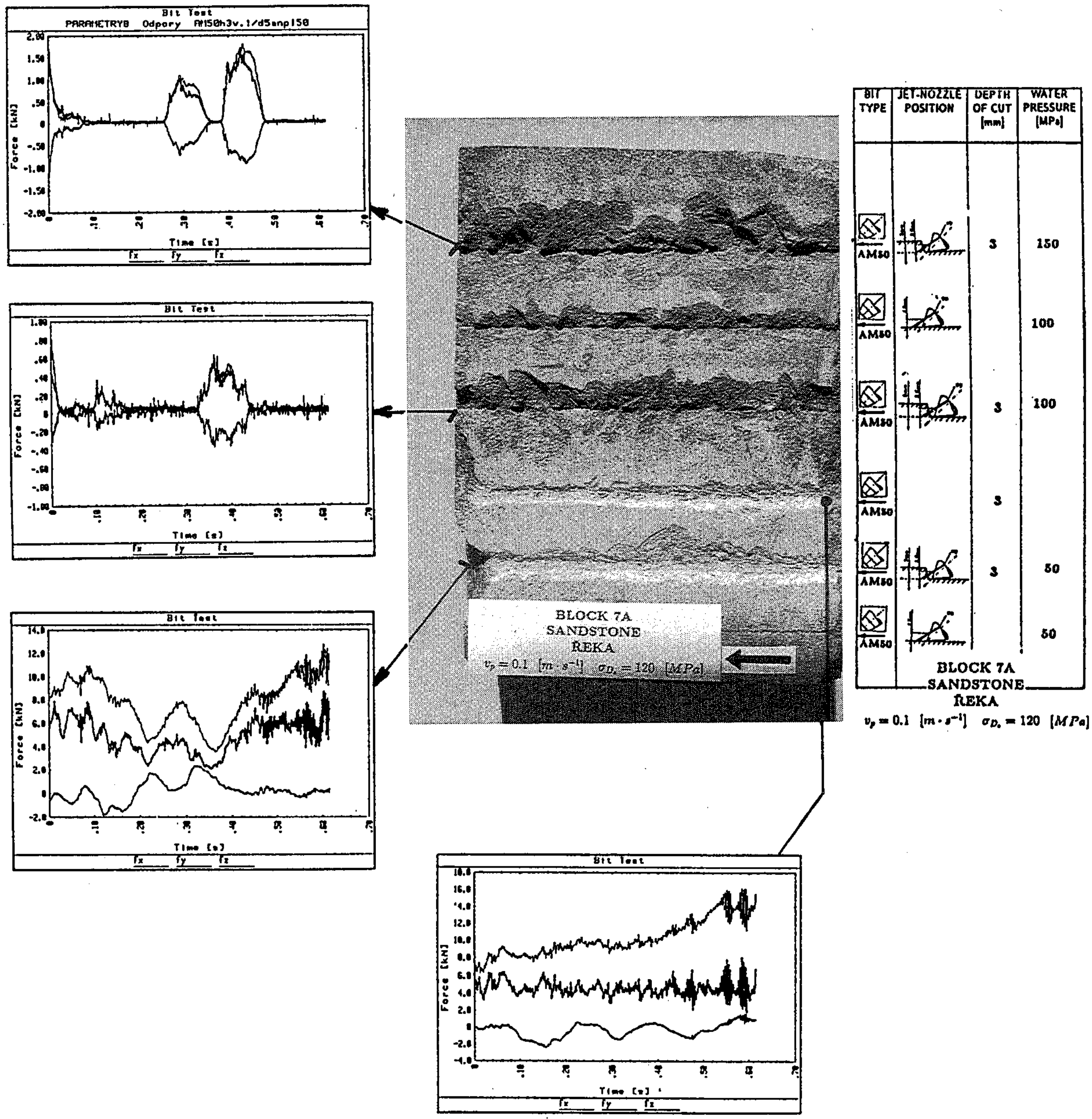


Fig. 8. Cutting grooves made in block of Godula sandstone No. 7A with assistance of water jet through point attack cutting bit (water pressure 150, 100, 100, 0, 50, 50 MPa, depth of cuts 3, 0, 3, 3, 3, 0 mm, compressive strength of the rock 120 MPa)

Table 1. Results of Measuring of Mean and Peak Cutting Forces (Water Jet Assisted)

Bit No.	Type of Bit	Cutting Depth	Water Pressure	Mean Cutting Force			Ratio F_z/F_y
		h [mm]	[MPa]	F_x [kN]	F_y [kN]	F_z [kN]	
AM 50	point attack bit	3	150	−0,16	0,35	0,33	0,94
		–	100	0,00	0,00	0,00	–
		3	100	0,04	0,12	0,12	1,00
		3	–	−0,38	10,25	4,55	0,44
		3	50	0,22	7,86	4,88	0,62
		–	50	0,00	0,00	0,00	–

Table 1. – continue

Peak Cutting Force			Ratio F'_z/F'_y	Rock Yield	Specific Energy	Block No.
F'_x [kN]	F'_y [kN]	F'_z [kN]		V [$m^3 \cdot 10^{-6}$]	SE [$MJ \cdot m^{-3}$]	
0,22	1,87	1,76	0,94	7,55	491,36	7A
0,00	0,00	0,00	–	2,45	1506,12	7A
0,14	0,88	0,63	0,72	4,40	840,27	7A
1,62	16,22	8,15	0,50	1,90	2085,79	7A
2,35	12,76	8,71	0,68	1,83	2165,57	7A
0,00	0,00	0,00	–	0,45	8200,00	7A

6. CONCLUSION

The harder and more abrasive the rock is, the less effective and more expensive the cutting process with an traditional cutting tools becomes. Water jet assistance ahead of the cutting tool did not provide expected results under given conditions. On the other hand, the water jet assistance through the cutting bit seems to offer a very progressive method for cutting of hard and abrasive rocks.

ACKNOWLEDGEMENT

The author is thankful to Grant Agency of the Academy of Sciences of the Czech Republic and Grant Agency of the Czech Republic for their support of the project No. 3165 and No. 101/94/1429 respectively. Collaboration with Prof. W.Khair from West Virginia University is also greatly appreciated.

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8th American Water Jet Conference
August 26-29, 1995: Houston, Texas

Paper **3**

ABRASIVE PERFORMANCE IN ROCK CUTTING WITH AWJ AND ASJ

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ABSTRACT

Results of a systematic research aimed at disclosing the set of optimum performance in linear cutting of granite and marble slabs using abrasive waterjet are illustrated and discussed. Tests have been carried out with the two different methods of abrasive jet generation (AWJ and ASJ) under variable experimental conditions (traverse velocity, abrasive feed rate) using various abrasives. It is shown that the key factor in stone cutting is represented by the productivity of the abrasive (specific erosion), which can be correlated to suitable parameters accounting for the different properties of the abrasive, such as specific gravity, particle size, shape factor and hardness.

Organized and Sponsored by the Water Jet Technology Association.

1. FOREWORD

A variety of technologies are available for processing stone blocks into shaped pieces:

— For block sawing into large slabs, reciprocating gangsaws are extensively employed, using either diamond-tipped blades (marble) or steel shot (granite). For the production of thick slabs diamond wire frame is becoming increasingly popular.
— For the mass production of tiles as well as for slab shaping into squared pieces, diamond disk is the dominant tool for both marble and granite.
— For flat-bed contour cutting, diamond wire is used in the case of thick slabs, whereas abrasive waterjet becomes preferable when slab thickness is less than 4-5 cm.

Abrasive waterjet can find interesting application also for surface finishing as a substitute of flaming, bush-hammering or sand-blasting and even in 3-D carving in competition or in combination with diamond tools.

Although the segment where waterjet can be economically viable is relatively small, compared to diamond-based technologies, the extent of the whole stone business is so large that interesting prospects of application can be predicted, giving significance to the efforts aimed at elucidating the most profitable ways of using the technology: optimization of jet parameters and nozzle driving variables and, especially, the most appropriate choice of the abrasive. Basically, two alternate ways can be used for producing an abrasive jet.

With the entrainment technique (AWJ) the abrasive is incorporated into a water jet generated through a primary nozzle and the abrasive stream is focussed to the target by means of a coaxial tube. The abrasive is sucked dry into the intermediate mixing chamber.
In abrasive suspension jetting (ASJ) abrasive is premixed inside a pressurized vessel from which the abrasive slurry is delivered to the nozzle through a flexible hose.
The features of the two methods are summarized in Table 1.

As a matter of fact, with low pressure systems much larger water flow rates and higher abrasive dosages must be used, requiring larger nozzle diameters.

Although different in concept, both methods appear suitable for rock cutting. Therefore it seemed interesting to undertake a research aimed at elucidating their performance in order to identify the respective field of application and to predict the technical and economic results.

2. EXPERIMENTS

2.1 Equipment

Two different machines have been used for the cutting experiments:

— AWJ, featuring a three-axis computer-controlled driving system, in which the

abrasive jet is generated according to the suction method by means of a Flow head fed by an intensifier pump.
— ASJ, connected to a triple-piston plunger pump capable of delivering a maximum flow rate of 54 l/min, suitable for operating the slurry-forming unit at 70 MPa with a nozzle diameter smaller than 1.8 mm, by-passing the excess water.

The lance can be traversed at a velocity variable from 0 to 150 cm/min with reasonably good steadiness assured by a set of axial bearings with ball-recirculation, sliding on steel bars.

2.2 Materials

Tests have been carried out on "Rosa Beta" granite (Sardinia) and "Bianco Carrara" marble (Tuscany).The samples have been obtained from thick gangsaw slabs, properly shaped into pieces having a trapeziform cross section in the plane of the traversing jet, so as to obtain a linearly increasing thickness from zero at the jet intake up to a maximum of 80 mm, as shown in Figure 1 (Agus et al., 1994).

This expedient was adopted in order to explore the maximum through-cutting depth at variable setting of operational parameters.

The "Rosa Beta" is isotropic in texture and has holocrystal, hypidiomorphic, uneven grain structure.

The "Bianco Carrara" is a metamorphic carbonatic rock with a typical saccharoidal appearance.

Their relevant characteristics are summarized in Table 2.

2.3 Abrasives used

The following abrasives, whose main properties are given in Table 3, have been taken into consideration for the cutting experiments:

— garnet (Barton);
— quartz sand;
— copper slag (J-Blast Supafine, IMI);
— steel shot (Grantag, Met. Toniolo).

Garnet and copper slag are commercially available products commonly used in AWJ cutting; steel shot is normally employed in granite sawing with reciprocating gangsaws; quartz has been prepared for the tests by concentration, grinding and classification of sorted-out rock. For each kind of abrasive two size classes obtained by dry screening have been used separately for the AWJ experiments with the AWJ equipment:

— Coarse fraction: -0.800 +0.425 [mm]
— Fine fraction: -0.425 +0.150 [mm]

The full size range was used for the tests with the ASJ.

2.4 Testing plan

Linear cutting tests have been carried out on the above described samples of granite and marble with the TIDRA and the DIAJet under comparable working conditions except for the parameters typical of each technology (Yazici et al., 1989).
Parameters kept constant in the tests were:

PARAMETERS	AWJ	ASJ
- Pressure [MPa]	300	65
- Nozzle diameter [mm]	0.325	-
- Focussing diameter[mm]	1.05	1.6
- Stand-off distance [mm]	4	8

Operational variables taken into consideration in the factorial plan were:

— Abrasive feed rate: from 50 to 350 [g/min] (AWJ)
  from 1 to 5 kg/min (ASJ)
— Traverse velocity: from 4 to 24 cm/min, step 4.

3. RESULTS AND DISCUSSION

3.1 - Cutting rate

With reference to Figure 1, the following measures have been taken for describing the depth of cut:

— through- cut depth H_0, irrespective of cut quality;
— height of the regular cut zone H_1, where striation does not exceed half the collimator diameter;
— total kerf depth H_2 in the case of blind cut.

Cutting rate, calculated by multiplying H_1 by traverse velocity V_t, represents the best technical performance achievable with a given abrasive consumption, at comparable cut quality.

It is to be underlined that waterjet can only provide a rough surface that can either be already acceptable or might need to be improved to the desired accuracy with diamond tools, according to technical specifications .

The discriminating value for striation, here assumed, reflects the average quality level commonly demanded at the intermediate stage of a stone working process, before the finishing step.

Maximum cutting rate achieved is shown in the bar diagrams of Figure 2 a and b. Experimental data have been corrected through interpolation for the sake of easier comparison at equal abrasive feed rate.

The following aspects are worth noting:

A - Abrasive water jet (AWJ)

— generally speaking, cutting velocity at equal feed rate is slightly higher the coarser the abrasive for both marble and granite, especially in the case of quartz sand and copper slag that have a lower specific gravity: only larger particles would provide a sufficiently strong impact force on the target, which depends on particle mass;
— of course the higher the feed rate, the higher cutting velocity will be, although with a different marginal increase. In fact it appears that the gradient of cutting velocity as a function of feed rate decreases for granite, whereas the opposite happens for marble;
— garnet gives a better performance (Foldyna, 1991; Vasek et al., 1993) compared to the other abrasives tested, followed by steel shot, quartz sand and copper slag. This last abrasive, although very poor on granite, provides acceptable cutting results on softer marble, maybe due to its favorable shape factor;
— however the disparity in performance of the various abrasives between marble and granite is not as remarkable as target material properties would lead to predict. It is likely that, at the pressure adopted for the experiments, cutting process develops in a more favorable way for granite (heterogeneous, harder and brittle) than for marble (homogeneous, softer and ductile);

B - Abrasive suspension jet (ASJ)

— similar evidence is reached also in this case: copper slag is very poor for granite despite increasing its dosage up to 5 kg/min, but for marble it approaches the performance level of garnet and quartz sand, especially at the higher feed rate (3 kg/min);
— however, the difference in cutting velocity between granite and marble is now considerable (200 cm^2/min against 300), meaning that with DIAJet the more favorable material properties are better exploited;
— due to the much higher feed rates employed, cutting velocity is about two times that achieved with the AWJ system for granite (except for copper slag) and around three times for marble.

3.2 Specific erosion

Abrasive productivity (specific erosion) generally decreases as feed rate increases, as shown in Table 4 a and b.

3.3 Cut quality

Cut waviness (Hashish, 1992; Guo et al., 1995) has been measured along a straight line parallel to the upper surface of the test sample at a distance equal to one third of the regular cut depth H_1.

Rugosity features have been determined by means of a Perthometer Mod S3P.

Average waviness measured over a 5.6 cm specimen length is shown by the bar diagrams of Figure 3 a and b for each size class as a function of abrasive feed rate.

The picture is less legible than that of cutting rate. However, the following aspects appear quite evident:

A - AWJ

— with all abrasives, cut surface is much smoother for marble than for granite (waviness is roughly four times less);
— for granite, cut quality is very sensitive to the kind of abrasive used and less so to particle size: quartz gives the best accuracy, followed by copper slag, garnet and steel shot, in the order as the sequence of their volumic mass. It is worth noting that waviness with quartz sand is about 2.5 times lower than with garnet;
— regarding marble, it seems that all abrasives have the same behavior with very slight differences between them, although copper slag seems to produce a rougher surface, maybe due to its higher shape factor;
— as for the influence of abrasive feed rate, distinct considerations can be advanced for granite and marble: waviness increases with feed rate for the first rock, whereas it seems substantially independent of it for the second. Copper slag has an anomalous behavior, not easy-to-explain, since in most cases waviness decreases towards the higher feed rates;
— traverse velocity is known to have a not secondary effect on roughness. Comparison of experimental data show that, as a general rule, waviness first increases with traverse velocity and then decreases, reaching a top value in the range around 12 m/min, maybe due to the fact that tracks cross each other beyond that point, thus producing a certain smoothing effect.

B - ASJ

— differences in rugosity features between marble and granite are less evident than in the case of AWJ;
— in granite cutting, waviness with the various abrasives again follows the same order of specific gravity, whereas for marble there is no significant difference;
— as for the influence of feed rate, considerations substantially similar to those with AWJ hold also in this case, although with some occasional discrepancies.

3.4 Correlations

Specific erosion given in Table 4 a and b can be correlated to suitable comprehensive parameters accounting for the various pertinent properties of the abrasives used.

The study was first developed on theoretical grounds in order to clarify the aspects of kinetic energy transfer from the water jet to the abrasive particles incorporated in the slurry stream. Particle velocity and impact energy of the abrasive jet on target material were then calculated as a function of pressure, mass flow rate, particle size and volumic mass of the abrasive (Cheng et al., 1991; Galecki, 1991; Guo et al., 1991; Isobe et al., 1988; and Miller et al., 1991). Hardness and shape factor were finally included as multiplicative coefficients.

Exponents for the different factors included in the global parameter were searched through a regression analysis on experimental data, taking the values giving the best fitting (maximum correlation coefficient), on the assumption of a linear relationship.

Results are represented in Figures 4 and 5.

It was found that parameters to be used for granite and marble are similar in structure but differ in some of the exponents, meaning that the influence of the various abrasive properties is not the same for the two cases, as expected.

In particular:

— For granite: $P_g = H^{1.4}S^{0.2}M^{-0.4}D^{0.3}F^{-0.5}$
— For marble: $P_m = H^{0.7}S^{2.1}M^{-0.3}D^{0.2}F^{-0.5}$ where:

— H = Knoop Hardness
— S = Shape factor difference between particle and a reference sphere
— M = volumic Mass
— D = mean particle size
— F = Abrasive Feed rate (by volume)

Correlation is very strong for both rocks in the case of AWJ, with a squared correlation coefficient well exceeding 95%.

Correlation using the same parameters was found to be poorer in the case of ASJ and could not be substantially improved by modifying the exponents. A more accurate study should be carried out on a larger population of experimental data.

Scattering of data points around the regression line with the ASJ is maybe due to a certain unsteadiness and a lack of accuracy in slurry flow rate setting, typical of the system (Summers, 1990). In spite of this, the influence of the various abrasive properties appears confirmed, pointing out that the cutting mechanism with the two systems is basically the same.

In particular, the following aspects deserve special consideration:

— The influence of abrasive concentration in the slurry is the same in all cases: specific erosion is reversely proportional to the square root of this parameter, meaning that abrasive efficiency is always penalized by increasing particle crowding;

- in granite cutting, abrasive hardness is more important, whereas shape factor clearly predominates in the case of marble;
- volumic mass does not play a major role, since the advantage of a greater particle mass is upset by the lower velocity imparted to heavier particles, with a resulting detrimental effect on the actual impact force against the target (exponent is small and negative);
- the influence of particle size is not remarkable, although coarser abrasives should be preferred.

It would be very interesting if the exponents in the correlation parameter could be represented as a function of target material characteristics, thus obtaining an expression of general validity, not only for rocks.

4. CONCLUSIONS

The appropriate choice of the abrasive is the decisive factor for cutting successfully any material and rocks in particular.

On the basis of experimental tests on granite and marble using different abrasives it is shown that garnet is technically superior, although quartz sand is economically competitive, taking into account that it provides a better cut accuracy.

Specific erosion can be correlated to comprehensive parameters accounting for the various abrasive properties. In granite cutting abrasive hardness is very important whereas shape factor predominates in the case of marble.

Abrasive efficiency is lower with the ASJ but higher cutting rates can be achieved due the much higher abrasive dosage allowable with this system.

5. ACKNOWLEDGEMENTS.

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Table 1. Typical features of AWJ and ASJ techniques for rock cutting applications

FEATURES	AWJ	ASJ
- Operating Pressure [MPa]	350	35-70
- Primary nozzle diameter [mm]	0.3-0.5	-
- Focussing diameter [mm]	1.0-1.2	1.0-1.8
- Length of focussing tube [mm]	75	30
- Water flowrate [l/min]	3-8	10-50
- Hydraulic power [kW]	20-50	10-60
- Abrasive feed rate [g/min]	50-500	1000-10000
- Mean particle velocity [m/s]	400-600	200-300
- Kinetic energy of abrasive flow [J/s]	100-3000	600-15000
- Abrasive concentration (by weight) [%]	2-15	2-20

Table 2. Mineral composition, physical and mechanical properties of rock samples A - Rosa Beta; B - Bianco Carrara

CHARACTERISTICS	A	B
- Approximate mineral composition		
- Quartz [%]	30.0	-
- K-Feldspar [%]	35.0	-
- Plagioclase [%]	25.5	-
- Biotite and others [%]	9.5	-
- Calcite	-	100
- Bulk specific gravity [kg/m^3]	2,662	2,720
- Absorption coefficient [%]	0.33	0.096
- Knoop hardness [MPa]	6,128	1,366
standard deviation	1,620	166
- Compressive strength [MPa]	165	128
- Flexural strength [MPa]	15.6	20.2
- Impact test (minimum fall height) [cm]	58	75
- P-wave velocity [m/s]	4,760	-

Knoop hardness for granite is the weighted average of the hardness of the various components: Quartz (8,786) K-Feldspar (5,450) Plagioclase (5,613) and Biotite (1,653)

Table 3. Characteristics of the abrasives used
A = Garnet; B = Quartz sand; C = Steel shot; D = Copper slag

PHYSICAL PROPERTIES	TYPE OF ABRASIVE			
	A	B	C	D
- Shape index*	6.89	6.84	7.12	7.07
- Knoop hardness [MPa]	12,897.5	8,557.5	9,851.0	5,049.6
- Volumic mass [kg/m³]	4,080	2,610	7,500	3,370
- Mean particle size [mm]				
- Coarse fraction	0.49	0.50	0.47	0.45
- Fine fraction	0.40	0.30	0.30	0.28
- Full size range	0.25 **	0.40	-	0.40

(*) According to ASBA Image Analysis procedures. Shape factor of a sphere: 5.09
(**) Full size range +0.15 -0.350 [mm]

Table 4.a. Abrasive productivity in stone cutting with AWJ

ABRASIVES	Granite FEED RATE [g/min]	Granite SP. EROSION [cm²/g]	Marble FEED RATE [g/min]	Marble SP.EROSION [cm²/g]
Garnet C.	70	0.570	75	0.667
	135	0.460	235	0.457
	235	0.347	260	0.338
Garnet F.	80	0.550	75	0.640
	140	0.457	200	0.400
	230	0.339	360	0.361
Quartz sand C.	50	0.384	80	0.500
	100	0.310	165	0.327
	170	0.223	320	0.218
Quartz sand F.	65	0.290	80	0.400
	110	0.272	180	0.256
	200	0.200	300	0.187
Copper slag C.	50	0.216	90	0.387
	100	0.144	210	0.238
	170	0.100	340	0.212
Copper slag F.	80	0.140	100	0.380
	150	0.096	210	0.238
	270	0.062	370	0.189
Steel shot C.	90	0.367	-	
	155	0.322	-	
Steel shot F.	95	0.347	-	
	160	0.287	-	
	240	0.171	-	

Table 4.b. Abrasive productivity in stone cutting with ASJ

ABRASIVES	Granite FEED RATE [g/min]	Granite SP. EROSION [cm^2/g]	Marble FEED RATE [g/min]	Marble SP.EROSION [cm^2/g]
Garnet	1000	0.065	1000	0.160
	2000	0.070	2000	0.110
	3000	0.067	3000	0.100
Quartz sand	-		1000	0.080
	2000	0.040	2000	0.090
	3000	0.057	3000	0.093
Copper slag	3000	0.012	2000	0.070
	4000	0.008	3000	0.087
	5000	0.007	4000	0.085

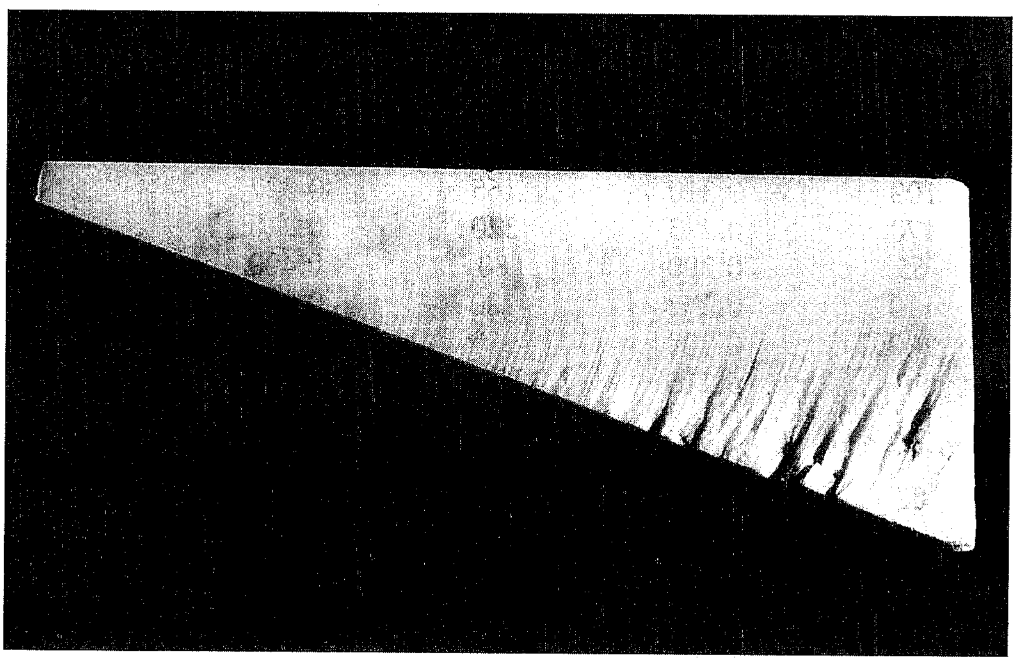

Figure 1. Appearance of cut surface of "Bianco Carrara" marble

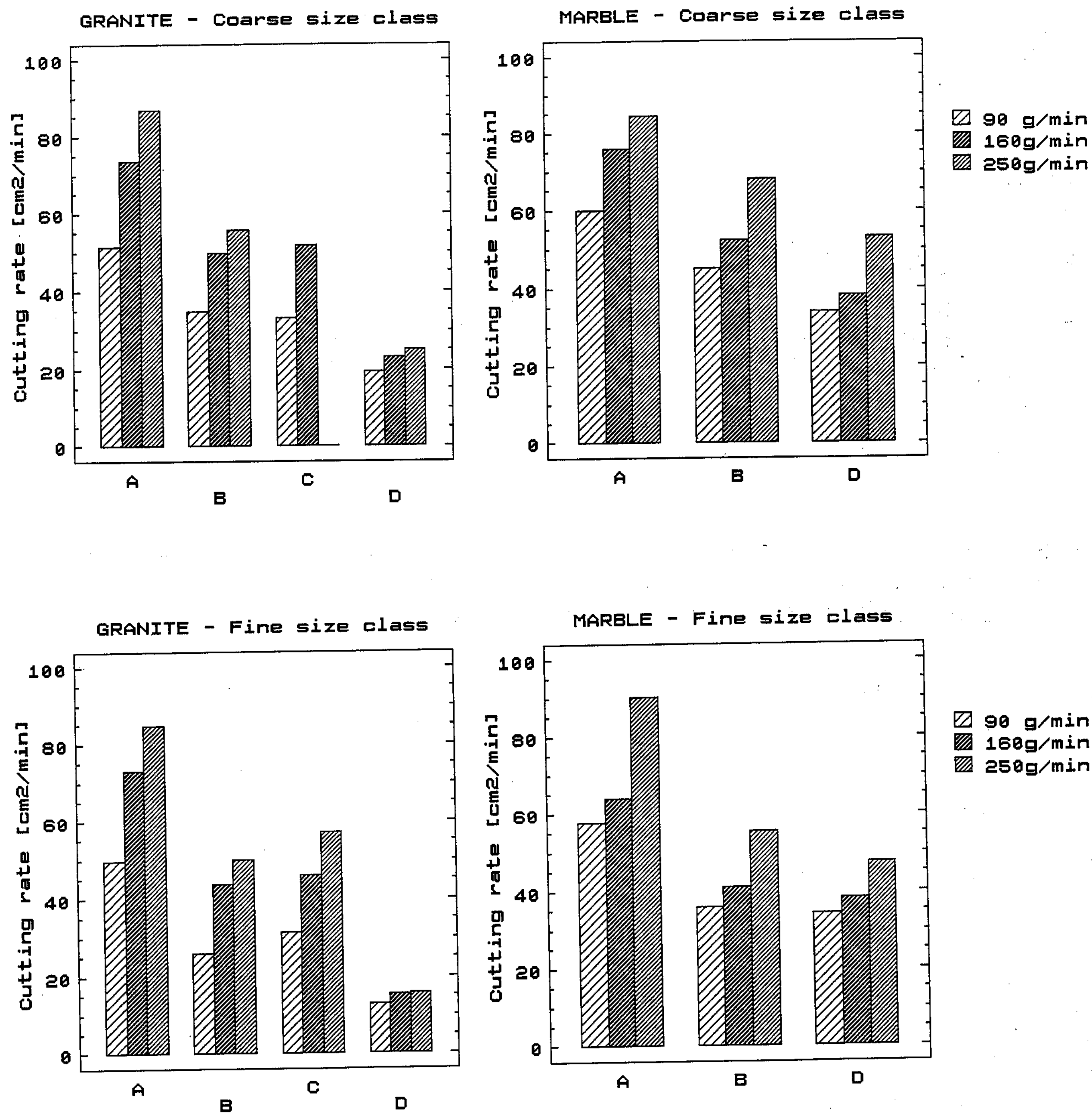

Figure 2.a. AWJ: Bar diagram of maximum cutting rate as a function of abrasive feed rate. A = Garnet; B = Quartz sand; C = Steel shot; D = Copper slag

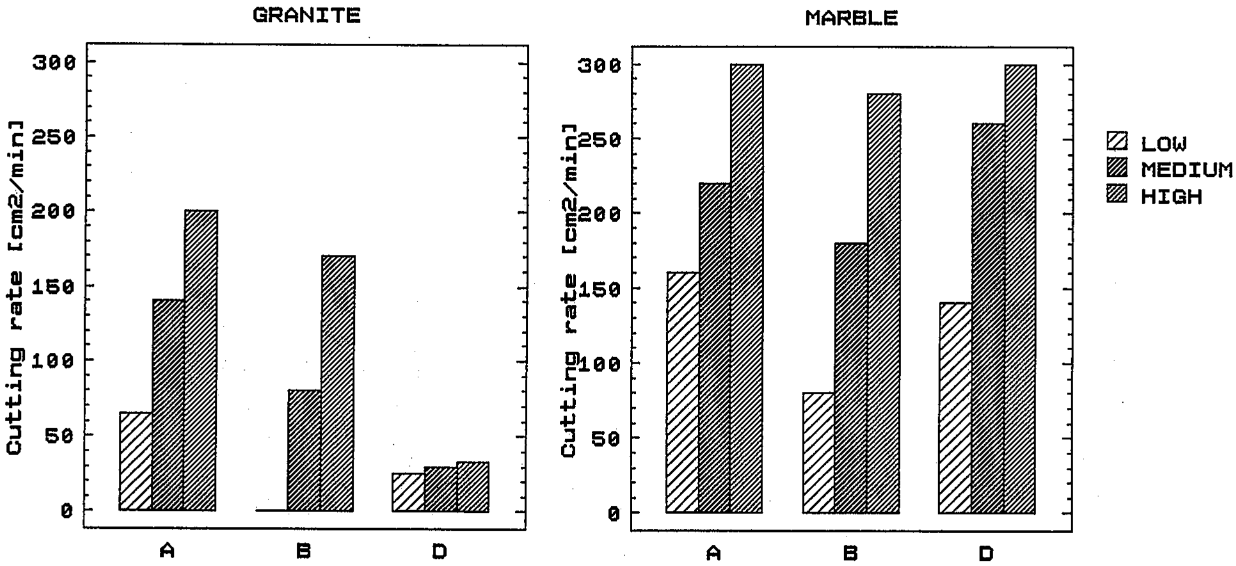

Figure 2.b. ASJ: Bar diagram of maximum cutting rate as a function of abrasive feed rate. A = Garnet; B = Quartz sand; D = Copper slag
LOW, MEDIUM and HIGH abrasive feed rate: see table 4.b

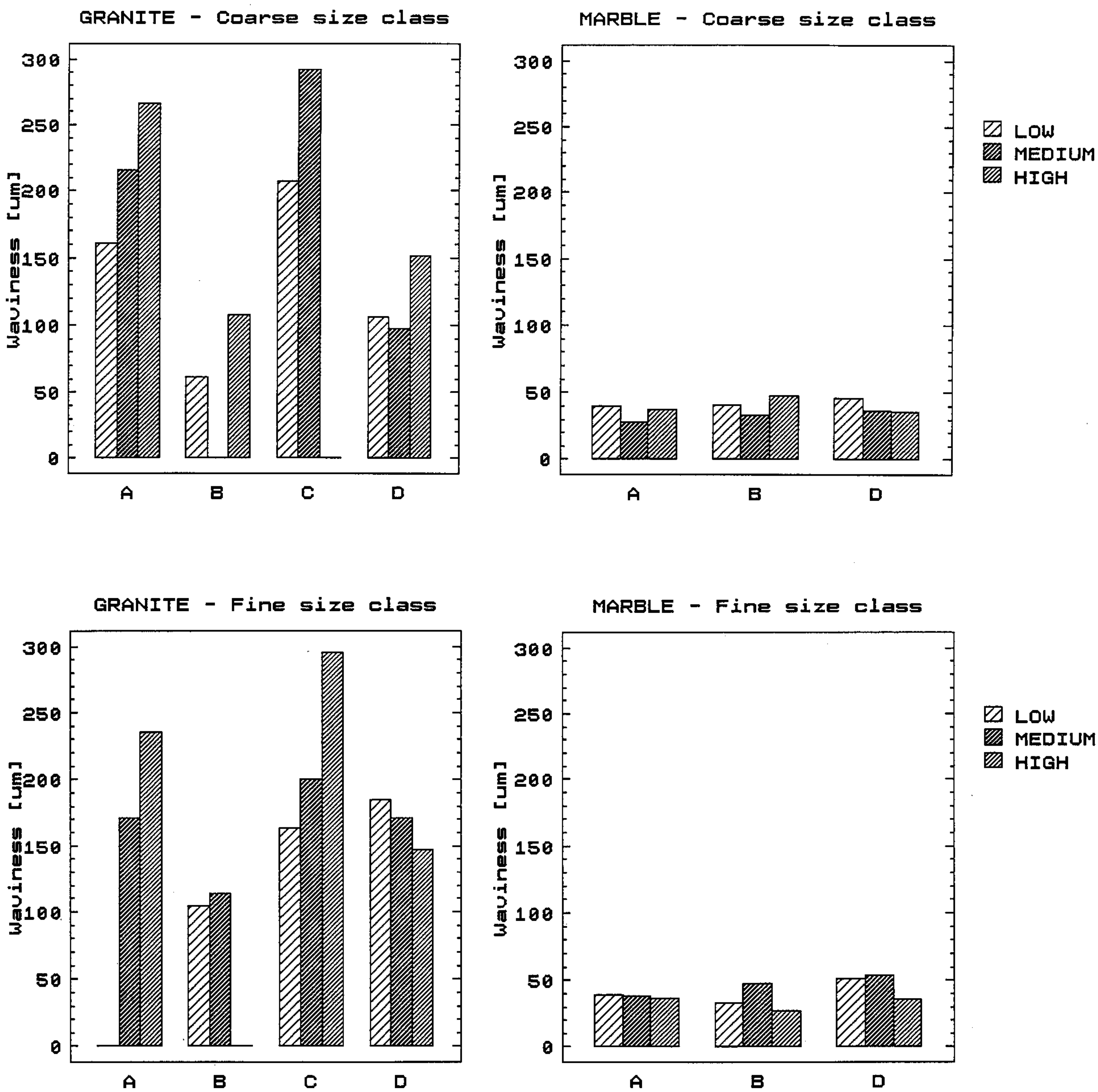

Figure 3.a. AWJ: Bar diagrams of waviness [µm] corresponding to the maximum cutting rate for the different abrasives used
A = Garnet; B = Quartz sand; C = Steel shot; D = Copper slag
LOW, MEDIUM and HIGH abrasive feed rate: see table 4.a

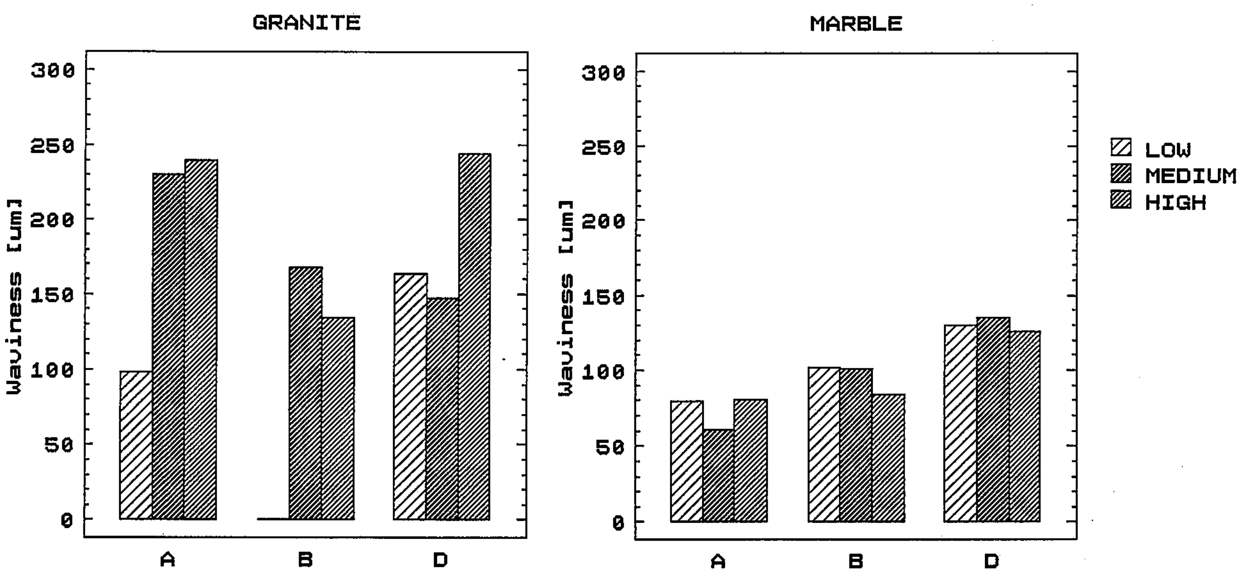

Figure 3.b. ASJ: Bar diagrams of waviness [µm] corresponding to the maximum cutting rate for the different abrasives used
A = Garnet; B = Quartz sand; D = Copper slag
LOW, MEDIUM and HIGH abrasive feed rate: see table 4.b

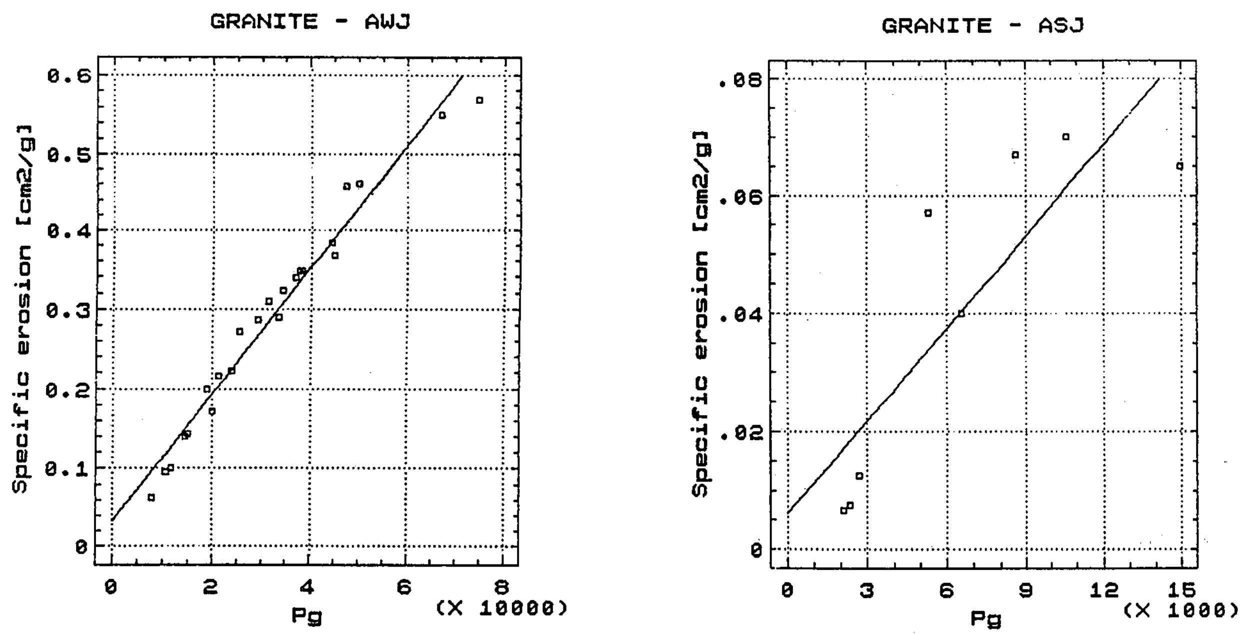

Figure 4. Correlation lines of specific erosion as a function of parameter P_g for granite with AWJ (left) and ASJ (right). Correlation coefficient R^2 97 % (AWJ) and 72 % (ASJ)

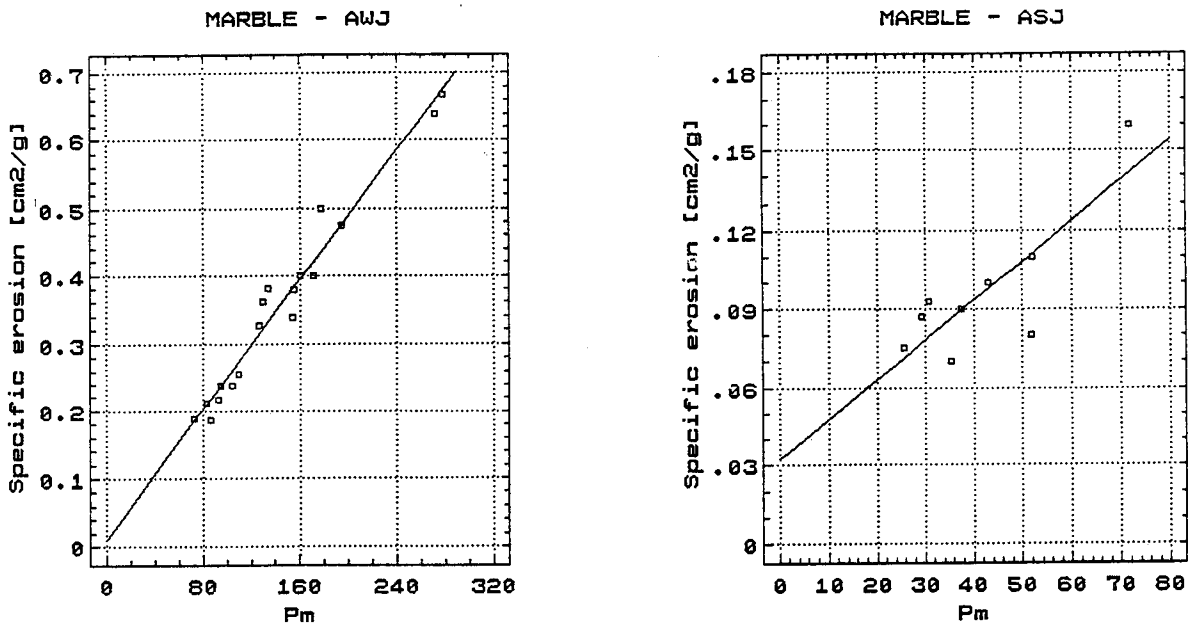

Figure 5. Correlation lines of specific erosion as a function of parameter P_m for marble with AWJ (left) and ASJ (right). Correlation coefficient R^2 96 % (AWJ) and 68 % (ASJ)

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Paper 4

TUNNEL BORING MACHINE ENHANCEMENT

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ABSTRACT

The increasing reliance of the United States on imported energy is most critical in the area of transportation. One solution which is beginning to receive more favorable consideration after having lain dormant for several years is the use of underground trains using magnetic levitation. The use of such a model of transport requires, however, a relatively rapid and inexpensive method of rock excavation. Conventional rock tunneling machines generally work by drilling the central axis of the tunnel first and then successively breaking rock to that exposed surface. This is relatively inefficient and a new approach, in which the kerf is first excavated is herein described.

The machine requires that a kerf be cut, wide enough to allow central core stress relief, around the edge of the tunnel before the rock inside the excavation is removed. A method for achieving this result at a productive rate is described. The method requires the combination of polycrystalline diamond inserts on the cutting head rotating at high speed, and interacting with adjacent high pressure waterjet streams.

Preliminary trials to develop the concept are described together with the subsequent experiments to validate that the design will be effective.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

The excavation of a tunnel through rock has traditionally required a strong, powerful machine that uses mechanical cutters and bits to continuously fragment the rock at the face of the tunnel, by generating high localized stresses. In order to generate these stresses, and to overcome existing ground stresses, conventional rock tunneling machines must provide a high thrust force to push the cutting head into the rock and a high turning force or torque to move the cutters and bits across the rock, removing material. It is well known that when a hole is made in a rock which has been loaded by its surroundings, that the portion of the load which was carried by the removed rock transfers to the material immediately around the opening. Thus the rock which surrounds the hole is subject to a higher loading. This is in the plane perpendicular to the axis of the tunnel and thus when the machine applies further loads to the rock, along the line of advance, the rock is subject to loading in all three directions. This gives a tri-axial confinement to the rock which makes it substantially stronger than it would be without those loads. Thus the forces which the machine must apply, through the cutters, to break rock working from a central penetration of the face of the tunnel outwards, must be significantly greater because of the pressures developed in the rock (Figure 1).

However, if the loads from the surrounding rock could be removed from the rock ahead of the machine before the rock was cut, and more particularly if this relief could be achieved by cutting an outer perimeter cut first (Figure 2), so that the rock would be free to break outwards in uniaxial tension, then the forces required to break the rock would be much lower. The stress relief on the cutting surface of the rock would enable the boring machine to excavate at a higher rate of penetration (ROP) and at lower levels of force, even through harder rock. It is conceived that this outer free surface would also allow the cutters to break the rock easily into bigger chips thus decreasing the specific energy required to excavate the rock. These gains can be used in either of two ways, the ROP of the drilling or tunnel boring machine can be increased at constant machine power (Nagano et al., 1974) or a less powerful machine can be utilized and still have an advance rate equal to the more powerful conventional machines. The latter option allows the use of a cheaper and smaller machine which can be used where a more expensive machine would not be practical (Summers, 1995).

The following investigation examines one option to achieve the purpose of pre-cutting a circular slot around the edge of the tunnel face. A circular slotting experimental machine with a waterjet assisted polycrystalline diamond compact inserts (PDC) on the cutting head rotating at high speed has been built and tested at the High Pressure Waterjet Laboratory (HPWL) in the Rock Mechanics and Explosives Research Center (RMERC) of the University of Missouri-Rolla.

2. DEVELOPMENT OF EXPERIMENTAL EQUIPMENT

2.1 A Visual Prototype of the Design of the Equipment

Before manufacturing the equipment, a 3-D solid model was established using a software package (I- DEAS) running on an HP workstation to design the structure and kinematics of the machine. Also a computer simulation of the PDC cutter/ Rock interaction has been developed using the Finite Element Method to analyze the cutting mechanism of the bit used in the testing. From the model, a physical slotting machine which could drill/cut a quarter circle slot with a diameter of eight feet (2.4 m) in rock was developed. This equipment (Figure 3) consists of a cutting head, a traversing mechanism, a stabilizer, a hydraulic system to power the hydraulic turning and thrust motors, and a data acquisition system.

2.2 Cutting Head

Conventional drilling equipment is designed to penetrate rock using a linear feed system, and with the bits oriented to cut the rock at the center of the face ahead of the tool. As discussed above, by cutting the rock at the gage of the hole first this would make it easier to break the central core of material. Concurrently by creating this initial slot at the gage it was anticipated that this would make it easier to turn the bit off-axis in a subsequent rotation, and thus allow the hole to be drilled in a circular or other path - thereby, when applied to the edge of a tunneling machine, creating the free slot required at the edge of the hole. Further considerations in regard to the depth of hole or slot required will be discussed below.

The loads to be carried by the cutting surface would likely be onerous and thus it was decided to use a Polycrystalline Diamond Compact (PDC) at the cutting tool. These materials while highly effective are sensitive to the high temperatures generated in cutting rock. However, as Hood has shown, (Hood 1977) the addition of water at relatively low pressure (around 6,000 psi or 42 MPa) will be sufficient, when properly directed, to not only cool but also to enhance the cutting operation of such tools. The equipment was therefore designed to include both systems. In order to validate the design a cutting head consists of a PDC drilling bit, wedge breaker and turning assembly were put together (Figure 4). The wedge breaker was included to allow a deeper kerf to be cut. By breaking upwards from within the drilled hole and out to the free surface a lower force would be required for fracture, and the slot could be deepened to more than 75 mm enhancing the gains from the presence of the slot.

The cutting assembly is mounted on the head of a radially rotating arm. The hydraulic motor is attached through a chain and drive sprockets to the drill shaft to provide a rotational movement to PDC drill bit. The center line of the drill shaft is angled away from the parallel path of the rotating arm to avoid a conflict between the drilling assembly and the rock face. A 15 degree and an adjustable 15^0-45^0 header were built in order to investigate the effect of angle away from the rock face. Two configurations of bit and breaker have been designed and tested in the project.

High pressure waterjets were applied to this machine and directed at the front of the PDC inserts through a swivel, and a hollow shaft and were then directed at the cutting edge of the breaker.

2.3 Driving Assembly

For the cutting head to follow in a circular path, a considerable amount of force is required to drive the bit along the required path. There are many ways to create this force but several factors had to be considered before a drive system could be developed. First, since the main purpose of this project is to excavate in harder rock, a large torque to move the arm is needed. Next, the thrust force is a variable parameter which should be adjustable or controllable. Finally, the drive must move the arm in a circular path. A conventional drive system was considered but was found to cost more because of the high speed motor and gear reducers, and might prove to be less reliable. Instead a new drive system emerged from several design patterns. A hydraulic motor powered by a 15 hp hydraulic pump with a 6 gpm flow rate and a maximum pressure of 3000 psi is fixed on top of an arm that drives the cutting head forward using a chain along a circular track to create thrust force on the bit. This type of drive system is compact, cost less and was reliable.

2.4 Hydraulic System

In the operation of this slotting machine, two independent variables should be controlled to ascertain the optimum parameters for machine performance. The two independent variables are the thrust force and the drill bit rotational speed.

A control panel was constructed to allow an operator to adjust each independent variable as needed. This was found necessary after the initial tests which showed that a simple pressure control was insufficient to give the adjustments needed. A way to continuously adjust the hydraulic pressures of the driving motor was needed during a test to ensure that while thrust was sufficient to optimize advance it was not too high as to jam the bit into the rock. The control panel (Figure 5) uses a modified pressure valve to adjust the pressures of the driving motor to achieve different values for the thrust force. Since the operator can continuously monitor the cutting procedure and adjust the thrust force when needed, a smoother flowing cut was achieved.

In order to reach the 1,000 rpm rotational speed of the bit, a high flow rate hydraulic pump driven by a separate diesel engine was used. A flow control valve was used to control the rotational speed of the bit.

2.5 Stabilizer

During the initial testing, it was observed that the cutting arm twisted when a large thrust force was applied. This twisting caused the drill bit to wear prematurely on the sides and also caused the whole machine to vibrate excessively. A plane touch stabilizer was added to the arm to minimize this twisting and vibrating. The stabilizer is attached firmly to the arm and then rides along the same track that the drive chain runs along. This stabilizer has proven a very effective means of diminishing the arm torsion and the vibration of the system.

2.6 Data Acquisition

Several measuring devices were used to accumulate data on the cutting process. An optical encoder was used on the drive shaft to measure the advance rate of the cutting head, and a pressure sensor was used to measure the thrust force through the pressure on the hydraulic system of the driving motor. Those sensors were operated and monitored using Labview software running on a SE30 Macintosh computer. The Labview program processes the data acquired from the encoder and pressure sensor and converts it into advance rate of the cutting head. The data can then be plotted comparing, for example the ROP and the thrust force. A Strobotac measured the rotational speed of the PDC drill bit during the testing.

3. EQUIPMENT PERFORMANCE

3.1 Experimental Design

Four factors: rotational speed, and thrust force on the bit, and the pressure and flow rate of the cooling and flushing waterjets were considered to be the independent variables during the testing of the slotting machine.

The rotational speed of the drill bit powered by the diesel hydraulic pump with 1,500 psi maximum working pressure and 20 gpm flow rate had three levels and was changed from initially 500 rpm to 750 rpm to finally 1,000 rpm.

With the aid of the control panel to control the hydraulic pressure in the driving motor, the thrust force was adjusted continuously to provide the proper thrust force. The pressure of the hydraulic fluid was changeable from 0 psi to 1500 psi.

Based on some data found in previous testing (D. Wright et al., 1994) for waterjet assist of a PDC cutter in removing dolomite, the waterjet pressure for this testing used 6,000 psi directed through 4 orifices each of .042 inch diameter to flush out the rock cuttings and cool the inserts.

Two configurations of bit and breaker were tested and the arrangement was modified based on the test results.

The tests were divided into two parts, one with a concrete target, and one with dolomite as the target rock. The first target was assembled as a concrete wall 5 feet high and 4 feet long. The second target was an identical concrete wall but with dolomite embedded into it to simulate a hard rock test. The main purpose of the test on the wall was to evaluate the design of equipment and provide data for the operating parameters along with preliminary experience in using it.

3.2 Test Results

3.2.1 General

As expected, the faster the drill rotated the better the cutting performance, specially at 1,000 rpm the machine could cut the rock smoothly and with less vibrations, and an increase in the velocity of the cutter at a consistent "bite" also gives a higher ROP.

During the testing, the driving motor usually operated between 300 psi and 600 psi. Below this pressure, the penetration rate could not achieve the desired values, while at higher levels, the bit would occasionally jam in the slot. But the proper level for this pressure also depended on how much depth was being cut by the bit below the surface. When the depth was more then the bit diameter during initial cutting or second pass cutting, the breaker would be breaking out the outside edges along the slot. This would require a slightly higher thrust force to break these volumes of rock. Usually, the pressure was raised to about 900 psi to give the additional force required.

In order for the bit to drill the rock faster, a shallower angle between the bit and the rock center line might demonstrate better performance for the PDC drill bit since the bit would be drilling more parallel to the path of motion. However, the choice of this angle also played an important part in assessing how much of the rock was crushed by the bit action and how much was broken away using the concept of "slot-and-break," an important factor in controlling the efficiency of rock fragmentation and ROP. Unfortunately, the configuration of the bit and breaker was limited by the size of components which could be used and the capabilities of manufacturing, so that the smallest angle which can be constructed between the breaker and the line of advance of the drill was 15^0 . This angle achieved a higher advance rate than tests carried out with either an 18^0 and 45^0 assembly when attached to either the "DS" or "DSX" bit. However it is felt more likely that the optimum angle for the breaker will change with different configurations of the bit, a change in the radius of rotation of the head and the type of rock being cut. This will be determined as a result of further testing.

3.2.2 Drill Bits and the Breaker Wedge

The drill bit, one inch diameter, used in the initial testing was of the DS type (Figure 6) which has previously been found to produce a higher penetration rate than a traditional bit configuration. The sharp outer edge of the PDC insert does, however, with this layout, carry the burden of the initial cut into the rock and thus may do most of the actual rock drilling. This will subject it to high temperatures, and within a confined space these are normally difficult to cool. Thus a critical part to the design was the addition of high pressure waterjets along the front of the PDC cutting edge to assist in drilling, to wash away the rock debris and to keep the drill bit cool.

During the testing, it was noted that the geometry with which the bit moved around the curved slot played a critical part in its effectiveness. For example, with the original configuration, the length of the drill body was cylindrical, and while it was turned within the slot the size was still sufficient to cause it to rub on the slot walls. This created a high frictional force which would resist the torque of the bit and stall the unit at a hydraulic pressure of 900 psi. While the bit could be backed up and the advance continued at a lower thrust force, this did not optimize performance and thus two separate solutions were adopted.

The first was to adjust the angle of inclination of the drill to the line of advance. Various angles were tested, and it was found that the smaller angles worked remarkably better than the larger. However, given the limitation of space, an angle below 15 degrees was almost impossible to achieve. The second approach was to change the geometry of the bit itself. The original cylindrical shape of the "DS" bit used in the testing had worn into a conical form after several test runs. The diameter of the bit body was reduced from one inch down to 3/4 inch. A new design was therefore implemented in which the bit was originally provided with a conical body of the same shape. This allowed the PDC to cut a slot one inch wide without contact between the rest of the bit and the rock walls. Under an actual test this did not work completely, due to variations in the bit alignment through varying rock, and a small amount of jamming continued to occur. A new design of bit identified for distinction as the "DSX" design was therefore built. This had two triangular PDC cutters mounted, one on each side of the bit to cut the rock and prevent the body of the bit from rubbing on the rock inside the slot. Additional work is still being carried out to adjust the bit angle for optimal effect.

If the tool is set to cut a slot greater in depth than the diameter of the drill, for instance from 1.25 to 3 inches with a 1.0 inch diameter tool, then a rock breaker must be used to cut away the excess rock above the tool. The first breaker designed and used in the initial testing was one inch thick, the same as the drill bit. This design was found to hinder the cutting process because it was not able to ride along the circular path without getting stuck between the curved walls. A 3/4 inch breaker was therefore designed and machined to alleviate this problem and was used for the remainder of the testing program.

Two different wedge shapes were used for this breaker. The first design had the breaker centered in the middle of the tool path. The second had, instead, two wedges located to cut along the edges of the tool. The latter provided better performance and was adopted into the design. To aid with the cutting of the rock, high pressure waterjets were directed along the wedge edges of the breaker.

At the present time, early in the development of the tool, performance still lies below that which will be required for a commercially viable piece of equipment. For example, when using a "DSX" bit to cut dolomite at 1,000 rpm with 600 psi hydraulic pressure to the thrust motor, a slot 1.25 inches deep has an ROP of 1.44 ft/ min. with large chips of rock, especially with jet assistance. A slot one inch deep was cut at 1.8 ft/ min. only with a thrust pressure of 350 psi, at 1,000 rpm, while a second deeper pass cut of the same size could be made with the same parameters. Thus a series of sequential cuts could be made to make a progressively deeper slot before the central core of the tunnel was removed. It was also noted that waterjet assisted tools cut dolomite much faster and more effectively than concrete, because of the presence of weakness and structural planes and because of the more brittle nature of the rock.

4. CONCLUSIONS

The use of a combined curved drilling and breaking tool has been demonstrated to be able to cut a perimeter slot which can be used to isolate the central core of rock in the face of an underground tunnel. In order for the tool to work the drill itself must cut its gage first, a step which can be achieved with the use of a PDC insert. The operational life of this tool, and its performance are enhanced when a jet, at a pressure of 6,000 psi is added to the cutting tip. Additional inserts are required, however, to ensure that the gage of the slot is sufficient to allow the passage of the tool. Deeper slots can be achieved by attaching a breaker to the drilling tool, and this will allow creation of a slot up to 3 inches deep. It is also possible to stack cutters one behind the other so that each cuts to its maximum depth, and a deep slot is made around the core of the rock face, stress relieving it, and allowing easier fracture of that rock in tension. At present the performance of this tool has not reached that necessary for commercial application, however, testing of the concept is continuing to further optimize the rate of penetration achievable.

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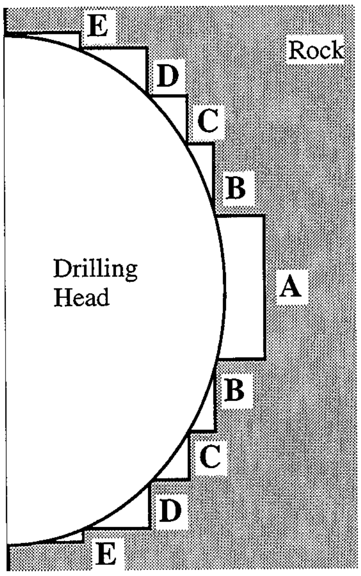
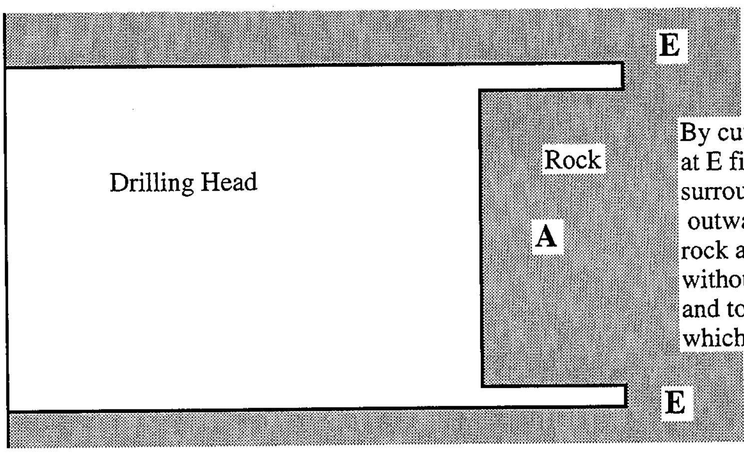
6. FIGURES



As the drill removes the rock at A, it moves the stress to the ring before B, as the rock at B is removed it increases the stress before the rock at C, and as the rock at C is removed the stress is increased in front of the cutter at D. As this progresses out to E more cutters are often needed to cut the greater volume of rock, under the greater confining pressure.

Figure 1. The conventional approach to drilling through rock (after Summers, 1995).



By cutting the rock at E first, the surrounding stress is moved outward and the central core rock at A can be broken without as great a confinement and to the larger free space which surrounds it.

Figure 2. Schematic of Tunnel excavation with the gage cut first.

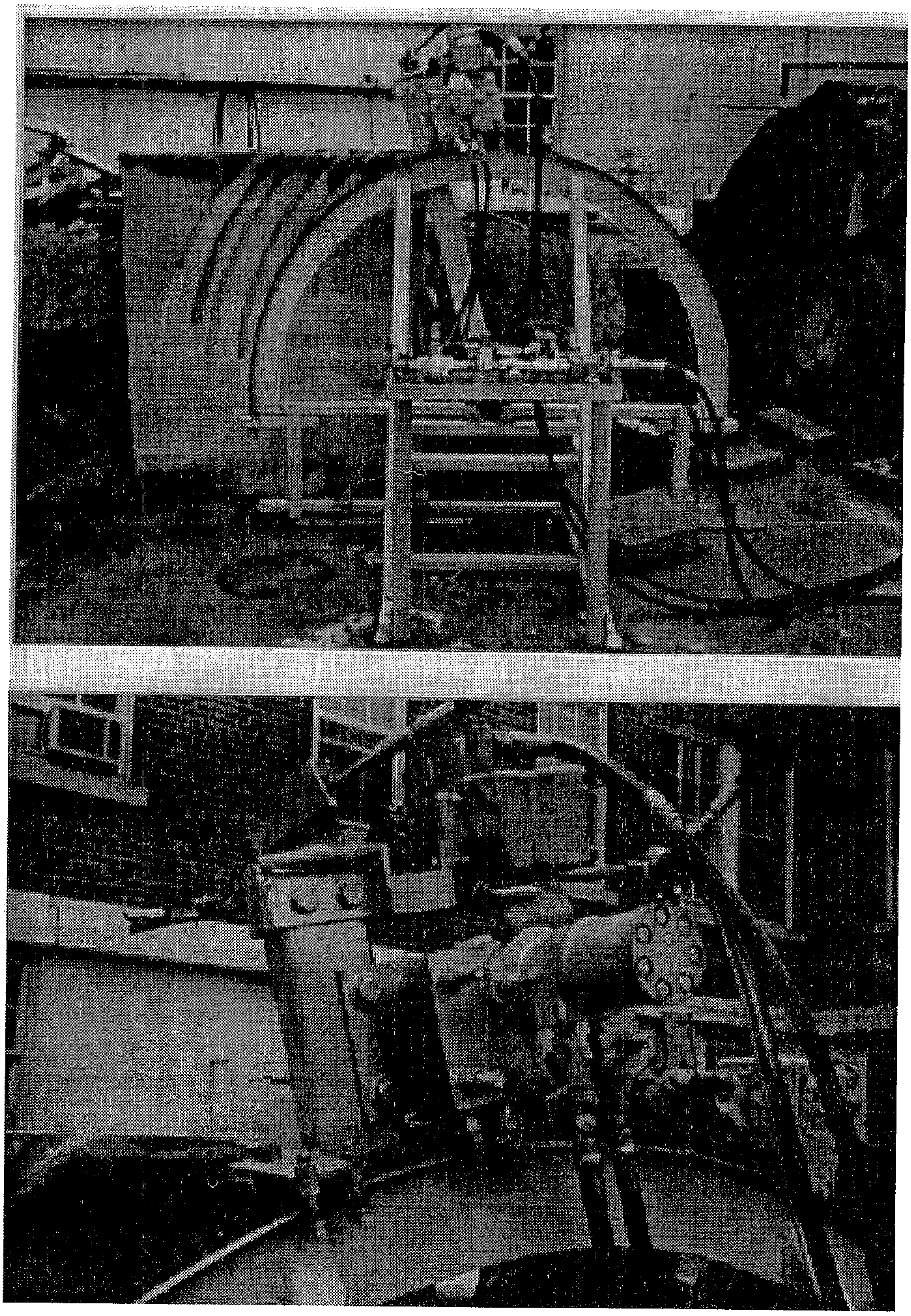


Figure 3. Waterjet Assisted Circular slotting Machine

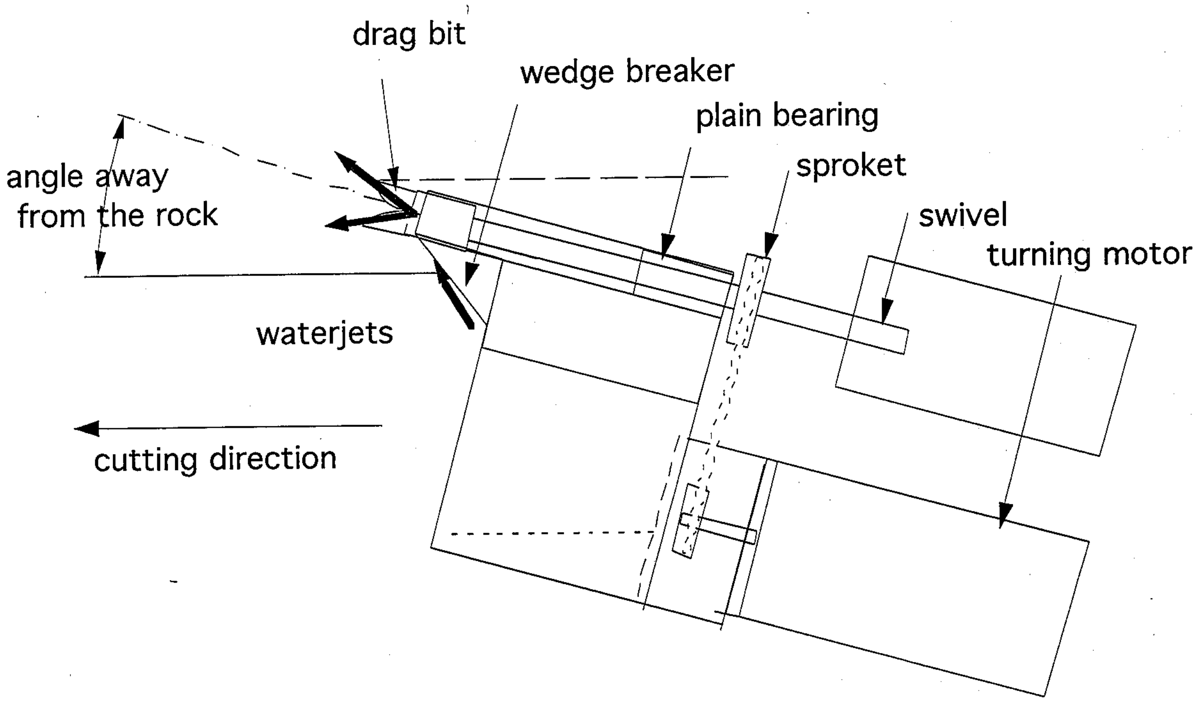


Figure 4. Schematic of Cutting Head

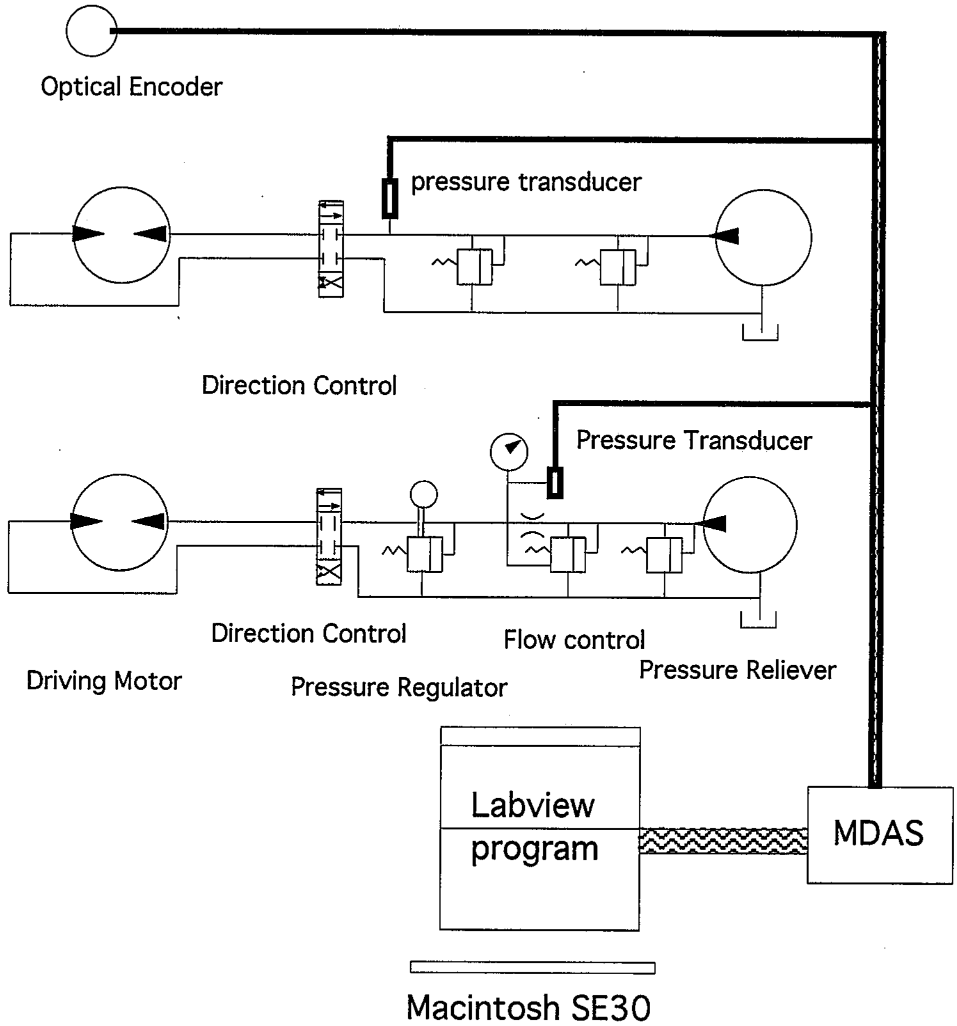


Figure 5. Hydraulic System and Data Acquisition

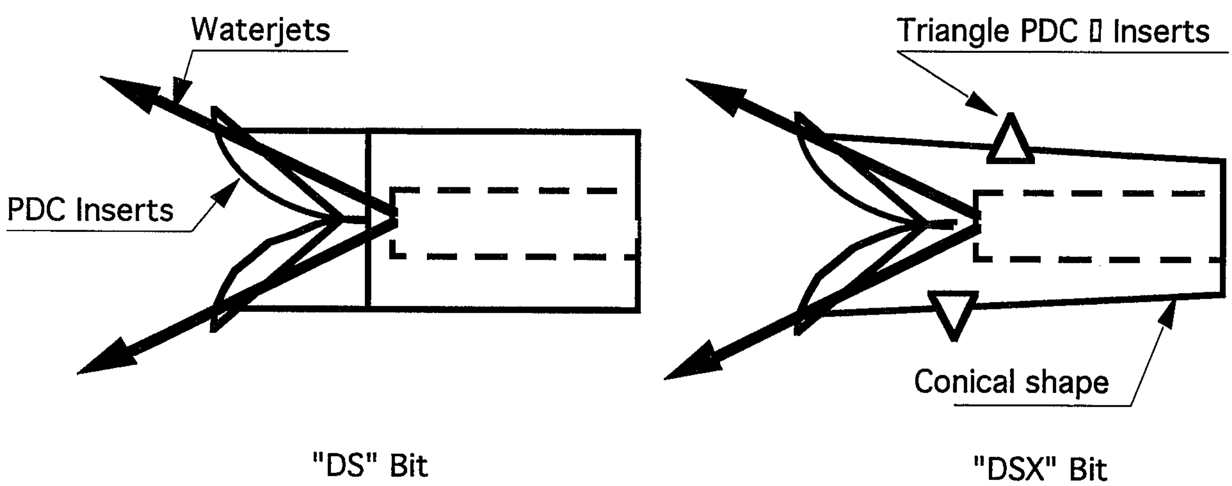


Figure 6. Configuration of the "DS" and "DSX" Bits

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Paper 5

A FRACTURE MODEL FOR HYDRODEMOLITION

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ABSTRACT

Hydrodemolition is a commonly used technique for concrete sanitation and building rehabilitation. A major optimization parameter of the process is the traverse distance, Δ, between two removal operations. In order to optimize this parameter, fracture studies on concrete have been analyzed and a simple fracture mechanics model for the estimation of the traverse distance is developed. This model is based on a relation between a fracture probability parameter, P_F, and the fracture width in the damaged materials. The fracture probability is based on the crack lengths in the material and the applied pump pressure. The fracture probability is linked to the traverse distance by a logarithmic regression fit. The model shows some good qualitative agreements with measured cut widths on concrete.

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1. INTRODUCTION

High energy plain water jets have been used to treat brittle multiphase materials, such as rocks and concretes, in the mining and quarrying industry, and in civil engineering for some years. Typical applications in the construction industry and for hydrodemolition processes are recently described by Momber (1993, 1994). Fig. 1 shows a water-jet based concrete processing unit, typically used for the heavy concrete removal, often called "hydrodemolition." Using traversing or rotating nozzle heads, these machines remove the concrete successively by breaking the material rib between two kerfs. The distance between the kerfs, in this paper defined as the traverse distance, Δ, is an important process parameter. Optimizing this distance can save energy and improve the quality of the created surface. As shown by Hamada et al. (1972) there exists an optimum traverse distance with a minimum specific energy for concrete removal. Puchala et al. (1986) and Momber et al. (1995) discovered that the material removal rate can be maximized by variations in the traverse distance. If the distance is too large, the rib between the kerfs can not be removed completely and has to be fractured in a second step using jack hammers. This case is described by Dinglinger (1991). The state-of-the-art calibration of the optimum values for Δ is based on empirical knowledge more than on theoretical analysis. A simple definition for Δ may be

$$\Delta = \frac{b_1 + b_2}{2}. \qquad (1)$$

Here, b_i is the width of the kerf fractured in the concrete. This value may depend on several process parameters, such as pump pressure, nozzle diameter, and standoff distance, as well as on the structure and the properties of the treated material. There exist only a few investigations regarding these problems. In an investigation on concrete-straw mixtures, Savanick et al. (1975) found optimum traverse distances of Δ = (12 to 38) mm. Momber (1991) summarized some published results on concrete and stated a strong relation between the optimum traverse distance and the diameter, D, of the used nozzles. Typical values for good removal performances are about $\Delta/D \approx 10$. Werner (1991) and Momber and Kovacevic (1995) discovered that the fracture width in concrete increases with an increase in the aggregate size and with a decrease in the water-cement ratio. It depends also on the aggregate type. Momber and Kovacevic (1995) developed a phenomenological model to explain these facts. Based on debris size measurements they assume a changing in the failure mechanism from erosion to fracture under certain conditions, especially at a critical specific fracture energy of the concrete materials. Another aspect related to the estimation of the traverse distance is the non-regular structure of the fracture geometry. As shown on concrete samples by Momber (1992), the fracture widths oscillate around an average value. Therefore, the actual fracture width, and thus the optimum traverse distance, has to be considered as a probabilistic parameter. It is one objective of this paper to show how this problem can be solved by applying simple fracture mechanics relations.

2. FAILURE OF PRE-CRACKED, MULTIPHASE BRITTLE MATERIALS BY WATER JET ATTACK

The mechanism of brittle multiphase material failure due to plain water jets is not well understood. Usually, the core region of a plain high speed water jet is used to cut and remove this type of material with pressures greater than 100 MPa. In this region of the jet, static loading due to a stagnation pressure p_S predominates. The stagnation pressure, which is distributed over the loaded surface, can be estimated using the equation

$$p_S = \frac{1}{2} \cdot \rho \cdot v_0^2, \qquad (2)$$

where p_S is the stagnation pressure, ρ is the fluid density and v_0 is the jet velocity. The stagnation pressure, which may characterize the intensity of loading, has a Gaussian distribution over the loaded area as shown in Fig. 2. For a jet diameter of 1.0 mm, which is a common value for concrete hydrodemolition, the pressure is distributed over an area of about 0.8 mm^2. This value suggests, that integral macroscopic material properties, such as compressive strength and Young's modulus, can not be used for the evaluation of material resistance against water jet attack. The local conditions, and so the local properties, at the point of impact are of decisive importance for the failure process. This important restriction may be the base of the model development. Concrete can be considered as a nonhomogeneous material which consists of grains, matrix, interfaces, pores and microcracks. To illustrate this assumption, the authors have carried out mercury penetration measurements on some specimens. The example given in Fig. 3 shows the high amount of irregularities in the near-surface structure of the material. These results suggest a simple model of local resistance parameter distribution on the material surface.

The first rigorous application of fracture mechanics methods to the failure of nonhomogeneous materials under water jet attack was done by Powell and Simpson (1969). Based on Griffith's fracture criterion, critical threshold pressure values were calculated as a requirement for material destruction. Additionally, the relation $p_C=30.s_T$ was found between the tensile strength, s_T, and the material's resistance against water jet attack, where p_C is a critical stagnation pressure. That means, if the pump pressure exceeds a value of 30-times the rock tensile strength the material resistance can be evaluated by the tensile strength. In the work of Forman et al. (1973), similar results were obtained by considering the permeability of the materials and the surface stresses due to water penetration into the pore system. A critical stress inside a material pore was calculated. These authors showed with a simple covering experiment that the stress wave induced fracture during the early impact period can not be the main source of the failure. This result is important because it underlines the importance of the flow of the pressurized water into the structural elements of the materials, such as pores, cracks, and interfaces. A model which is based on permeation processes in pores was developed by Rehbinder (1977, 1978). There, an erosion force was suggested which acts on single grains and leads to the failure of the material. In the works of Evers et al. (1984, 1986), a model of stress generation in pores by moving water jets was created and values of stress amplification in capillaries of about 3.5 were calculated. Yong (1988), who considered capillaries as well as cracks, estimated stress magnifications of about 3. In Wiedemeier's (1981) model, the destruction of rocks by water jets is regarded as a fracture mechanics determined process. The author found a significant correlation between the threshold pressure and the stress intensity factor of the investigated rocks. In the works of Momber (1992, 1992a, 1992b), Momber and Louis (1994), and Momber and Kovacevic (1994, 1994a) on concrete, the influences of interfaces, cracks, and inclusions on the failure process were investigated. As suggested, the predominant mechanisms of the material failure are propagation and intersection of pre-existing microcracks. It was found that the destruction process due to water jets is introduced in the interfaces between the matrix and inclusions. Inside a crack, the water is pressurized as illustrated in Fig. 2 which leads to forces acting on the crack wall surfaces. If the generated stresses exceed critical material values, for example critical stress intensity factor, the crack starts to grow. It was shown experimentally and by simple analysis that inclusions in the material may act as crack arrestors and energy dissipators (Momber and Kovacevic (1994b). The intersection of several single cracks leads to a macroscopical material removal. In an advanced version of the model, a computer-based calculation of the fluid dynamics inside a microcrack is presented (Momber et al. 1994). Momber (1992b) developed a preliminary idea for the probabilistic discussion of concrete failure in the case of hydrodemolition.

3. EXPERIMENTAL EVIDENCE FOR THE MODEL

The relation between the applied pump pressure and the average fracture width as shown in Fig. 4 (Momber 1992) can be used for the model development. It can be seen that the width of the fracture increases linearly with rising pressure in the lower pressure range but it seems that a "saturation" fracture width, b_{MAX}, exists, which may be identical with the maximum possible fracture width for the given material under the given conditions. The function asymptotically approaches this maximum value. Fig. 5 shows typical fracture width distribution diagrams. It was found that the distribution of the fracture widths can be described by a Gaussian Normal Distribution function as given by the equation

$$f(b)=\frac{1}{\sqrt{2\cdot\pi}\cdot d_b}\cdot e^{\frac{-(b-\bar{b})^2}{2\cdot d_b^2}} \tag{3}$$

In Fig. 6, the standard deviations of the fracture width distribution functions, d_b, are plotted against the applied pump pressure. Here, the pump pressure can be understood as loading intensity. The function starts to increase at a pressure of about 20 MPa and is developed with a steady progress. The standard deviation rises with the intensity of loading. The specimen surfaces show an adequate nonhomogeneous failure profile. Fractured areas alternate with low damaged parts. One can assume that the stresses inside the specimen are not able to destroy all parts of the material but only the parts with local weak zones, for example zones with accumulated microcracks or pores. This situation changes in a pressure range of about 60 MPa. The function starts to decrease and the standard deviation becomes lower. One can assume a qualitative change in the failure behavior of the material. The material reacts in a more regular manner. This suggests a stronger influence of integral material properties. It was shown by Momber (1992b) that the "transition" pressure is in qualitative agreement with the simulations of Powell et al. (1969). Consequently, the integral material tensile strength seems to determine the material resistance beyond this pressure range. More information about the transition from local probabilistic failure to integral regular material failure give grain size measurements of the removed material particles as carried out and discussed by Momber (1992a). A typical grain sample is shown in Fig. 7. An analysis of the removed particles showed that they can be characterized by a Rammler-Rosin-Sperling (RRS)B-distribution (see Schubert, 1988) according to the equation

$$P_S = 1 - e^{-\left(\frac{d_P}{d'}\right)^n}, \tag{4}$$

where P_S is the sieve passing, d_P is the grain diameter, and d' and n are parameters of the distribution. The values of both distribution parameters can be estimated graphically by using a RRS(B)-distribution-standard diagram. The distribution parameter d' is a characteristical grain diameter for $P_S=0.63$ and, under some limitations, can describe the fineness of the grain samples. Their values are estimated using a RRS(B)-distribution standard diagram and lie between 2 mm and 9 mm. The parameter n can be assumed as a regularity number. For conventional comminution processes, this parameter ranges between 0.7 and 1.4 (Schubert 1988). In the range $n>1$ it can be used to describe the homogeneity of the grain size distribution. The value for n is infinite if the grain sample consists of grains with identical diameters. Related to the present problem this would be valid in an idealized homogeneous removal process. So the regularity number can characterize the "homogeinity" of the removal regime. Fig. 8 shows the relation between the applied pump pressure and the fineness parameter d'. It is seen that the diameter d' increases linearly with the pump pressure. The function shows a significant change in its progress at a pressure of about 70 MPa. Beyond this value the characteristic diameter rises rapidly. This result may be interpreted as a more integral fracture process at higher pressures. Because the failure is not precedencly local in the range of high pressures, the size of the removed material grains increases. Fig. 9 which shows the relation between the applied pump pressure and the regularity number, indicates an increase in the regularity at high pressure levels. To explain the trend in Fig. 9 it can be assumed that at low stress levels the size of a removed grain depends on the local fracture conditions. This should lead to a large range of different grain diameters which results in a relatively inhomogeneous grain size distribution. Increasing the pressure leads to a more controlled removal process. The removed grains are larger and exhibit a narrow range of grain size.

4. DEVELOPMENT OF THE MODEL

The experimental evidence presented in the previous chapter clearly shows that the destruction of pre-cracked brittle multiphase materials by high velocity water jets is characterized by effects of randomness and non-regularity. The basis for the discussion of these results is the assumption that the structure of the used concrete samples is nonhomogeneous. It consists basically of a matrix, inclusions, interfaces, and a network of flaws, as microcracks and pores. This assumption is supported by Fig. 3. Pressure fluctuations are neglected. Considering further experimental results by Wiedemeier (1981) where a linear relation between the threshold pressures of rocks and their critical stress intensity factor was found, one can write

$$p_C = C_1 \cdot K_{Ic}. \tag{5}$$

It may be noted here, that a strong relation between the fracture toughness and the threshold velocity for the destruction by water drop impact was found experimentally as well as analytically for brittle materials by Evans et al. (1978). The threshold pressure as a minimum pressure required for the introduction of the failure in a given material under given process conditions may also be expressed as a critical stress inside a material flaw (Scott et al. 1954), which yields the equation

$$\sigma_C = C_2 \cdot K_{Ic}. \tag{6}$$

From the linear elastic fracture mechanics (Blumenauer et al., 1982) it is known that

$$\sigma_c = \frac{K_{Ic}}{\sqrt{2 \cdot \pi \cdot l_c}}. \tag{7}$$

For , $\frac{1}{\sqrt{2\pi \cdot l_C}} = C_2$, Eq. (7) is identical with Eq. (6). These results suggest that the threshold pressure of a material is proportional to its fracture toughness, but inversely proportional to the 0.5th power of the flaw length. These relations are given in Fig. 10. The fracture toughness values in these calculations are applied from Hillemeier (1976). The flaw lengths are based on mercury penetration measurements carried out by Momber (1992), together with the assumption $l_F \approx 10.b_F$. Typical critical flaw lengths for concretes are between 20 μm and 200 μm (Mindess, 1983). Fig. 9 shows that the critical fracture stress depends on the local situation in the loaded area. For a given stress of 7.5 MPa, fracture occurs only in the interface between matrix and inclusion. A matrix failure can happen only if the stress is increased up to 18 MPa. This simple discussion leads to the conclusion that a plain matrix has a higher threshold pressure compared to a multiphase material. This observation was in fact made by Momber (1992, 1992b) who found a threshold pressure relation between multiphase material and matrix of 0.6-0.7. These values depend on the sort of the added inclusions. If one transfers this idea into the present problem it is simple to find that the non-regular fracture in the multiphase material is related to the distribution of the local material resistance parameters. A simple assumption for further discussion may be that the material is characterized by a range of flaw lengths, such as microcracks, and pores. This range may be:

$$l_{\min} \leq l_F \leq l_{\max}. \tag{8}$$

The area which is enveloped by the flaw size-stress curve of a given fracture toughness (see Fig. 10) can be expressed by

$$F = \int_{l_{\min}}^{l_{\max}} \sigma(l_F) dl_F = \frac{K_{Ic}}{\sqrt{2 \cdot \pi}} \int_{l_{\min}}^{l_{\max}} \frac{dl_F}{\sqrt{l_F}} \tag{9}$$

The area F is defined now as the maximum fracture potential. That means that for a case represented by Eq. (9) all flaws can be widened at the given stress. If the stress is reduced the area F will be reduced, too. The relation between the reduced area F(σ) and F is given by Eq. (10) and can be interpreted as the probability of failure.

$$P_F = \frac{F(\sigma)}{F} = \frac{\int_{l_F(\sigma)}^{l_{max}} \frac{dl_F}{\sqrt{l_F}}}{\int_{l_{min}}^{l_{max}} \frac{dl_F}{\sqrt{l_F}}} \tag{10}$$

For F(σ)=F, one obtains $P_F=1$. The equation (10) is graphically solved in Fig. 11. This figure shows two important relations. First, the probability of failure increases with the applied stress, and, second, the failure probability depends on the fracture toughness of the material phases. To obtain an average failure probability of $P_F=0.5$ a stress of 7 MPa is necessary for the interface, whereas a stress of 18 MPa is necessary for the plain matrix. Also, two different "threshold stresses" can be found. As estimated experimentally by Mazurkiewicz et al. (1986), the water pressure on the bottom of a crack is about 20% of the applied stagnation pressure. Comparing the critical fracture stresses ($P_F=0$) in Fig. 11 with the measured threshold pressures of the used materials (18 MPa for the multiphase concrete material, 40 MPa for a plain reference matrix) one obtains relations between 0.19 and 0.21 which is in excellent agreement with the values estimated by Mazurkiewicz et al. (1986). A regression of the functions in Fig. 11 leads to

$$P_F = A + B \cdot \ln\sigma. \tag{11}$$

It can be assumed now that the fracture width is related to the failure probability by

$$b = K \cdot P_F \\ 0 \le P_F \le 1' \tag{12}$$

with $b=b_{MAX}$ at $P_F=1$. The parameter K can be estimated by a reference experiment. Combining Eqs. (11) and (12), and assuming $p=k.\sigma$ yields

$$b = K \cdot \left[A + B \cdot \ln\left(\tfrac{p}{k}\right)\right] \tag{13}$$

In Eq. (13), the local width of the generated kerf is related to the local material structure by the regression parameters A and B. Here, further work is needed to establish these relations. Eq. (13) considers also the influence of the applied load. Using average material properties for the given concrete material, the average fracture width can be calculated for given pump pressures. Here, the constant k can be approximated by k≈5 as discussed above. Eq. (13) is able to describe the experimental estimated relation between the pump pressure and the average fracture width as given in Fig. 4. This equation may also be used to describe the fracture width standard deviation by plotting a group of lines for different local fracture parameters in the diagram. Probably, at a certain stress level, the space between these particular lines will be reduced. This stress level may be identical with the pump pressure in Fig. 6, where the standard deviation of the fracture width starts to drop.

5. SUMMARY

The conclusions from this investigation can be summarized as follows:

- Cutting of pre-cracked multiphase materials with high pressure water jets is a highly localized process.
- For the evaluation of the resistance of the materials in this kind of loading the distribution of local material properties is of decisive significance in a pressure range up to 30-times the material tensile strength.
- Beyond this pressure level the integral material properties characterize the failure behavior of the material.
- The width of the generated fracture in the processed specimens is proportional to the local fracture probability which depends on the applied stress (pump pressure), the local fracture toughness, and the local microcrack distribution.
- A semi-empirical model is developed to describe the relation between the pump pressure and the width of the generated kerf.

The final equation for the estimation of the traverse distance for a hydrodemolition process is given by

$$\Delta \approx K \cdot \left[A + b \cdot \ln\left(\tfrac{p}{5}\right)\right]. \tag{14}$$

6. ACKNOWLEDGEMENTS

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Figure 1. Concrete Hydrodemolition Unit.
(Photo: WOMA GmbH, Duisburg)

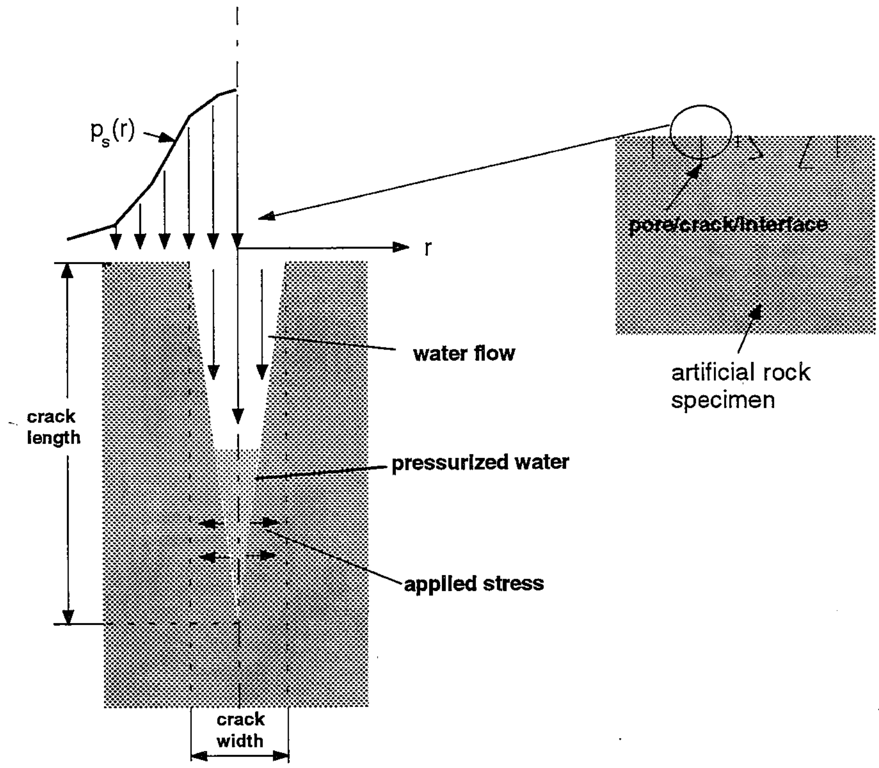

Figure 2. Mechanism of Brittle Pre-Cracked Material Destruction by High Energy Water Jet.

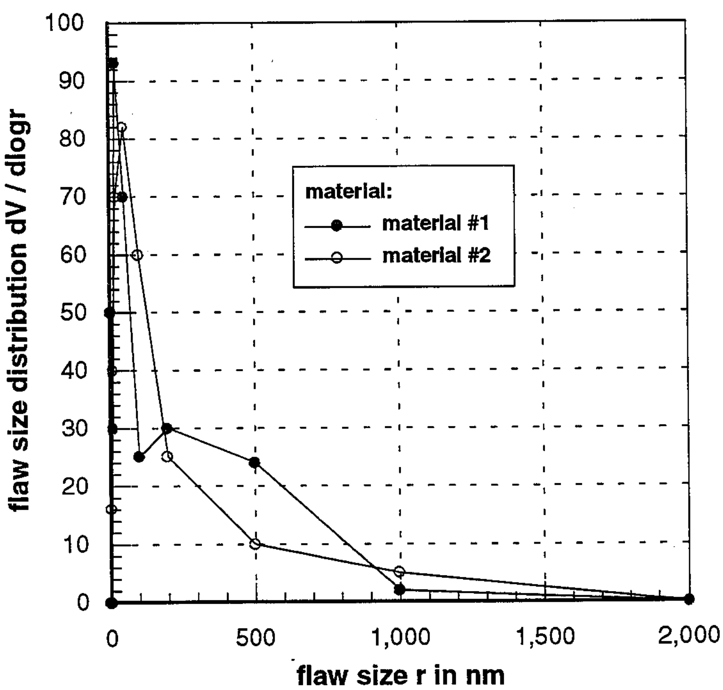

Figure 3. Results of Mercury Penetration Measurements.

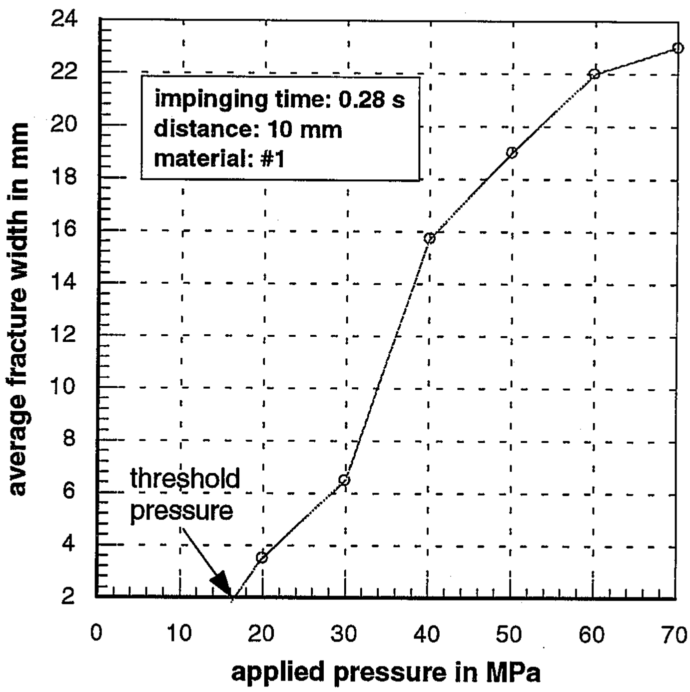

Figure 4. Relation Between Applied Pump Pressure, and Average Fracture Width (Momber 1992).

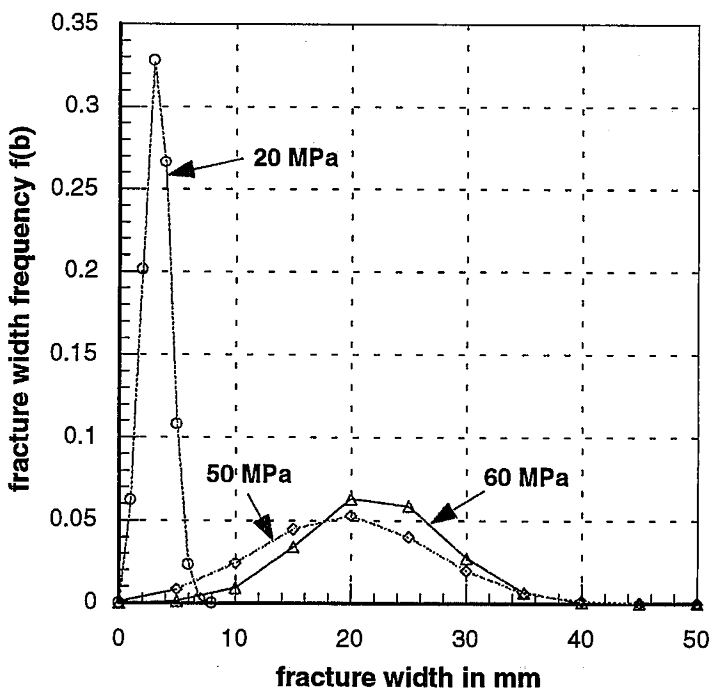

Figure 5. Examples for Fracture Width Distributions.

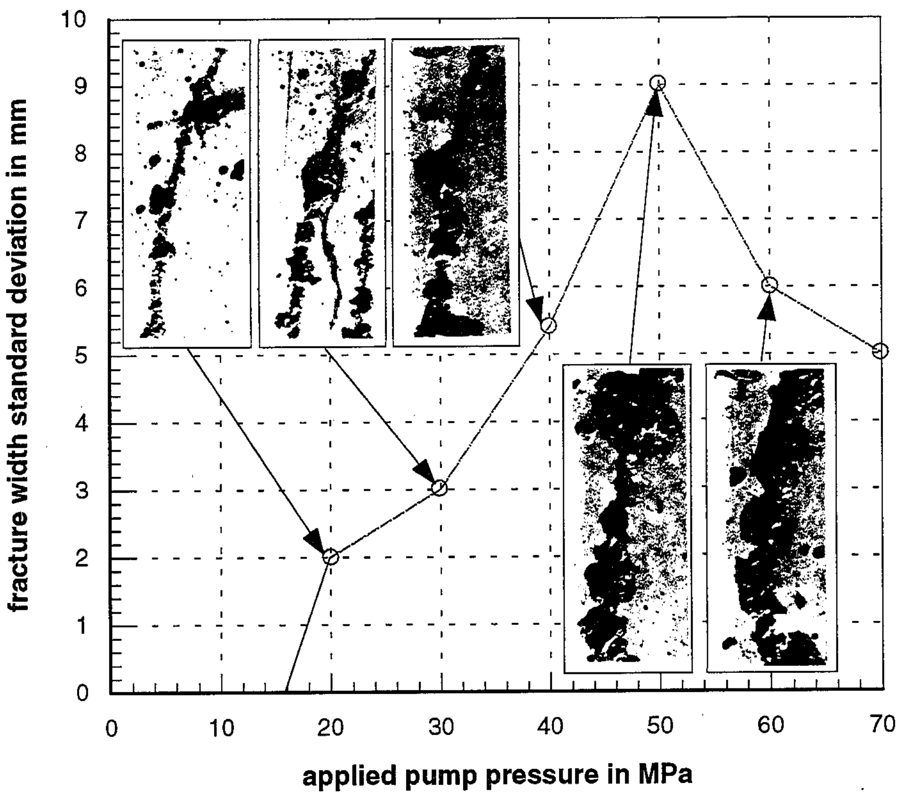

Figure 6. Relation Between Applied Pump Pressure, and Fracture Width Standard Deviation.

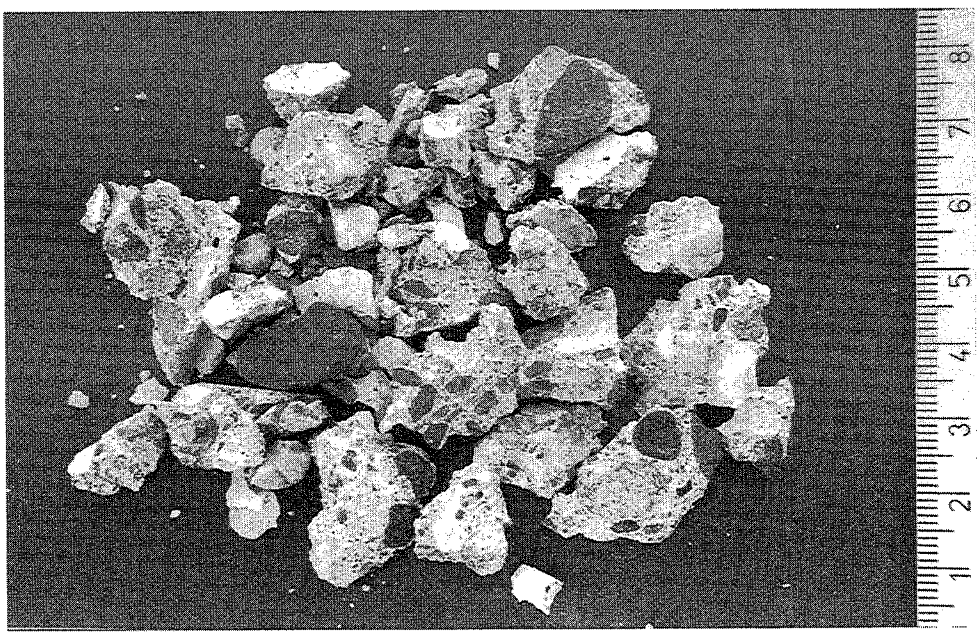

Figure 7. Typical Grain Distribution of a Removed Material Sample.
(Pump Pressure: 70 MPa)

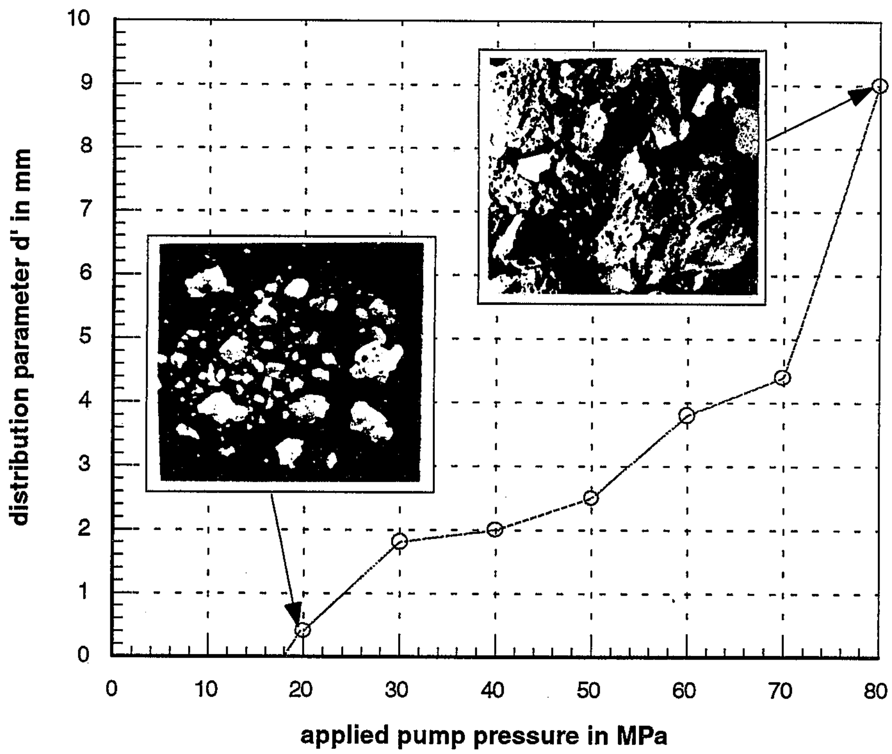

Figure 8. Relation Between Applied Pump Pressure and the Fineness Parameter d'.

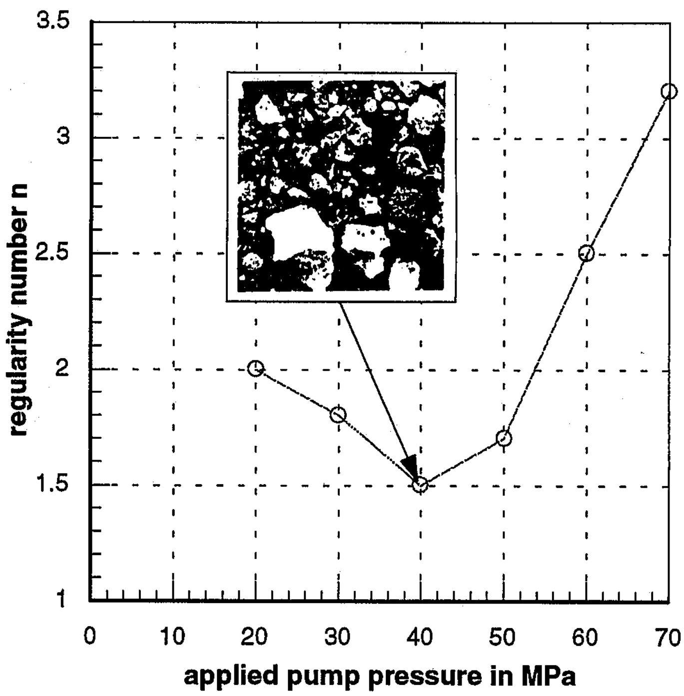

Figure 9. Relation Between Applied Pump Pressure, and the Regularity Number n.

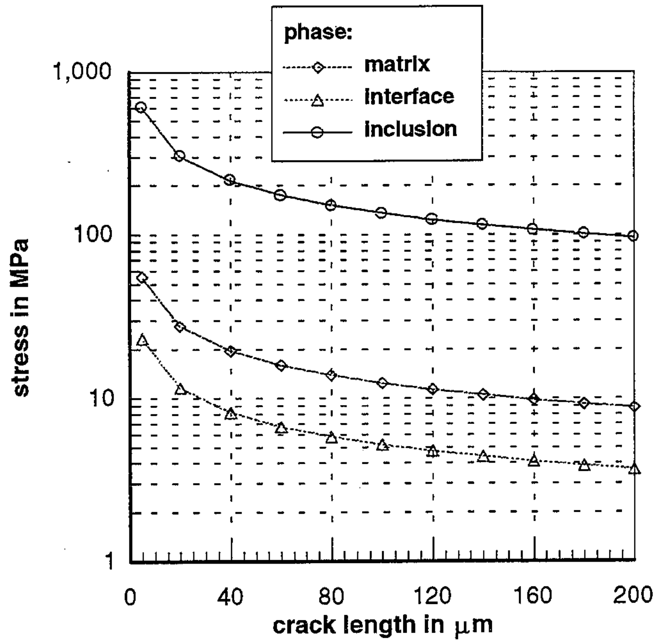

Figure 10. Relation Between Fracture Stress, Crack Length, and Loading Location.

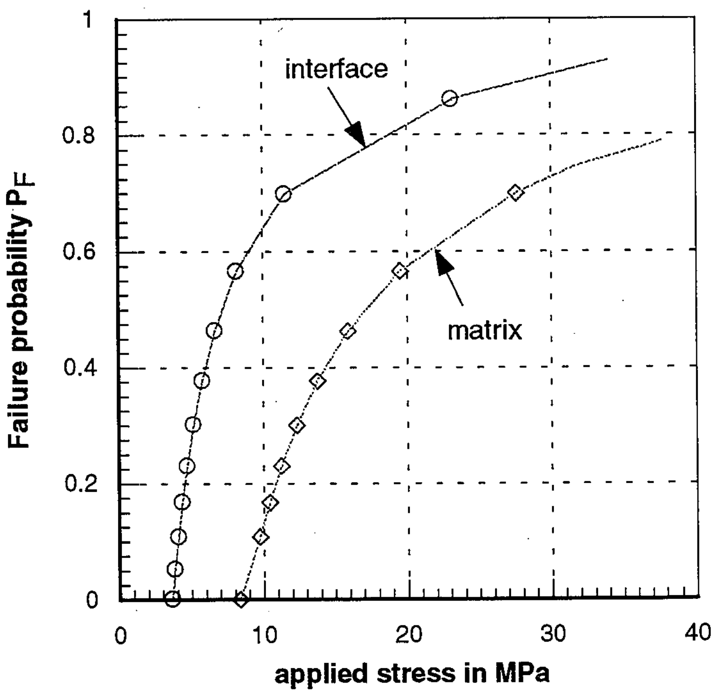

Figure 11. Relation Between Fracture Probability, Applied Stress, and Loading Localization.

8th American Water Jet Conference
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Paper 6

HISTORICAL VIEW ON THE SOFT GROUND IMPROVEMENT METHOD UTILIZING WATER JET

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ABSTRACT

A soil improvement method utilizing water jet has always played a vital role in this field since its conception by the authors in 1968 in Japan. The main driving force for the development was the fact that most cities in Japan are located on soft alluvial soil as the land is mostly mountainous.

During these years, the basic concept of the method was not only expanded into similar systems in Japan, but also exported to European countries such as Germany, Italy, etc. and has evolved to fit local requirements.

This paper focuses on the development history, the current status and the future outlook of this method.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

Most cities in Japan are located on the thick soft flooded alluvium which contains relatively high ground water table and the slightest additional load would easily cause deformation and settlement. Some sophisticated soil modification is required accordingly.

With the rapid increase of social infra-structural works started around the early 1960s, soil improvement works for soft ground, such as open-cutting, tunneling, annually amounted to 200 billion yen at the peak in 1990.

Users have some options for soil improvement methods, such as mechanical soil mixing, chemical injection, and high pressure jet mixing (normally called jet grouping), according to the respective requirement.

In Japan, the annual output of jet grouping amounted to 30 billion yen, thanks to the versatility in quality and quantity of improvement.

2. APPLICATION OF WATERJET FOR SOIL IMPROVEMENT

Chemical grouting has been widely used as the main soil improvement system since 1960, but this method has an inevitable disadvantage. The uniformity of the modified mass is uncontrollable. There has always been a need for a more reliable method. There were two groups of methods developed for the solution to this problem in the early 1970s. (Table 1)

The first group utilizes grout jetting (including cement slurry) at high injection pressure (200 bars) for cutting and mixing soil (one-fluid process), and the second group utilizes both water jetting and grout injection. Water jetting for cutting soil, and grout injection for displacing the grout (three-fluid process). Jet grouping is the total coverage. The former and latter are different in concept. While the objective of the former method is to create a modified soil column, the latter, modified soil panel work as water barrier. These processes basically differ not only in grout material, but in the added air surrounding the cutting agent.

In the 1980s, a new concept of a material jet enveloped by compressed air (two-fluid process), benefited from both the above methods. In early 1990s, the necessity of a larger improved body enabled new concepts to appear by utilizing larger energy i.e. either higher pressure or higher pump rate, for example. Several modified jet grouting processes were introduced in the market in 1990 and 1992 respectively. The specifications for the methods and the concept of jetting are shown in Table 2 and Fig. 1.

All methods mentioned so far have the disadvantages of obtaining different diameters of cut soil, according to the nature of the soil, because a certain amount of energy can carve a softer layer farther than a harder layer.

The appearance of a unique concept of dual jets colliding with each other is definitely a breakthrough in the problems in 1994. The jets collide with each other and terminate at an exact aimed spot with sufficient cutting energy to go still further. The basic concept is shown in Fig. 2.

However, soil modification method utilizing mechanical blades has enjoyed a considerably large share since mid 1970s. Several methods combining mechanical mixing with jetting appeared in the early 1980s, whose concepts are shown in Fig. 3. These aimed at improving the efficiency of mechanical mixing by providing grout jetting from the edges of the mixing blades. In 1994, a combination of mechanical mixing and colliding jets gave birth to a new soil improvement process which enabled each column to securely overlap. Fig. 4 explains the concept.

3. DEVELOPMENT OF JETTING TECHNOLOGY

In late 1960s when jet grouting was born, it was an accepted idea that jetting horizontally through a simple orifice should perform adequately. However, S. J. Leach and G. L. Walker have proved that a nozzle vitally affects the cutting ability of water jet.

Based on this fact, further research has led us to obtain real nozzles as follows.

- Quality of material - The harder, the better. The inner surface should be mirror-finished. Currently, tungsten carbide is used as the nozzle material.

- Shape of the nozzle - From the results shown in Fig. 5 to Fig. 7, the contraction angle should be 13 degrees and the inner straight length should be 2.3 to 3.0 times the nozzle diameter. The nozzle efficiency is about 1.1

Jet grouting is performed underground and in most cases below the ground water table. When jetted in water, the attenuation of kinetic pressure is significant. The farthest cutting reach is the primary concern with a given energy to yield a cost-effective operation. Therefore, a technology to sheath the water jet by compressed air for this purpose was developed. Fig. 8 shows the relation of the kinetic pressure of the jet in water and the distance from the nozzle. The figure clarifies the increasing velocity of air lessens the attenuation in the kinetic pressure of the nozzle center axis. The figure also explains the kinetic pressure corresponding to the increase of air velocity when it exceeds half the sonic speed. From these experimental results, we make is a rule to adopt compressed air with a velocity greater than half the sonic velocity, in jet grouting.

Increasing the jetting energy has become a main technical trend for sophisticated jet grouting developed in early 1990s. Fig. 9 clearly explains that both discharge pressure and flow rate similarly affect the cutting reach. Since increase in the pressure is restricted due to the safety aspects of the operation and durability of the equipment, injection rate is preferably increased to achieve longer cutting reach.

As previously described, a sophisticated nozzle is very essential for controlling the attenuation of kinetic pressure, as well as an upper stream condition toward the nozzle, as apparent from Fig. 10. As shown in Fig. 2, the nozzle is fixed perpendicular to the direction of fluid flow in the main pipe to enable horizontal jetting. Securing an adequate straight portion toward a nozzle as indicated in Fig. 10 means enlarging the whole body which would never meet the design requirement. This difficulty leads to the development of a discharging device equipped with a smoothly bent pipe toward a nozzle for a solution.

In the 1990s, further upgrading of soil improvement has been required. Homogeneous modification in quantity and quality has become a primary issue regardless of the types of soil, especially in the reclaimed land at the water front with a wide variety of soil layers. An equal jetting energy surely brings different diameters to be modified according to the nature of the soil. To minimize the variation in diameters, either the jetting energy or the time exposed to that energy is the key parameter. Neither is viable for a thorough determination of the characteristics of the soil prior to modification nor changing the parameters with the progress of work even if the factors were to be learned.

A new concept has proved to be the solution to this problem. Two angled water jets colliding with each other at the specified distance from the nozzles extremely attenuate the energy. Pressure measurement films clarify the assumption. As shown in Fig. 11 the kinetic energy is drastically dissipated after the collision point. To make this phenomenon really valid, each jet has to be well focused and quite identical. Photograph 1 displays typical cross-jetted water streams generated from the specially devised tool for this purpose.

As stated so far, jet grouting methods which cut the soil with water jet and solidify it with cementitious material consist of a wide variety both in technology and process. Fig. 12 shows that the relationship between various given energies and improvement diameters for each treatment method. Although, in general a modified diameter increases in proportion to the jetting energy, some exceptions may occur in certain methods. It implies, extending a cutting reach depends not only on increasing energy but also on further developed technology. So there is still much room for investigation.

Fig. 13 shows that the relationship between the jetting energy needed to modify $1m^3$ of soil and the stiffness of the sandy soil (SPT. or N value). One - fluid method can no longer achieve a larger diameter even with higher jetting energy, owing to underground water, while an improved jetting and developed device does not suffer from the stiffness of the soil.

4. APPLICATION OF WATER JET TO CONSTRUCTION FIELD

The application of water jet technology to construction field has become popular in the form of jet grouting for open-cutting, tunneling and foundations, for example, as shown in Fig. 14.

Other than jet grouting, various soil improvement methods also take part and their optimum applications are usually categorized by unconfined compressive strength of the modified soil. To be rough, chemical grouting functions below 1 kg/cm^2, mechanical soil mixing, between 1 to 10 and jet grouting between 10 to 100, respectively. Fig. 15 illustrates unconfined compressive strength for sandy soil. Usually the modified soil has much more severe variation in the strength resulting from the types of soil and the grout used in comparison to concrete at the surface.

Fig. 16 sums up the treatment by jet grouting between 1991 and 1992 with the respective type of the soil and explains its wide applicability to both sandy and clayey soils. Jet grouting challenges an expansive application to rather solid layers, as it covers more than 70% in sand exceeding 50 SPT. and more than 80% in clay exceeding 3 SPT., respectively. No other soil improvement based on grouting is considered to overcome such solid a layer as the above.

5. FUTURE OUTLOOK OF JET GROUTING

Although jet grouting is accepted as a steady method, it is still necessary to improve cost-effectiveness, and to improve quality for new markets. Improving the cutting efficiency is one of the answers vital to success. The development of a means to provide more focused water stream is anticipated for this case. Reducing spoils is also essential for better economy. The efficiency of the execution process has to be totally remodeled with completely new ideas. The new concept utilizing cross-jet will prove to be one of the solutions for the requirement, however, it still needs further sophistification.

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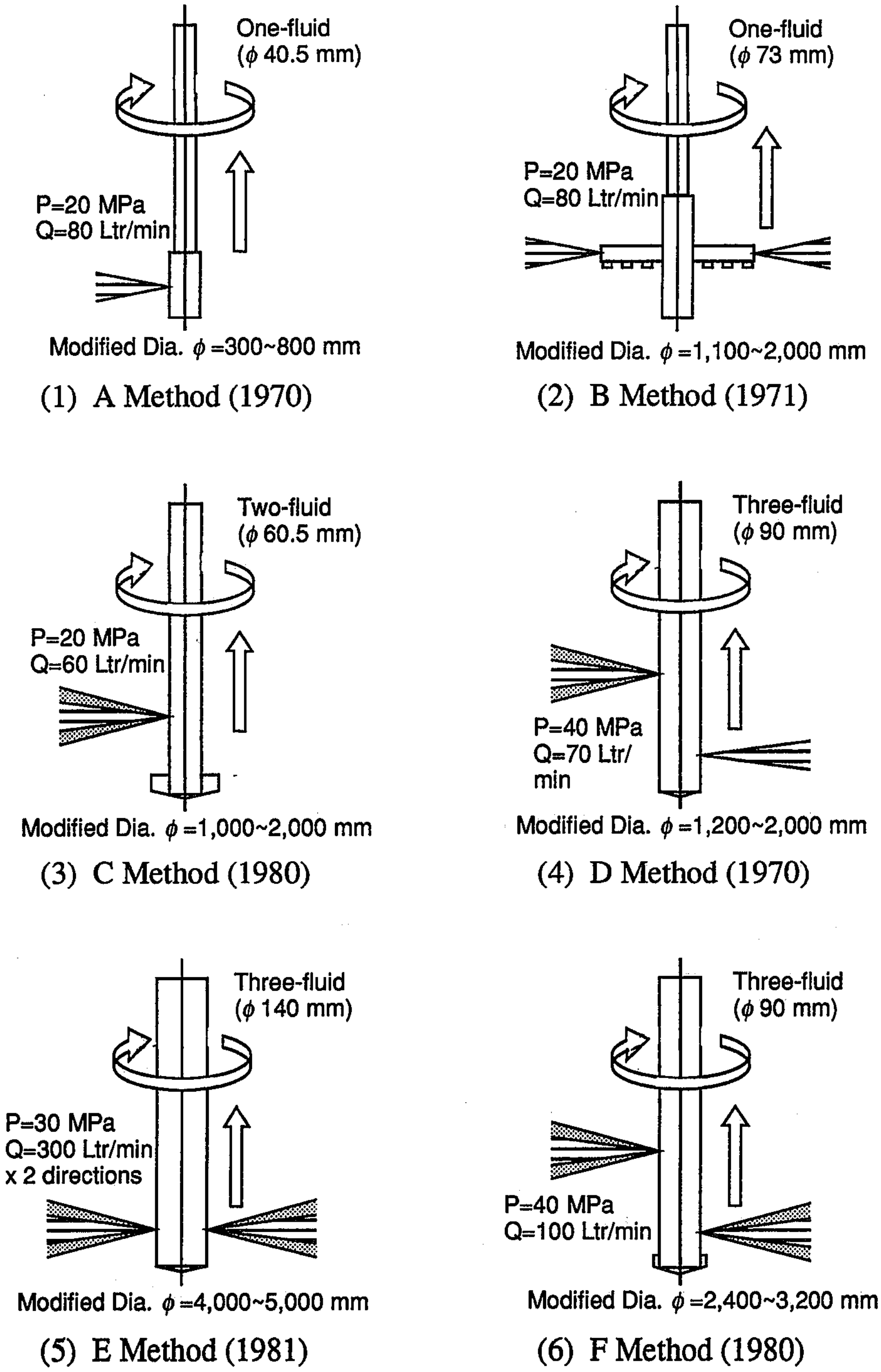


Fig. 1 Concept of Various Jetting Methods

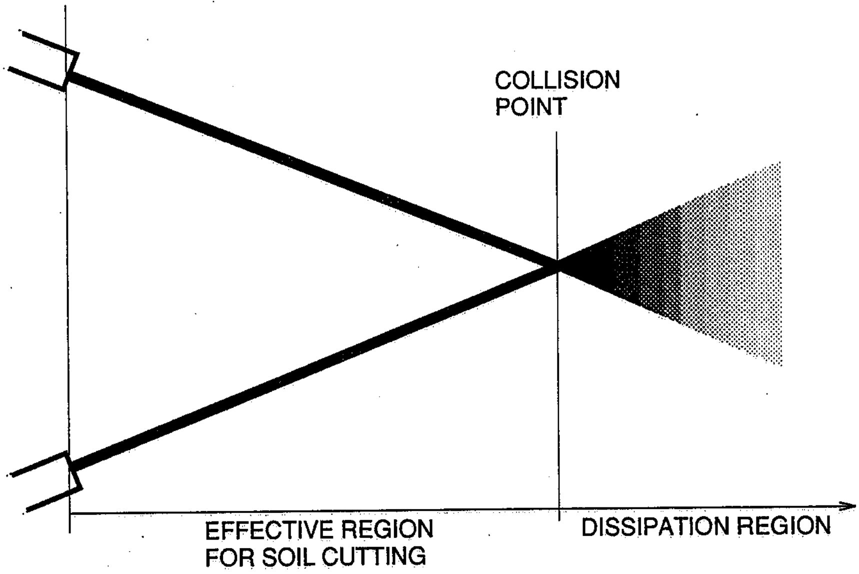


Fig. 2 Collision Jet for Soil Cutting

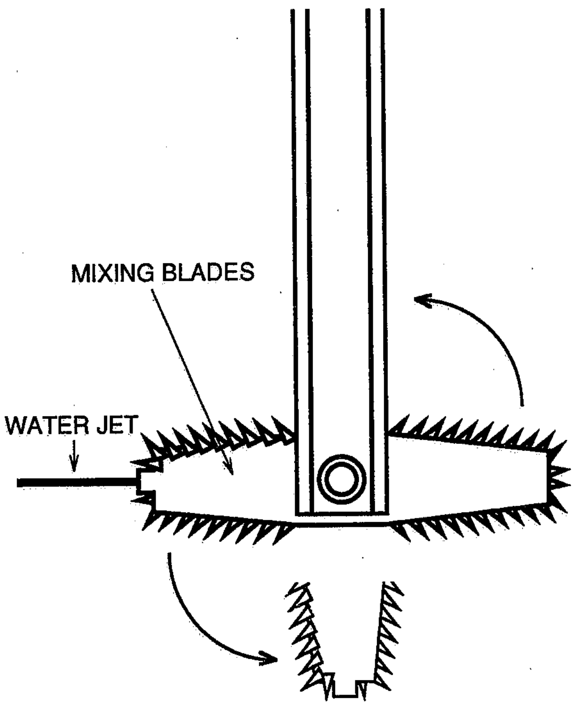


Fig. 3 Combined Method (Mechanical Mixing + Jetting)

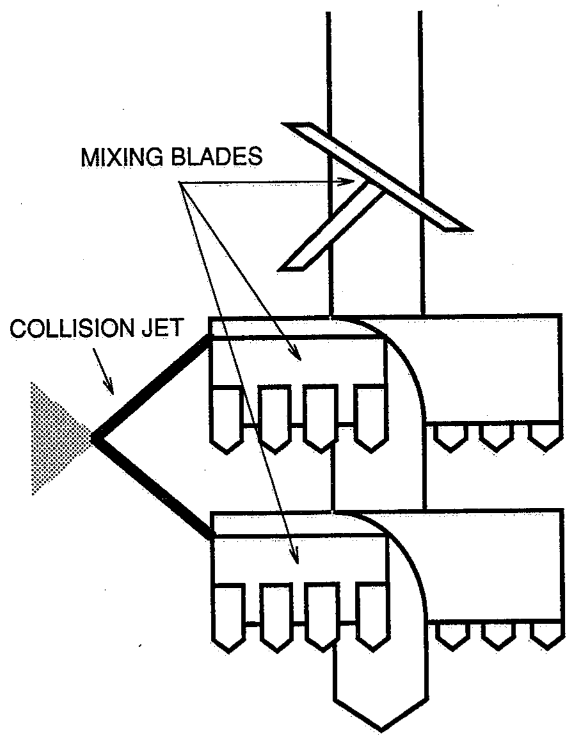


Fig. 4 Combined Method (Mechanical Mixing + Collision Jetting)

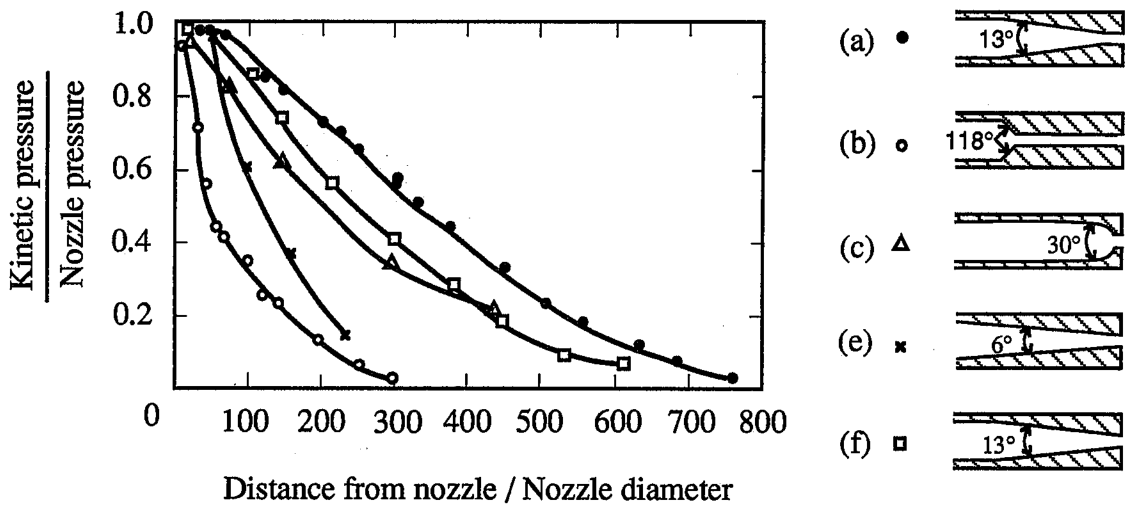


Fig. 5 Effect of Nozzle Shape on Performance

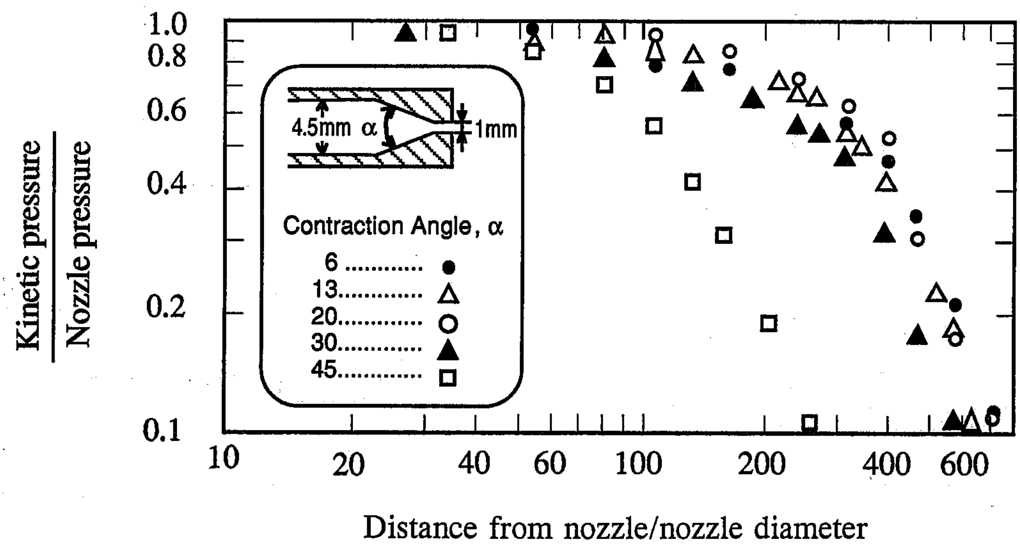


Fig. 6 Effect of Contraction Angle on Nozzle Performance

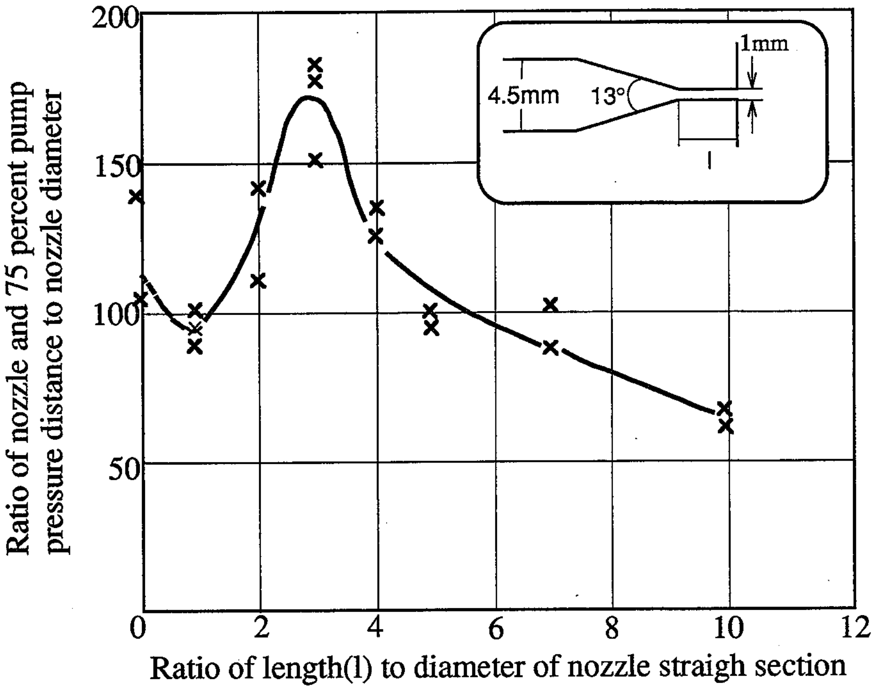


Fig. 7 Effect of Length to Nozzle Straight Section on Performance

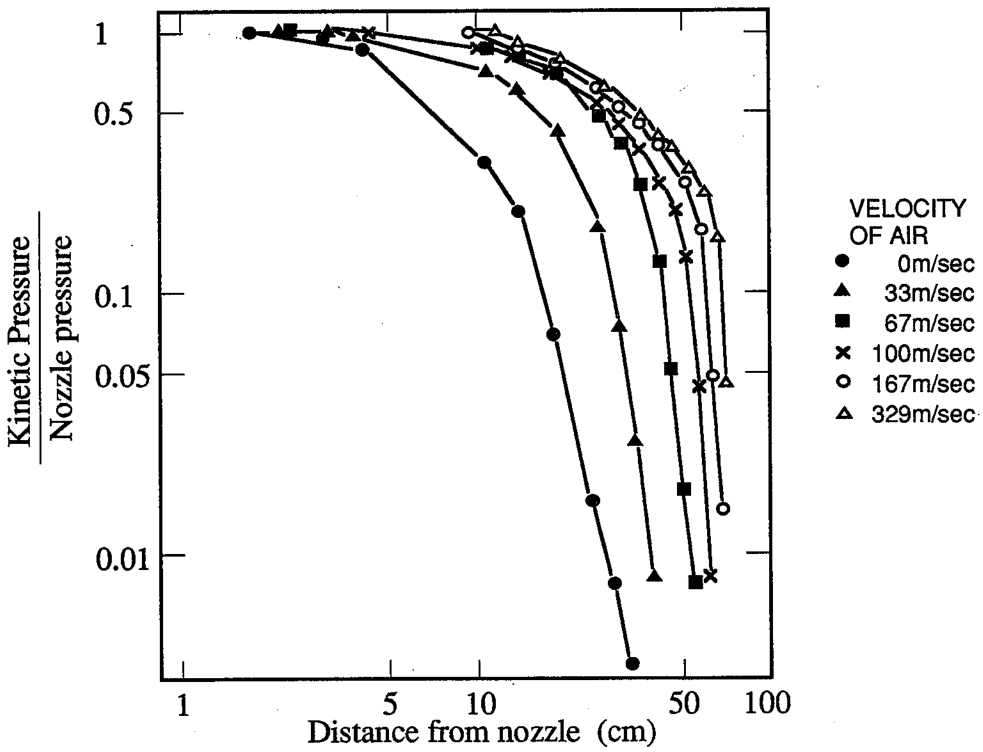


Fig. 8 Reduction of Central Pressure of Water Jet in Water

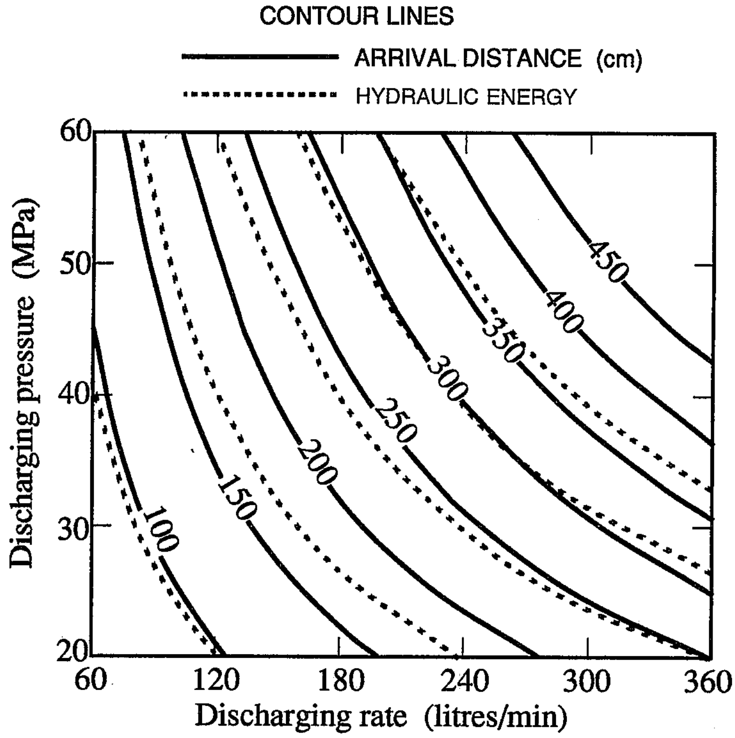


Fig. 9 Contour Lines of Arrival Distances and Hydraulic Energies

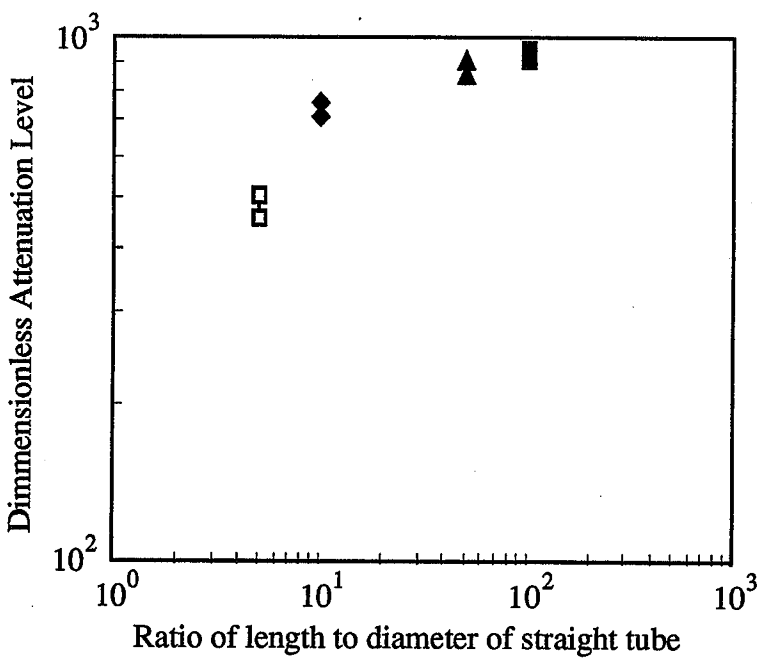
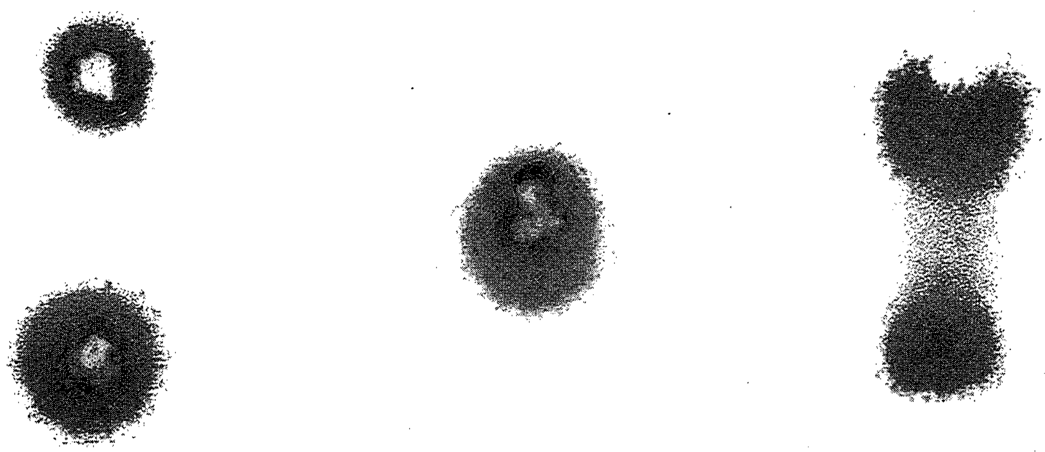


Fig. 10 Relation between Length of Straight Tube and Attenuation Level



(1) Before Collision (2) Collision Point (3) After Collision

Fig. 11 Characteristics of Water Jet on Presure Measurement Film

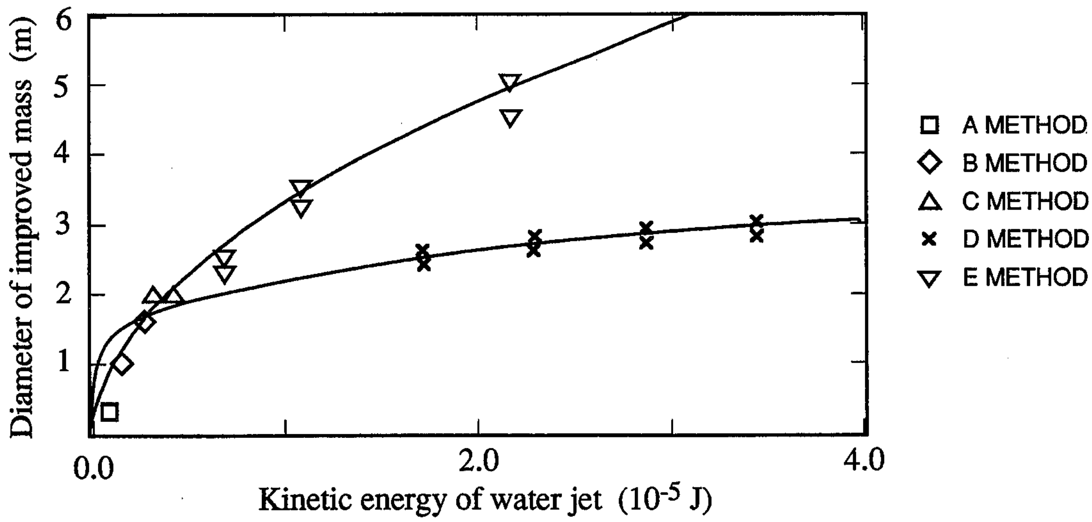


Fig. 12 Relationship between Kinetic Energy of Water Jet and Diameter of Improved Mass

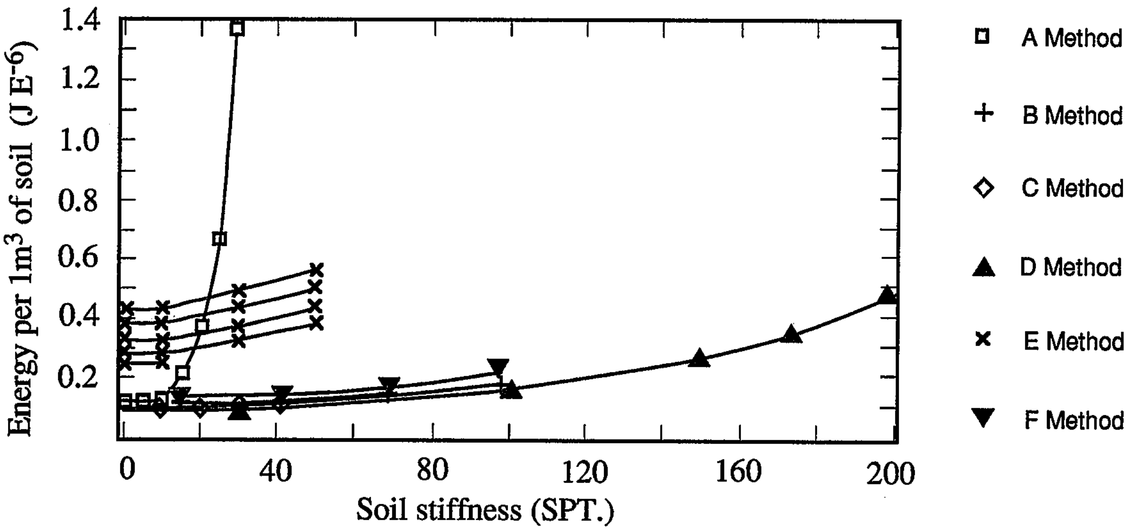
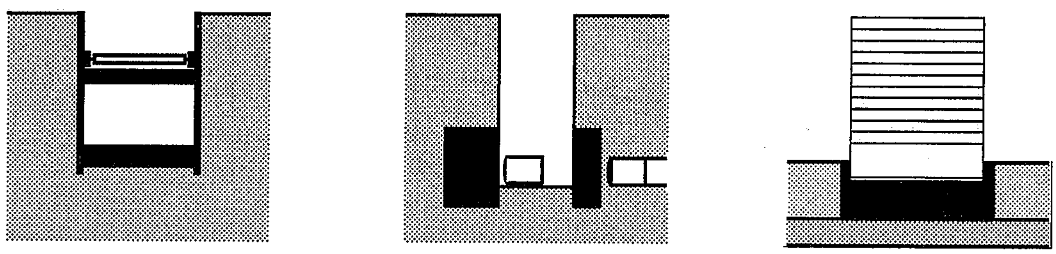


Fig. 13 Relationship between SPT. and Energy Required for Soil Improvement



(1) Construction of Kicker Bracer andPrevention of Upheaval

(2) Rainforcement of Shield-starting/arrival Area

(3) Foundation Rainforcement

Fig. 14 Applications of Soil Improvement Method Using Water Jet

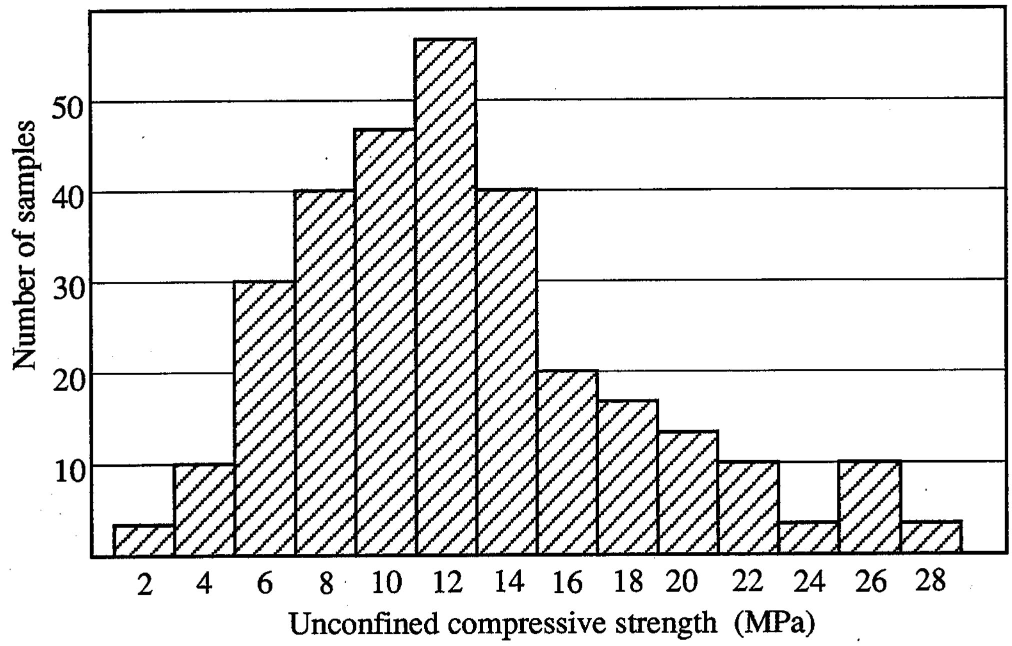


Fig. 15 Distribution of Unconfined Compressive Strength of Modified Sandy Layer Samples

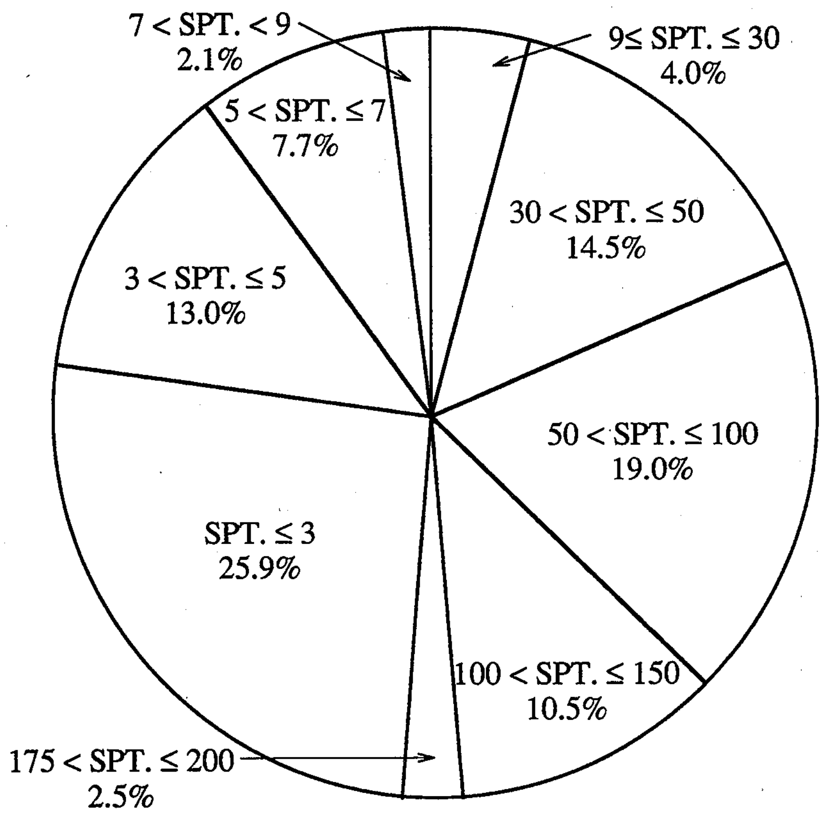


Fig. 16 Utilization Trend of Jet Grouting Based on SPT.

Table 1 Development History of Jet Grouting

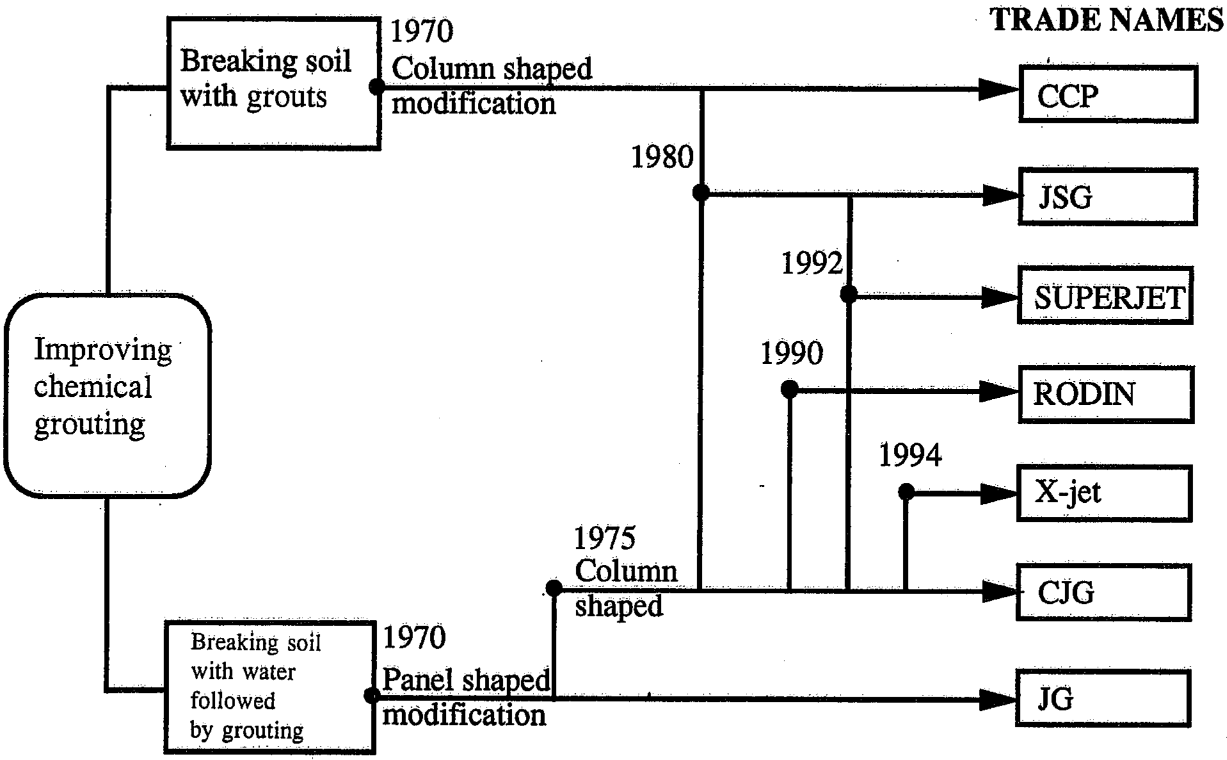
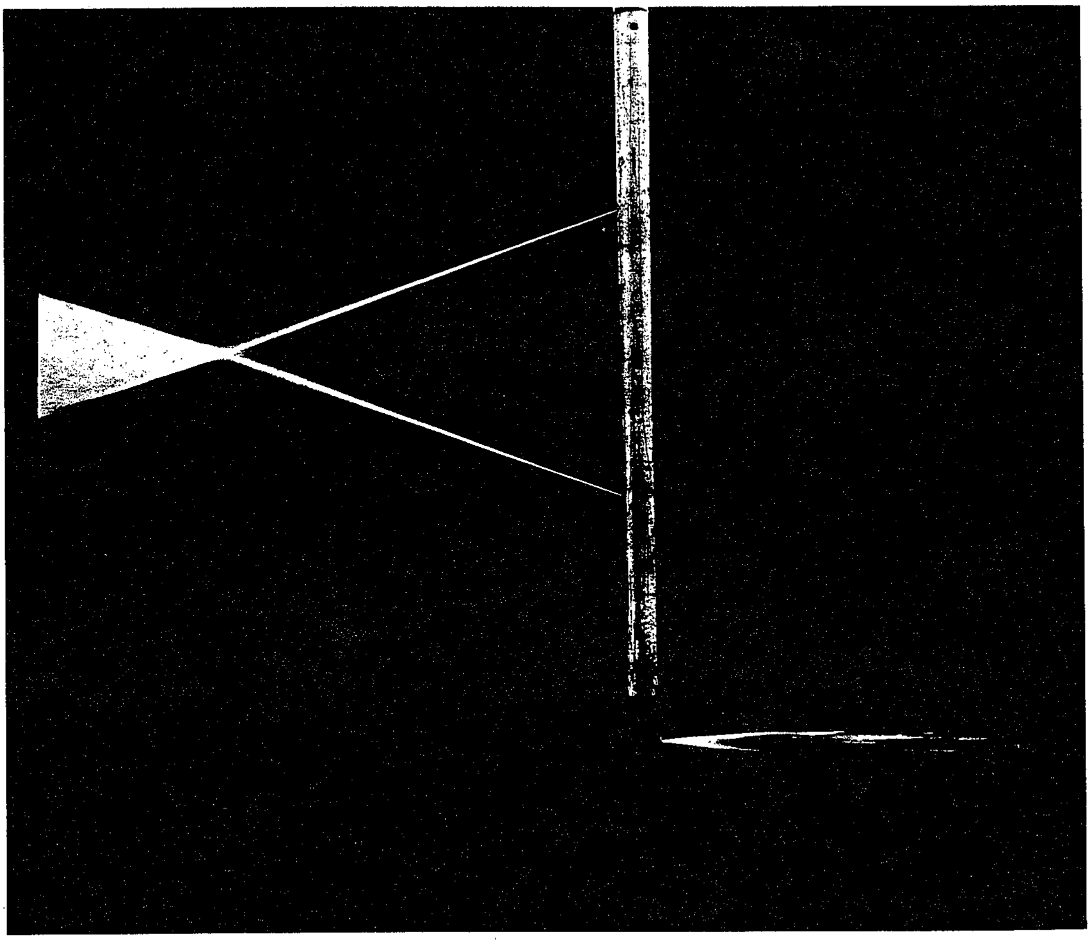


Table 2 Specifications of Various Jet Grouting

Description		Methods / Unit	CCP	Minimax	Minicolumn	JSG	CJG	X-jet
Type			One-fluid	One-fluid	Two-fluid	Two-fluid	Three-fluid	Three-fluid
Discharging Fluid			Grout only	Grout only	Water +Grout	Air +Grout	Grout+ Water+Air	Grout+ Water+Air
Air (with or without)			w/o	w/o	w/o	w	w	w
Water jet flow rate			N/A	N/A		N/A		
Water jet pressure		kg/cm2	N/A	N/A	10~30	N/A	400	400
Grout flow rate		ltr/min	20~31	80	30	60	180	190
Grout Pressure		kg/cm2	200	200	300	200	20~50	40~60
Withdrawal rate		min/mtr	3~5	2~4	10	16~40	16~25	6~10
Rotation		rpm	20	20	10	5~15	4~5	4~5
Cutting energy		Joule	1.81xE-7	3.63xE-7	6.81xE-7	2.54xE-6	5.05xE-6	4.20xE-6
Clay	SPT.	SPT	N<=4	N<3	N<3	N<=4	N<=9	<-
	Modified Dia.	cm	40~50	70~80	80~120	120~200	100~200	230
Sand	SPT.	SPT	N<=15	N<=10	N<10	N<=50	N<=200	<-
	Modified Dia.	cm	30~50	50~70	80~100	100~200	120~200	23
Modified Diameter for clay w/N=0		cm	50	80	120	200	200	200~280



Photograph 1 View of Typical Cross-jet Water Streams

8th American Water Jet Conference
August 26-29, 1995: Houston, Texas

Paper 7

HIGH PERFORMANCE, DUAL COLLIDING WATER JET ON GROUND IMPROVEMENT

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ABSTRACT

A new soil improvement method using a dual colliding jet was developed which forms a homogeneous, uniformly cylindrical, solidified body in the ground. This could be achieved by applying the following principles: the cutting ability of a water jet formed from two colliding jets decreases significantly if the angle of collision is over 40 degrees; and, by slightly extending the straight tube connected upstream of the nozzle, the water jet's concentrated structure can be maintained over a much longer distance. In this improvement procedure, a high performance dual colliding water jet is issued from a 90-mm-diameter jet rig inserted into the ground. As the rig is pulled up, the jet cuts the soil cylindrically, and the rig injects solidifying material into the ground. Performance tests in the field verified that the new method formed a cylindrical, homogeneous, solidified body 2.3 m in diameter. Furthermore, the waste generated by the new method was less than half of that created by a conventional method using a single water jet. These tests showed that the high performance dual colliding jet was effective in controlling soil cutting area for ground improvement.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

Buildings, bridges, etc. in every metropolis in Japan are constructed on soft alluvial layers with a high water content. Therefore, soil solidification and/or cut-off of water must be carried out prior to construction.

The usual method for accomplishing this is soft ground improvement with a single water jet as shown in Fig. 1. A jet rig connected to a triplex pipe is inserted into a vertical guide hole. Then, as the rig is rotating and being pulled up, an air-coated water jet and solidifying material are issued from the rig, forming an improved body in the ground. Since the ground consists of various thin, nonhomogeneous layers, the cutting range of the water jet is variable. As a result, the shape of the resulting body is often irregular and its strength is not uniform. The injection of sufficient slurry to ensure the strength of the improved body produces much waste. A soil solidifying method using a dual colliding water jet overcomes these problems by cutting out a uniform cylinder in the ground.

To facilitate the examination of the dual colliding jet, it can be divided into two regions. The first consists of two water jets for soil cutting. The jet formed after collision belongs to the second region. If the angle at which the two jets collide is larger than a critical angle, then the cutting ability of the dual colliding jet in the second region diminishes immediately. By exploiting this principal, the cutting area can be controlled.

As reported by Miyoshi and Hirayama (1973), such a soil improvement method had been developed which used a dual colliding jet issued from the ends of 0.9-m-long, horizontal soil mixing blades, penetrated into the ground. However, the efficient application of the dual colliding jet had not been developed. As a result, the two water jets in the above collided at 60 degrees, 0.58 m away from the nozzles. This dual colliding jet limits the solidifying area, but the method requires a large-scale machine to penetrate the 0.9-m-long blades into the ground.

To form a solidified body more than 2 m in diameter with a compact machine, a new method was developed using a jet rig 90 mm in diameter for a dual colliding jet. In designing the new jet rig, each of two water jets had to be able to cut soil for a distance of over 1 m, and the jets were required to collide. In addition, the critical angle of collision at which the resultant jet can no longer cut the soil had to be established.

The critical angle of collision was determined by experiment, and a jet rig which produced a high performance dual colliding jet capable of maintaining its concentration over a long distance before collision was developed. Then the rig was tested in the field.

2. EXPERIMENTS AND RESULTS

2.1 Angle of Collision

This experiment was conducted to determine the minimum angle of collision at which the resultant jet loses its ability to cut soil.

In a study of surface working using a confluent jet with four nozzles (Hongawa et al., 1992), it was reported that the mass of steel eroded by an abrasive jet was constant for an angle of collision greater than approximately 40 degrees. In addition, it has been established that a dual jet with a collision angle of 60 degrees can control the cutting area. Thus, in the presented experiment, the impact pressures after collision of two water jets colliding at 50 degrees and less were measured by pressure measurement film.

In this experiment, the two water jets collided 1.00 m from a line connecting the two nozzles from which the jets were issued (Fig. 2). The impact pressure was measured by exposing pressure measurement film protected by a film pouch and brass foil (both 0.1 mm thick) to the dual colliding jet for 10 seconds as shown in Fig. 3. The jets were pressurized at 30 MPa by plunger pumps. The shapes of the nozzles are shown in Fig. 4 (b).

The ratio of the measured impact pressure to that of one of the single axial jets at a distance of 1.00 m from the nozzle is shown in Fig. 5. These results show that there is a critical angle of collision at which the resultant dual colliding jet shows a significant reduction in pressure. The pressure reduction was about the same for collision angles of 20 and 30 degrees, but the pressure reduction for the 40 degree angle was much greater. Furthermore, the pressure reduction occurring with a collision angle of 50 degrees was approximately the same as that occurring with 40 degrees.

Therefore, for the new ground improvement method, 40 degrees was adopted as the minimum angle of collision at which the resultant jet loses impact pressure and cannot cut soil.

2.2 Jet Rig for Dual Colliding Jet

To control the cutting area, the two water jets composing the dual colliding jet must meet the following conditions:

(1) The water jets both must be concentrated enough to cut soil before they reach the collision point.

(2) The characteristics of the water jets must be similar so that their cutting ability is canceled after collision.

A jet rig was developed to meet these requirements. The flow rate of each water jet was 75 liters per minute at a discharge pressure of 40 MPa, and the jet rig diameter was 90 mm so that conventional execution machinery could be used.

Yoshida et al. (1994) reported that a slight extension of the straight portion connected upstream of a nozzle enables a water jet to maintain its concentrated structure for a longer distance from the nozzle than if the straight portion is short. Thus, the length of the straight portion of the nozzle in the new method is much longer than that of the conventional method as shown in Fig. 4. The conditions of the two water jets were almost identical because of the contrived watercourse in the new jet rig. The jet rig issuing a high performance water jet and slurry is shown in Photo 1. The angle of collision was 40 degrees and the collision point was 1.00 m away from the central axis of the rig.

The pressure measurement films exposed to water jets from the new rig and from a conventional one are shown in Fig. 6. Some of the centers of the reacted marks are damaged and lost colour due to high impact pressure. The two water jets from the new jet rig were concentrated and could damage the film 0.90 m from the axis of the rig, while a water jet from a conventional rig was not capable of damaging the film. Although the two water jets could damage the film until collision, the resultant high performance water jet could not.

From the experiments, it was confirmed that the high performance jet issued from the new jet rig met the conditions for forming a solidified body with uniform diameter.

Pressure reduction on the jet axis of a water jet in water becomes similar to that of a water jet in air by coating the water jet with air issued at over Mach 0.5 (Yahiro et al., 1975). Based on this, the water jets used in the new method are coated with high speed air, just as the jet used in the conventional method is.

3. FIELD TEST

3.1 Field Test Conditions

The performance of the new ground improvement method was evaluated through a field test comparing it with the conventional method.

The experimental apparatus is shown in Fig. 7. While issuing air-coated water jets for soil cutting and injecting slurry, the jet rigs used in both the new and conventional methods rotated and were pulled up at regular intervals during solidifying procedure. The test conditions are listed in Table 1. The discharge pressure of the water jets in both methods was 40 MPa and flow rate of each water jet was 75 liters per minute. To equalize soil cutting energy per improvement depth in both methods, the rate at which the new jet rig was pulled up was twice that of the conventional rig. The volume of slurry injected during the ground improvement process was determined by the fact that the resulting solidified body must have a minimum strength of 1 MPa. The volume of slurry injected during the new procedure was about half that of the conventional process because the high performance dual water jet cut the soil uniformly.

The soil boring log for the test site and execution depth are given in Fig. 8. The ground at the test site consisted of alternating layers of sand and silt. The ground was very soft, exhibiting an N-value of not more than 5. The water table was located at approximately minus 3 meters.

3.2 Results of Field Test

To examine the diameter and quality of the solidified bodies, they were cored and dug out.

The top 0.7 m of the bodies were dug out (see Photo 2), and their north-south and east-west diameters were measured at 0.1 m depth intervals (see table 2). The solidified body formed using the the conventional method was irregularly-shaped due to the jet's variable cutting range.

However, the body formed with the new process was of uniform shape because the dual colliding water jet could cut a nearly perfect circle in the ground.

The experiment revealed that the jet resulting from two jets colliding at 40 degrees was able to cut soil approximately 0.17 m beyond the collision point. It was determined that the guaranteed diameter of a body formed with the new method is 2.3 m. The new process can form a solidified body 1.7 times larger than the conventional method.

Seven days after execution, samples for unconfined compression strength tests were cored from the bodies. The results are illustrated in Fig. 9. Only three of the samples taken from body produced by the conventional process could be tested for compression strength because pockets and/or layers of pure soil were in the samples. Furthermore, some of the samples cracked due to only partial solidification. The strength of the body formed by the new process was uniform. These results can be attributed to the following:

(1) Slurry concentration was uniform with the new method because the slurry was injected into a regular area cut by the dual jet.
(2) Few pockets or layers of soil lay in the body formed with the new method because the blocks cut out by the upper water jet were smashed by the lower jet.

The above indicate that the solidified body formed by the new method was homogeneous because an area with a regular diameter could be cut at any depth.

Since a controlled cutting area requires a lower volume of injected slurry, waste can be reduced. The waste volume produced with the new method was less than half that produced by the conventional process. Furthermore, the faster rate at which the rig is pulled up in the new method can shorten execution time.

4. CONCLUSION

A new ground improvement method was developed by applying a high performance dual colliding water jet with a long controllable cutting range. The method can from a homogeneous, uniformly cylindrical solidified body 2.3 m in diameter. The following conditions are required of the dual colliding water jet:

(1) The two jets composing the dual jet must maintain their concentrated structure over a significant distance before colliding.
(2) The characteristics of the upper and lower jets must be similar.
(3) The angle of collision must be 40 degrees or more to control the cutting range.

A field test of the new process verified that a uniform, homogeneous, solidified body 2.3 m in diameter could be formed regardless of the soil conditions. In addition, the waste volume was less than half of that produced by the conventional method. Thus the test results proved that the high performance dual colliding water jet is effective in controlling the cutting area, resulting in efficient ground improvement.

ACKNOWLEDGEMENTS

We would like to thank Mr. Shunji Jinbo, Mr. Yukinori Matsumoto and Mr. Takashi Nagai for assistance in performing the field test.

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Table 1 Field Test Conditions

	New method	Comventional method
Discharge pressure of water jet, MPa	40	40
Flow rate of water jet, liters/min	75*2	75
Injection rate of slurry, liters/min	184	180
Mass ratio of water to cement	1	1
Rate of pulling up jet rig, min/meter	10	20
Increment rig is raised, millimeters	20	25
Number of rotations per stage	1	2.5

Table 2 Dimensions of Solidified Body

	Maximum diameter	Minimum diameter	Average	Standard deviation
New method	2.39	2.31	2.35	0.03
Conventional method	3.28	1.96	2.68	0.46

(m)

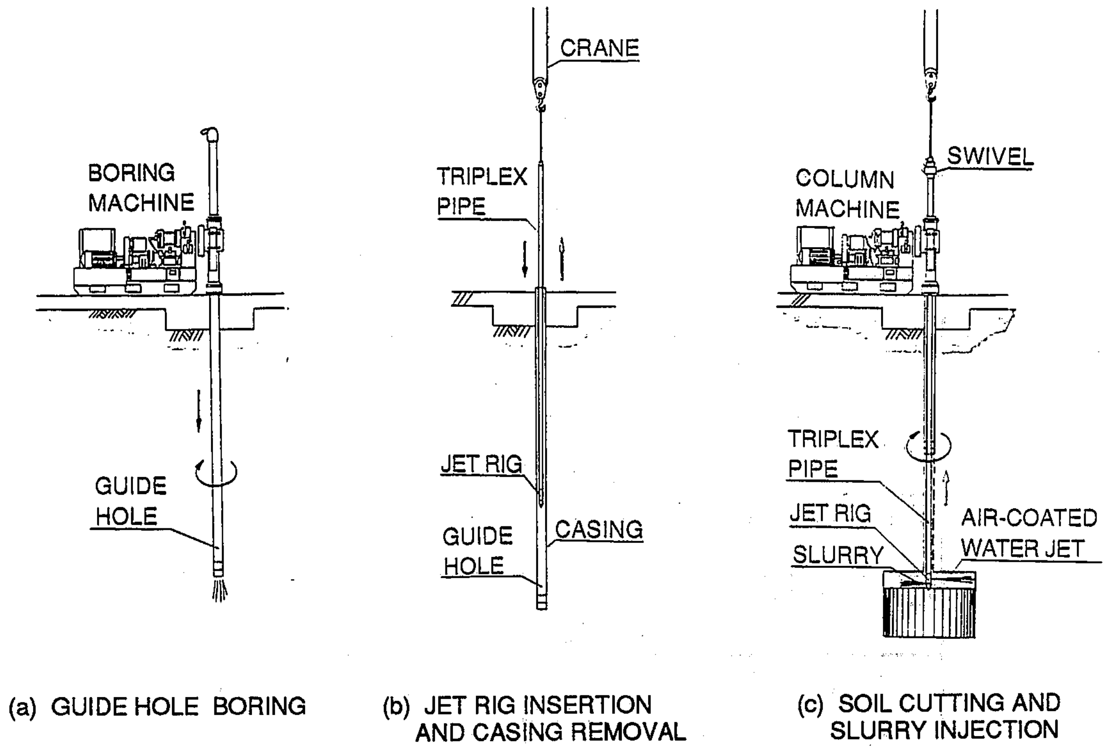


Fig. 1 Procedure for Ground Improvement Using Water Jet

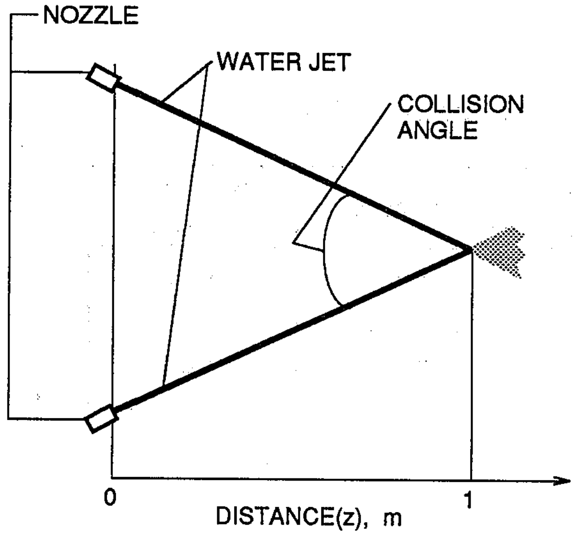


Fig. 2 Experiment to Determine Critical Angle of Collision

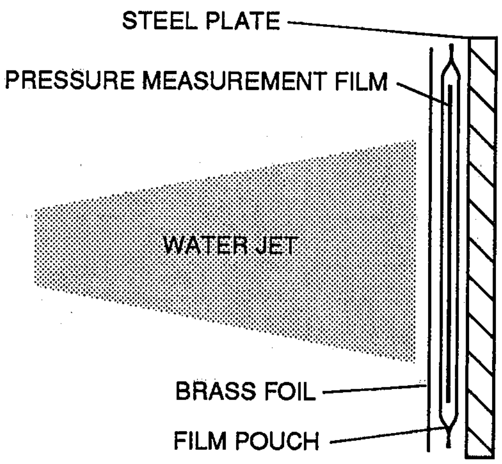


Fig. 3 Pressure Measurement

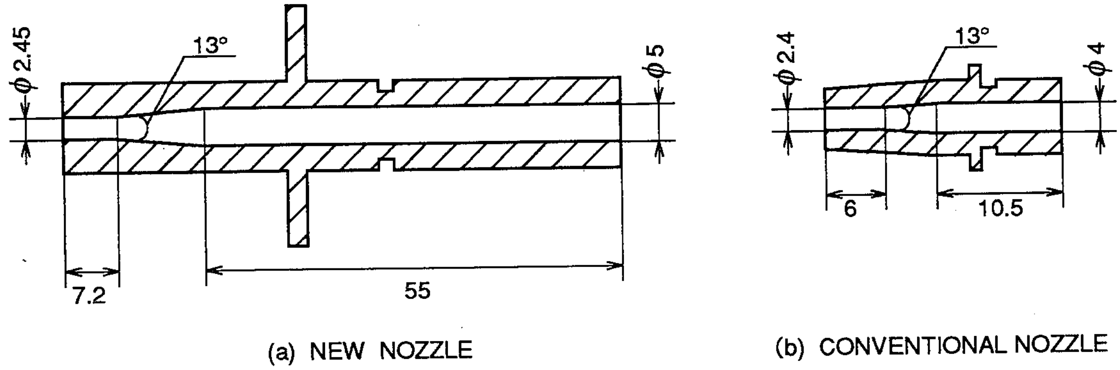


Fig. 4 Shapes of Nozzles

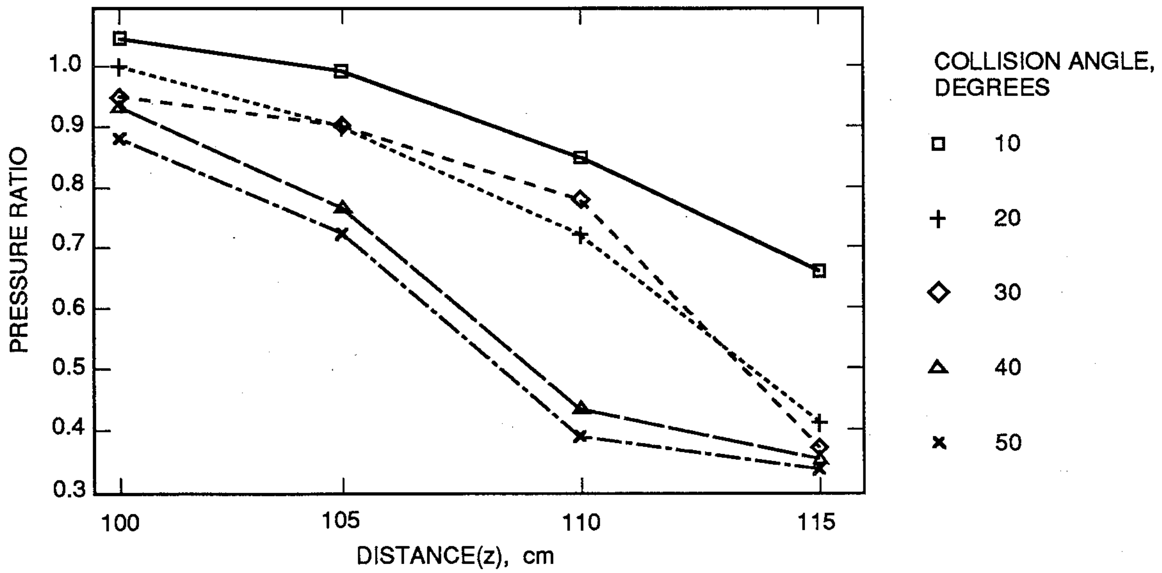


Fig. 5 Reduction of Impact Pressure

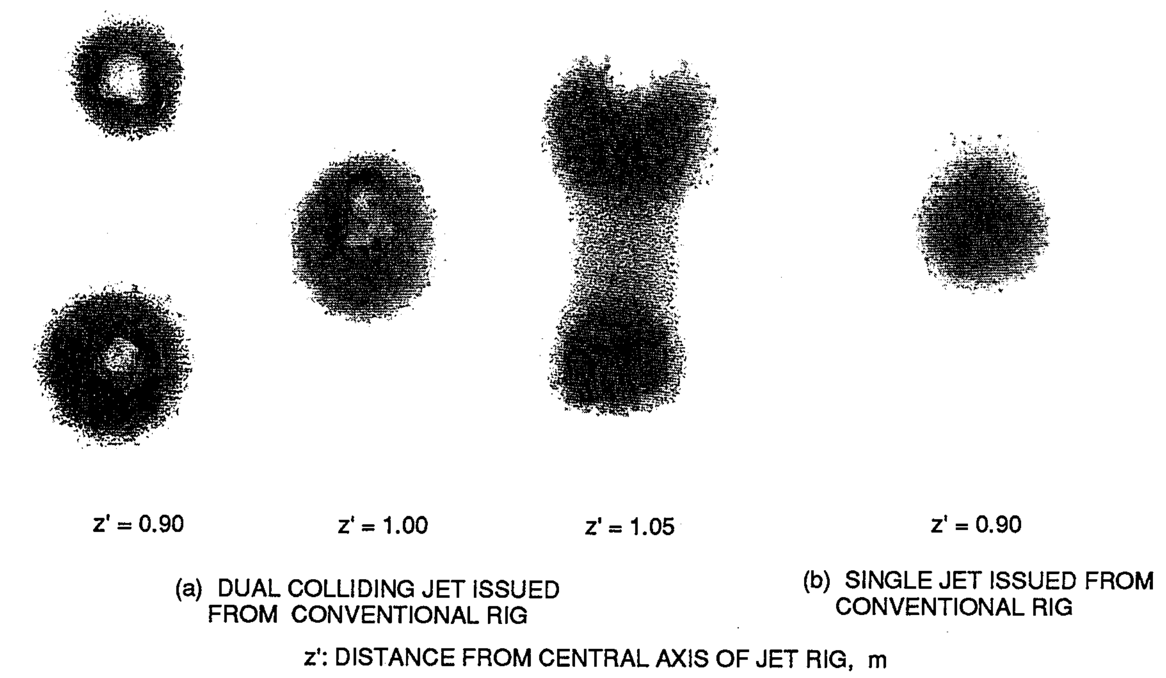


Fig. 6 Characteristics of Water Jets Exibited on Pressure Measurement Films

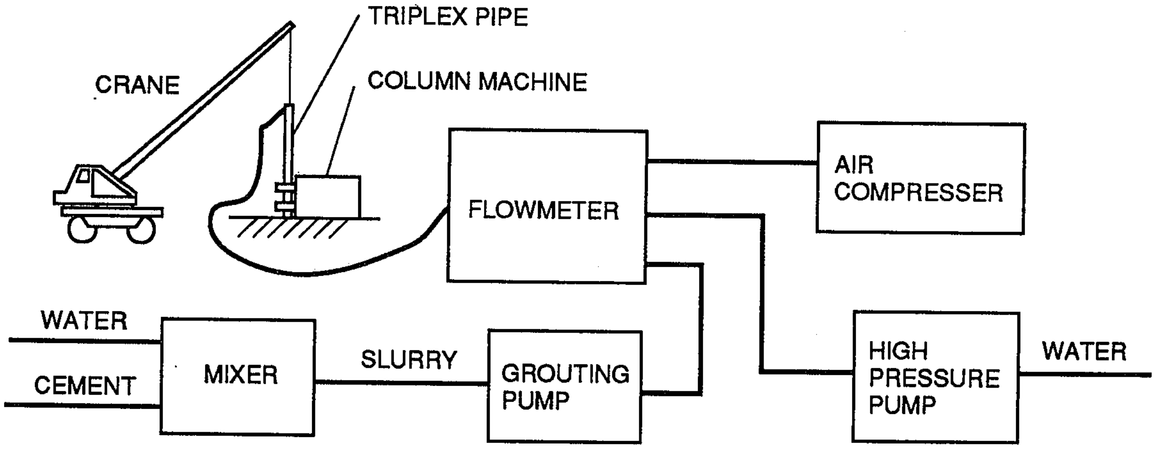


Fig. 7 Field Test Apparatus

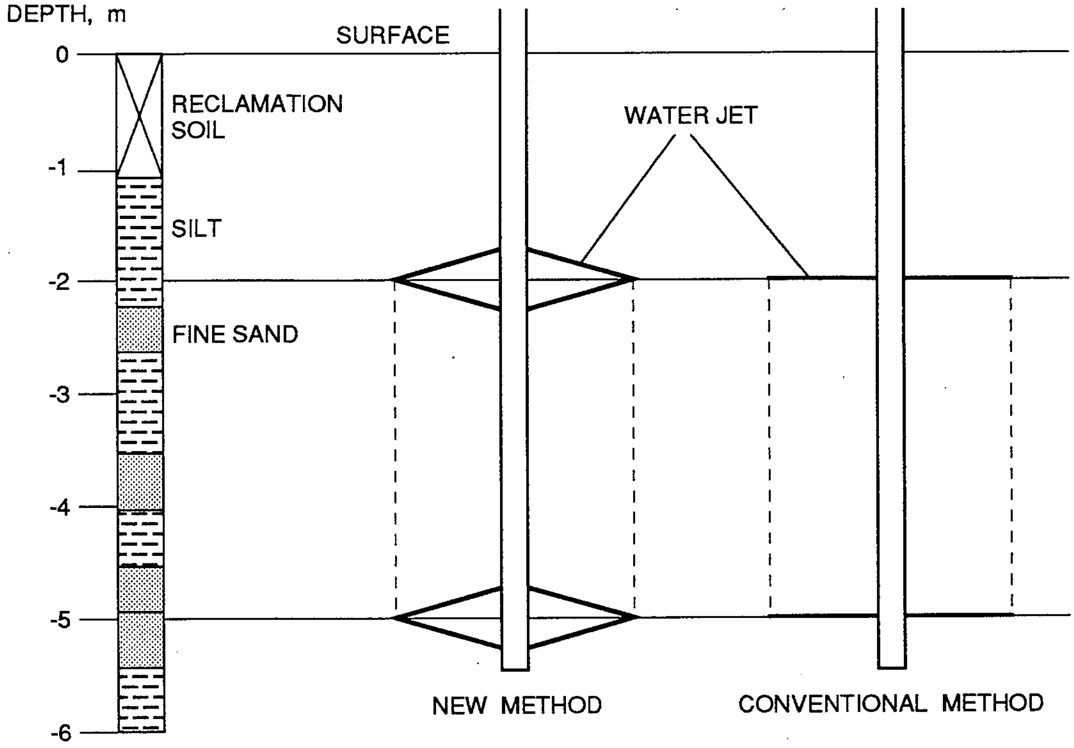


Fig. 8 Soil Boring Log and Execution Depth

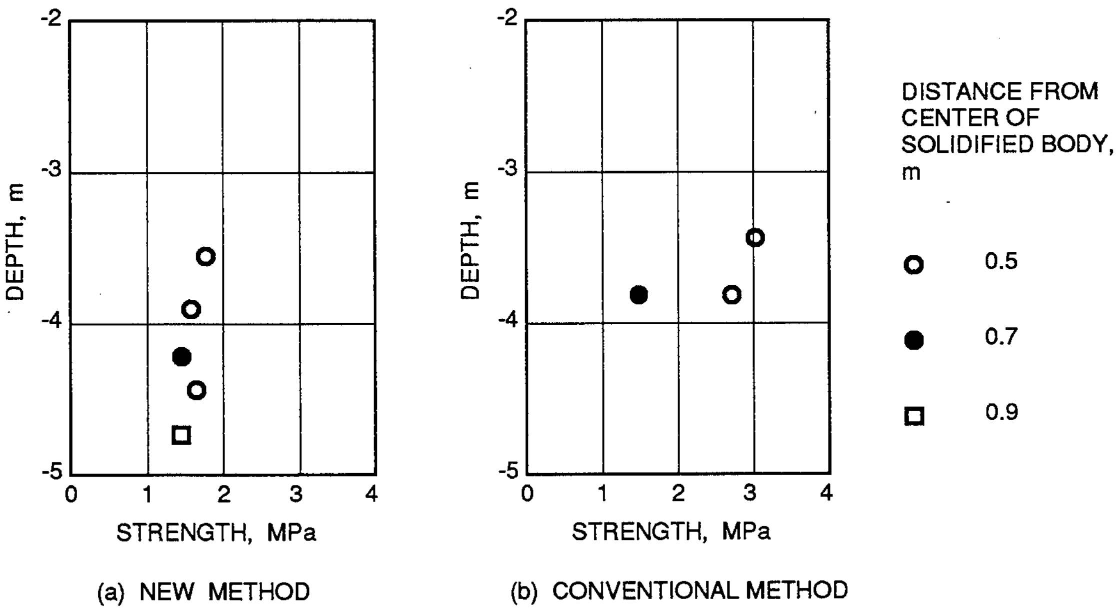


Fig. 9 Unconfined Compression Strength of Solidified Bodies

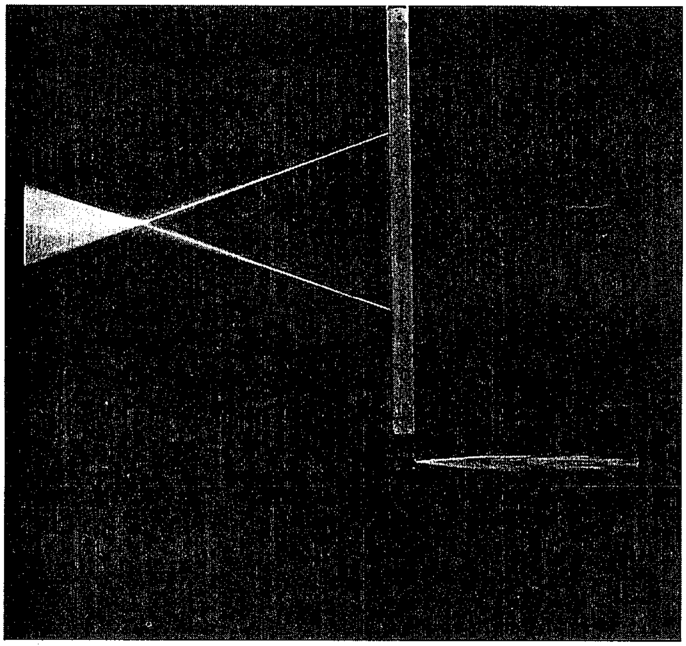
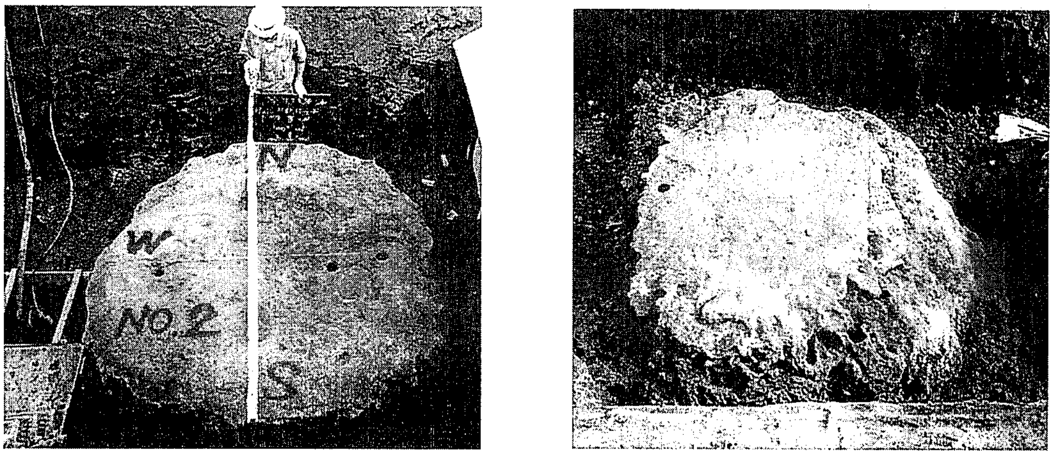


Photo 1 The New Jet Rig Issuing Dual Colliding Water Jet and Slurry



(a) SOLIDIFIED BODY BY NEW METHOD

(b) SOLIDIFIED BODY BY CONVENTIONAL METHOD

Photo 2 Solidified Bodies Formed by Each Method

8th American Water Jet Conference
August 26-29, 1995: Houston, Texas

Paper **8**

CUTTING STEEL & CONCRETE WITH ULTRA-HIGH PRESSURE WATER AND ABRASIVE

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ABSTRACT

A special division of HydroChem is using ultra high pressure water jets with abrasive to cut a variety of materials including steel, concrete, alloys and refractory. Most of the work is done in the petrochemical industry on steel tanks, vessels and towers. This includes dismantling work, demolition of process systems and cutting access openings in areas where open flame would be prohibited.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

The use of ultra-high water pressure jets in the field has become popular in the last few years with the advent of more dependable high pressure pumps and intensifiers. A special division was formed by HydroChem (formerly Hydro-Services) to do ultra-high water jet cutting and cleaning in 1988. Since that time, the special group has cut steel reactors in the petrochemical industry, concrete conduit, refractory, tanks, and towers. A paper by Zeng et al. (1993) discusses the viability of an abrasive waterjet in cutting operations. Their work with the machinability number and cutting rates could be used to estimate the cost of field jobs. At this time, however, estimating is done by our company from historical data and some jobs are done on a time & material basis. Figure 1 shows a crane attached to the top of a reactor, and when the first section is cut using the wet abrasive jets, the crane lifts the top of the reactor and the next section is then cut by the same method (also see Figure 5). The cutting part of this job took about 18 hours to complete and the cost to the customer was about $21,000. The reactor was 45 feet in diameter with 7/8" thick steel and 5" of refractory. The ultra-high water jetting equipment has also been used to clean tanks, towers (de-coking), heat exchanger tubes (I.D. & O.D.) and all types of polymers.

2. DESCRIPTION OF THE EQUIPMENT

The ultra-high pressure water jetting units used in the cutting operation includes a 36,000 psi intensifier unit, diesel powered, trailer mounted. The systems used by our special division also have a control console as shown in Figure 2. Several new jigs, fixtures and devices were developed to do linear cutting, circular cutting and cleaning jobs. The set-up often includes working from scaffolding and involves the use of cranes and lifting equipment. In Figure 3, workers are attaching a linear track with the cutting nozzle to the side of a vessel for cutting operations.

3. SPECIAL CUTTING HEAD AND NOZZLES

The special nozzles and tracks were developed and adapted by the pioneers in the field application of ultra-high pressure water/abrasive jet cutting. The first portable 36,000 psi intensifier units appeared only a few years ago and the field operators began to need special tools. Our company is fortunate enough to have some of these innovators in the special services division that make the tools needed to do their job. Figure 4 shows a nozzle and track mechanism being setup to cut an access into a pressure vessel. Flame cutting or any spark producing equipment is often not allowed on the job site, so wet abrasive cutting must be used. Figure 6 shows an abrasive cutting head being used at 36,000 psi with garnet to cut a pipe section.

Abrasive delivery and control has also been an area of prime concern. Ming-qing et al. (1993) report their investigation of abrasive flow and coking. Our present hoppers, controls, feeder and supply hose arrangement have been mainly developed through experimentation and field experience.

4. EQUIPMENT FOR UKRAINE

The Defense Nuclear Agency requested quotes on equipment last year to send to the Ukraine. The purpose was to cut steel away from a train wreck where nuclear devices would be present. Figure 7 shows the equipment that we proposed to do the wet abrasive cutting. The equipment included four Ultra-High pressure pump units, four sets of cutting accessories and personnel training in the Ukraine. The government specification and red-tape were bad enough, but they insisted that the operator must hold the abrasive gun and cut 2" thick steel at a given rate. The specification also called for an abrasive delivery distance of 200 feet from the pump unit. Our demonstration of these parameters did not result in a satisfactory showing. It turned-out that there was no train wreck; but there might be some day and it would be great to have the equipment and the people trained in cutting steel with a hand held gun.

5. SAFETY PROCEDURES

The policy for the special division is to do no hand held cutting. The bounce back from the 36,000 psi (high velocity) jet and abrasive is dangerous to a would-be gun operator and visibility is very low. A track mechanism as shown in Figure 3, keeps the operator at a safe distance. The mechanical device also produces a cleaner cut which is dimensionally exact. Operator fatigue is reduced and the visibility is improved.

An accident recently occurred at the site of an ultra-high pressure job that was the result of a come-along breaking, rather than a water cut. The come-along was holding a steel plate (36" diameter by 8" thick) that was being cut out of a tank. Just as the cut was completed, the come-along broke 3 links above the hook that was holding the plate. The plate, weighing 2600 pounds, crashed through the scaffolding to the ground 20 feet below. The supervisor was held by the safety harness until help arrived, but it took 2 hours to get the supervisor safely to the ground. He suffered two broken legs and lacerations to his arms and hands.

Other accidents involving ultra-high water jets and our company, have been very few. The only accident reported to date, involved a flex lance being used at 36,000 psi that "hydrauliced" out of the tube, cutting the operator. Ref. 5 is a good guide for water blasting safety and it is a good idea to have regular safety meetings and "tailgate check lists" to help keep safety on the minds of the field personnel.

6. CONCLUSIONS

The future for abrasive water jet cutting seems to be very promising. The study of abrasive as reported by Ohman (1993) and Vasek et al. (1993) will undoubtedly improve the cutting process. Their investigations of natural abrasive and ways to improve cutting performance suggests that additional research is needed.

7. ACKNOWLEDGEMENTS

The authors want to thank the employees of HydroChem Industrial Services, Inc. that helped to obtain the photos used in the paper. Thanks to Brian McMillion for helping with the preparation of the illustrations.

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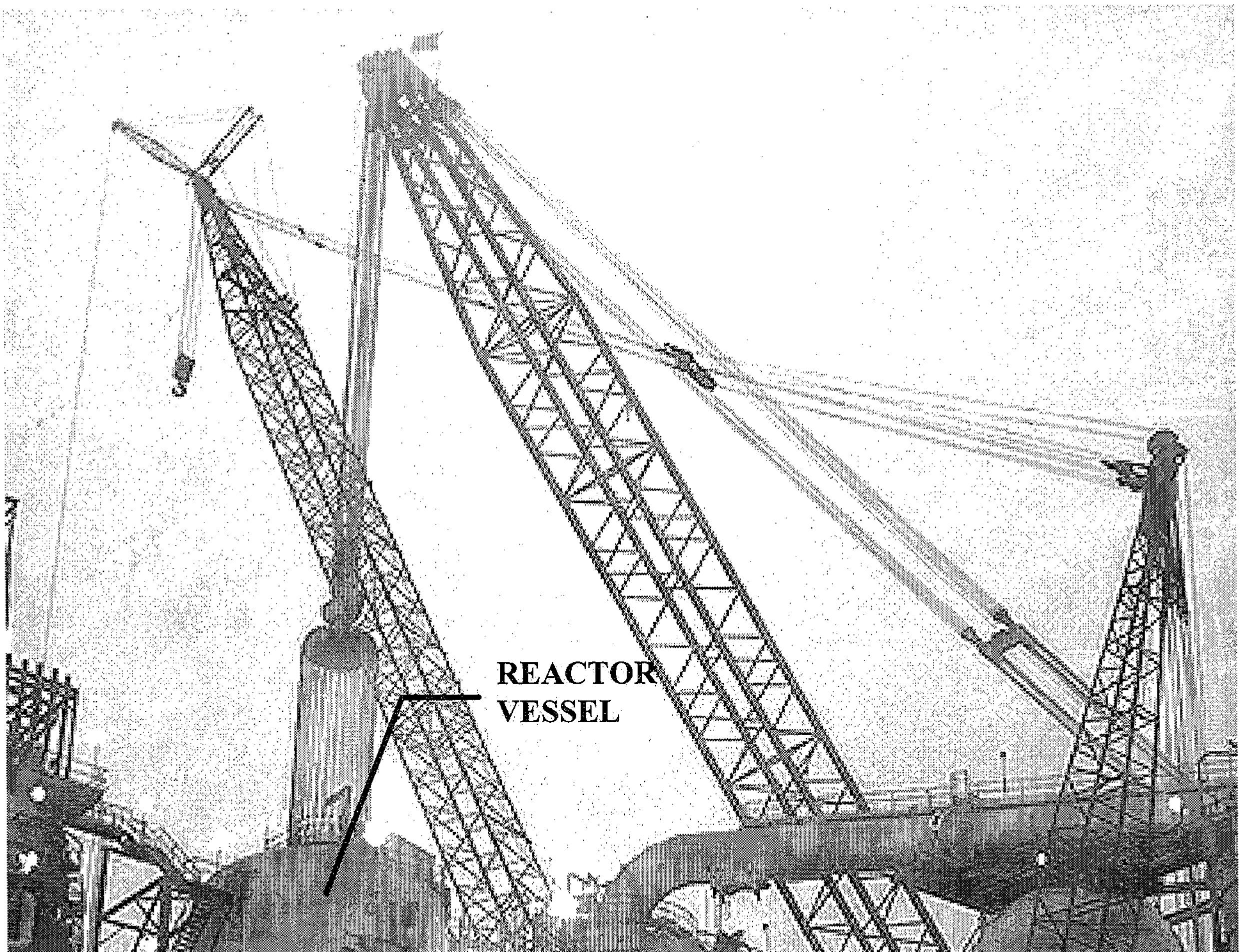


Figure 1

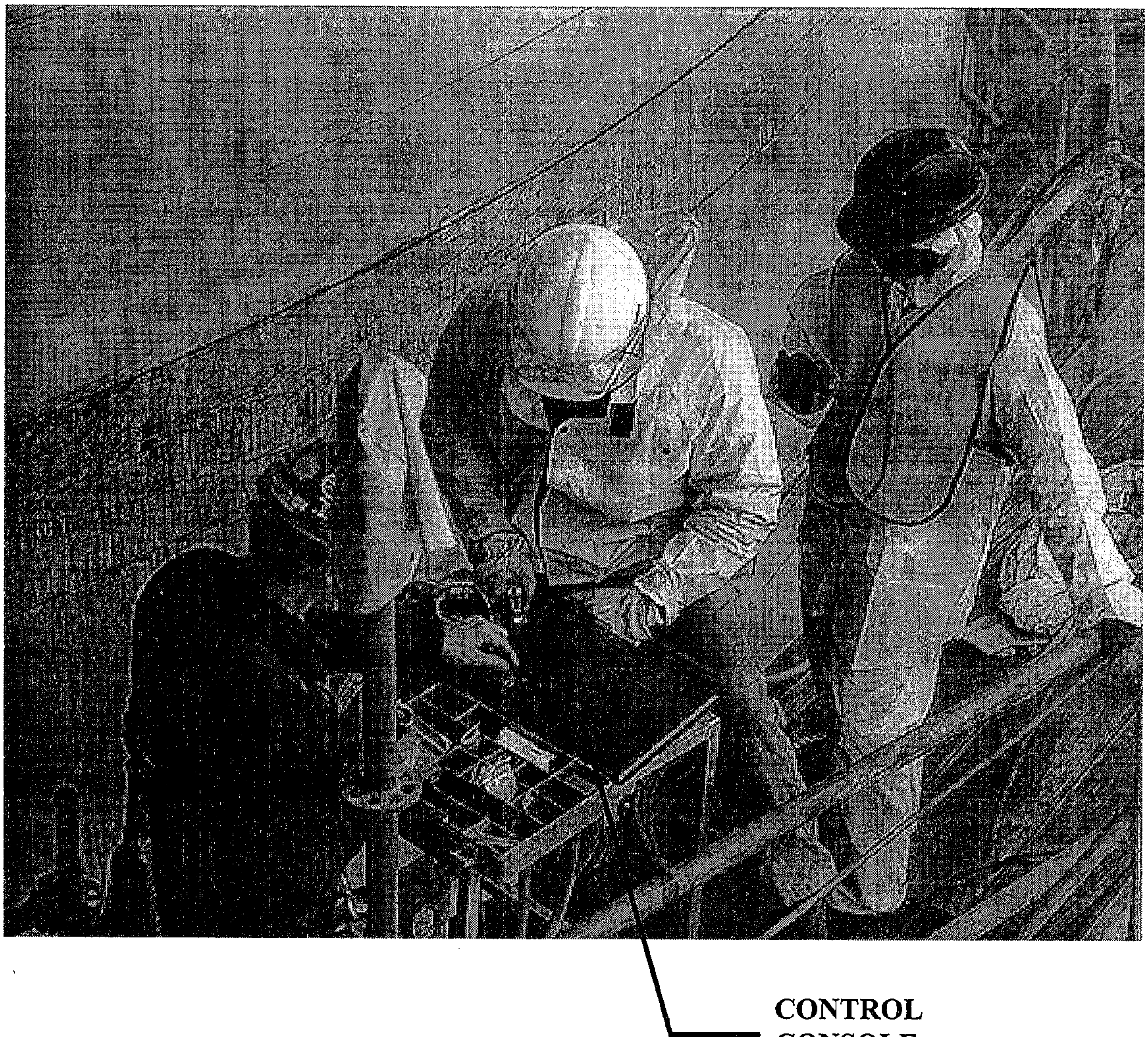


Figure 2

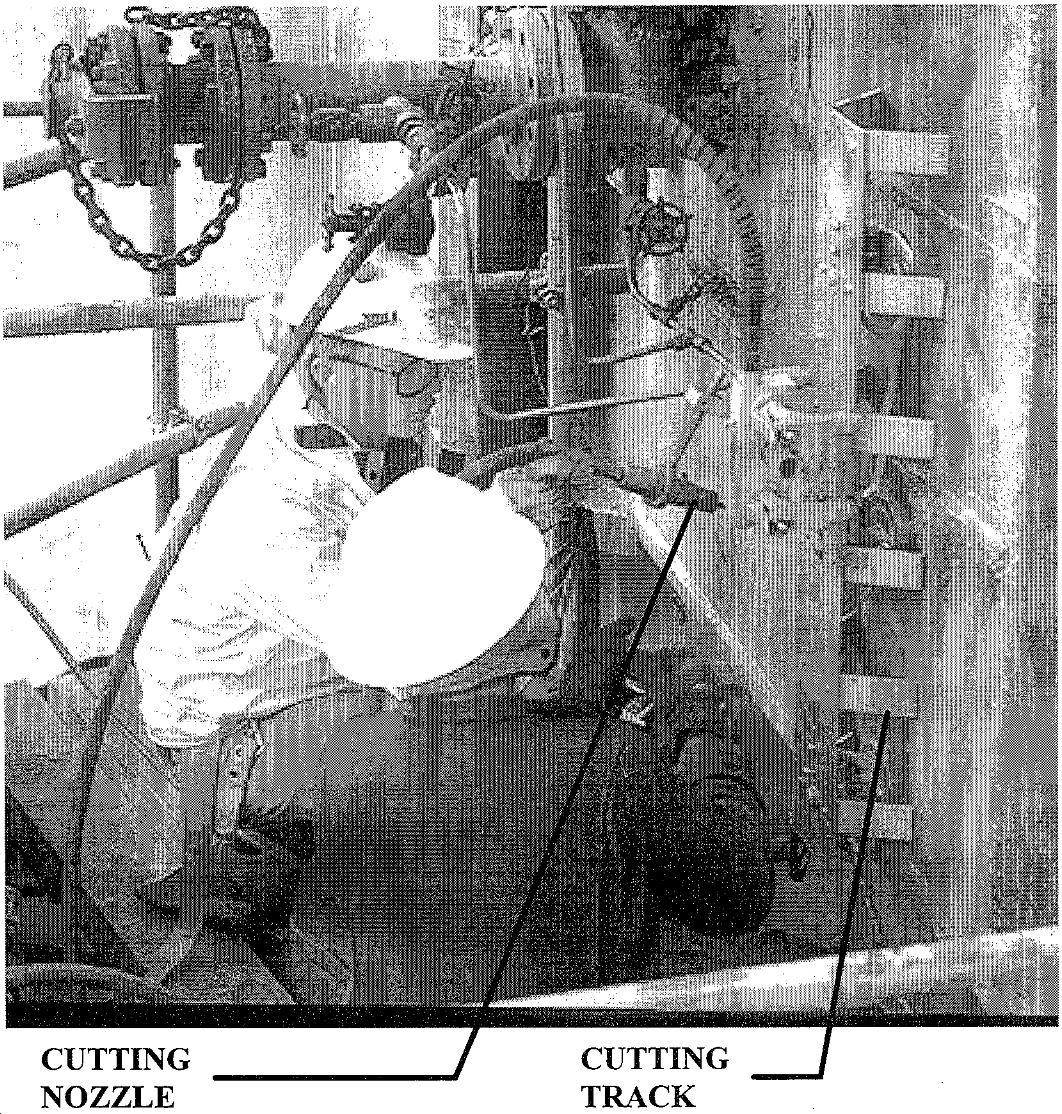


Figure 3

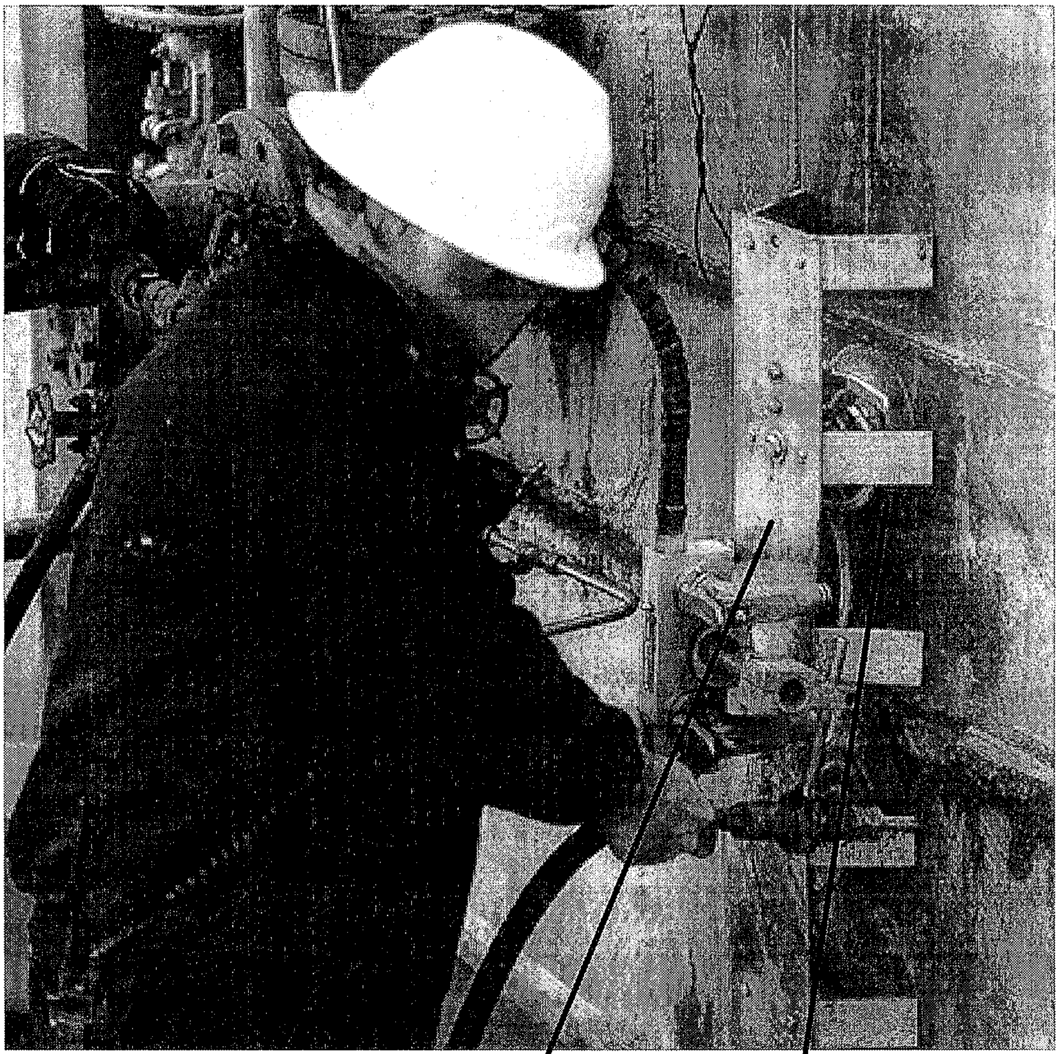
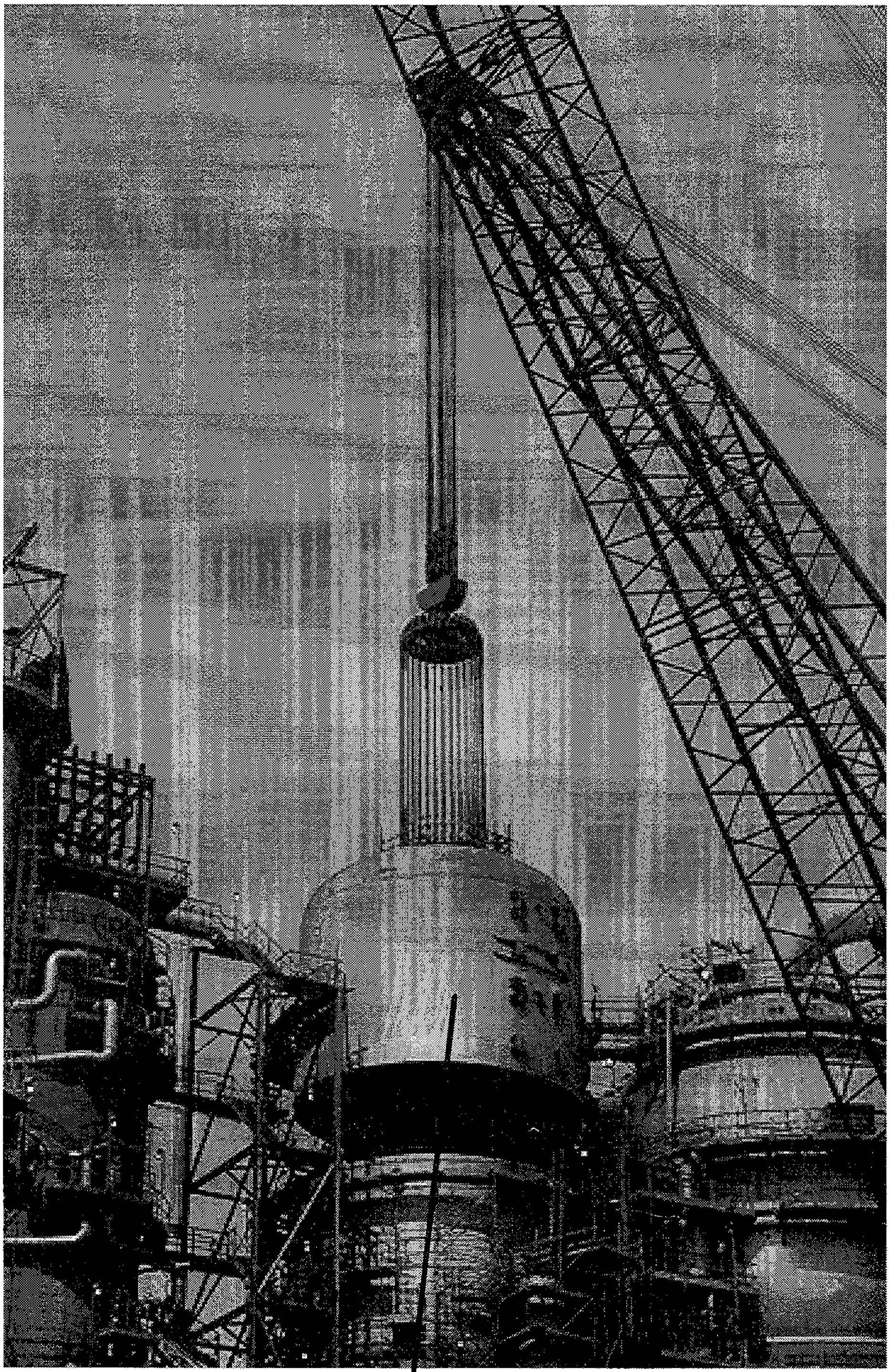
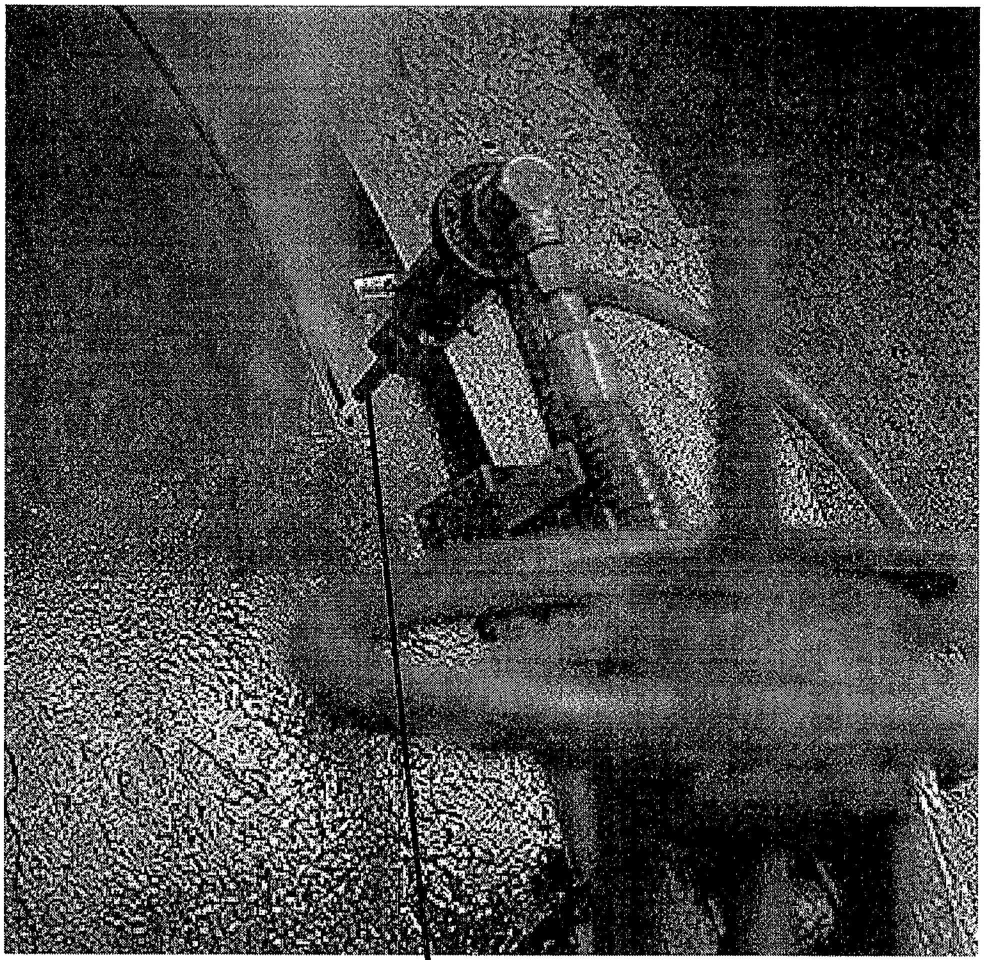


Figure 4



"CUT" SECTION

Figure 5



CUTTING TIP

Figure 6

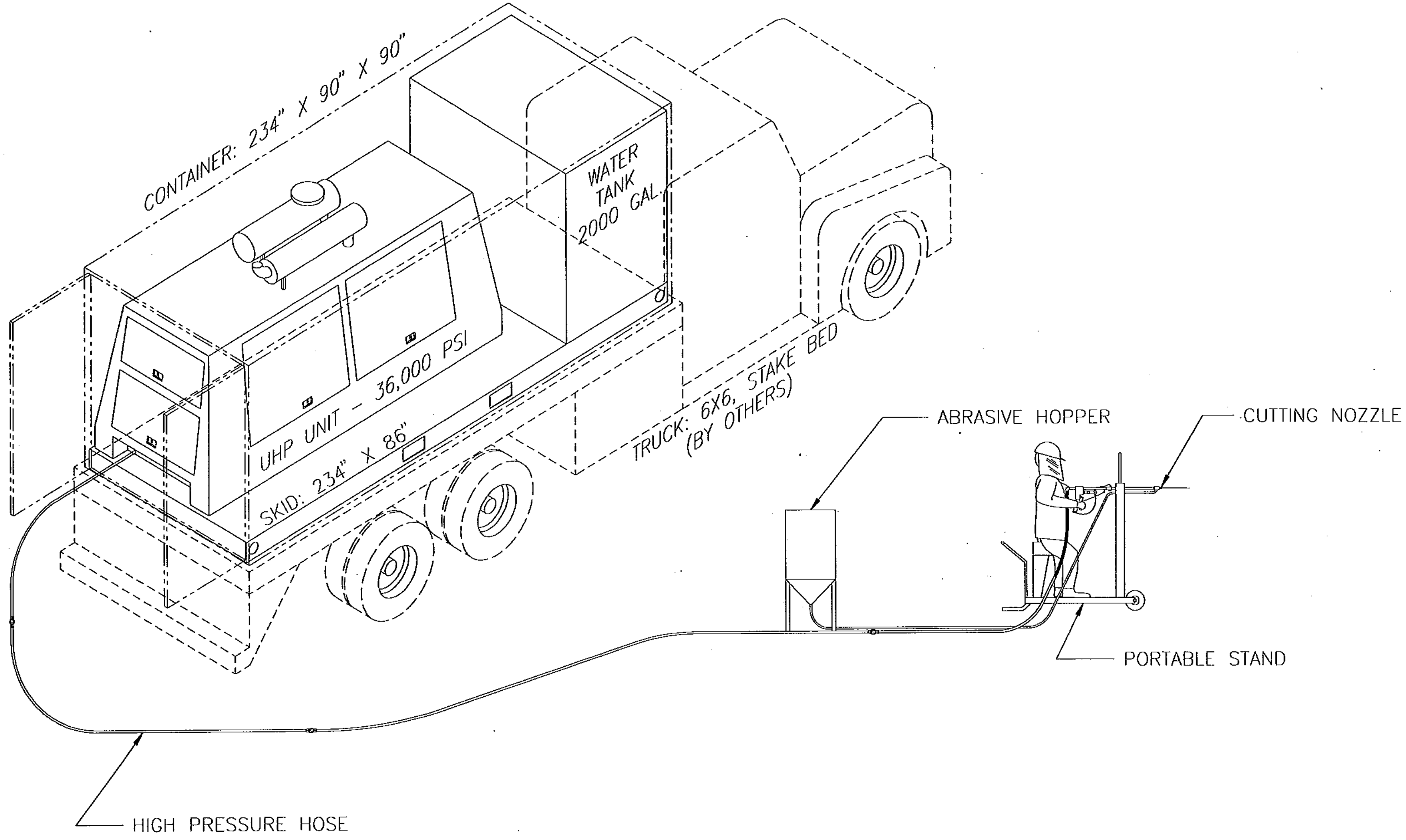

CONTAINER: 234" X 90" X 90"
WATER TANK 2000 GAL.
UHP UNIT - 36,000 PSI
SKID: 234" X 86"
TRUCK: 6X6, STAKE BED (BY OTHERS)
ABRASIVE HOPPER
CUTTING NOZZLE
PORTABLE STAND
HIGH PRESSURE HOSE

Figure 7

8th American Water Jet Conference
August 26-29, 1995: Houston, Texas
Paper 9

THE APPLICATION OF WATER BLASTING AND WATER JETTING IN SURFACE PREPARATION OF INDUSTRIAL AND MARINE STRUCTURES

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ABSTRACT

Air/Abrasive/Water Blasting and Water Jetting have been used for years for surface preparation in the removal of old coatings, linings, and rust prior to repainting and lining. The use of water, with and without the addition of abrasives, has been slow to find acceptance in the industrial maintenance industry among the facility owners. The consideration of the U.S. Navy of the adoption of water jetting as an environmental friendly procedure has placed renewed interest in this application.

This paper will probe the advantages and disadvantages of water blasting and water jetting compared to air/abrasive blasting. The work procedures and specifications which have been in discussion for ten years at the National Association of Corrosion Engineers and the Steel Structures Painting Council will be presented.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

With the advent of the Clean Air Act, the industrial maintenance industry is recycling, reclaiming, and containing the solid abrasives which are used for the removal of old coatings, paints, and linings. The environmental costs to dispose of solid abrasives continue to rise as solid waste management practices become more sophisticated. Contractors who have been exclusively using air/abrasive blast cleaning are considering air/water/abrasive cleaning, water/abrasive cleaning, and water jetting as alternatives to controlling the dust generation and containment requirements.

Water blast cleaning contractors who go into the removal of paints quickly learn that there are several obstacles to recognize and overcome in order for the job to be accepted by the end facility owner and the inspector. One of the more significant obstacles is "Surface Preparation." Surface preparation is the surface cleanliness and adequate profile which is essential for good adhesion of the applied coatings. Surface preparation is the key factor in the performance and protection of protective coatings. Ninety percent of premature coatings failures is traced to inadequate surface preparation. Common methods used to perform surface preparation are: hand cleaning; power tool cleaning; abrasive blasting; and waterjet cleaning. The most widespread and familiar cleaning method is Air/Abrasive blasting referred to as "sand" or "grit" blasting.

In addition to reduction of air-borne dust and elimination of the solid waste stream, cleaning with water removes SOLUBLE SALTS from the surface. Within the past ten years, soluble salts has been recognized as a major contributor to unexplained coatings failures. The European marine community has adopted water jetting. That action is forcing the US marine community to seriously look at water jetting as a viable surface preparation method.

A contractor must know the current abrasive blast specifications and the pending specifications for the use of water in coatings or corrosion removal applications. Large industrial jobs will have inspectors on site. Coatings inspection is activity associated with measuring, testing, witnessing, and documenting the painting process and results. Coating inspection is necessary to prevent coatings failures which cause loss of equipment to corrosion, costly rework, pollution, and unsightly facilities. The inspectors are not well versed in the appearance of surface preparation done by water blasting and water jetting. The inspectors are trained in the dry abrasive blast methods. Even if the facility owner and contractor are in agreement, the inspector will reject the appearance of the surface preparation done by water jetting because it appears different from abrasive blasted standards with which they are familiar.

In this paper, the terms hydroblasting and water jetting are used interchangeably to denote cleaning without abrasive added to the stream. Slurryblasting, air/water/abrasive, and water/abrasive cleaning are used to denote cleaning with abrasive added to the stream. Discussion is directed towards maintenance operations of rusted steel substrates or removal of existing coatings as it is felt that the new construction will continue to utilize air/abrasive blast cleaning. The use of water jetting in concrete maintenance is covered in a specification on concrete surface preparation which is in preparation.

2. SURFACE PREPARATION

There are three requirements for the substrate conditions prior to painting:

Extent of Cleaning
Roughness (Profile)
Residues

The requirement of extent of cleaning is defined by the written blast cleanliness standards and augmented by visual standards. These standards or specifications are prepared as third party consensus documents. Organizations which provide documentation and guidance are:

National Association of Corrosion Engineers, Int. (NACE), Houston, Texas
- Cleanliness Standards
- Training, Certification of Inspectors
- "Material Performance" magazine
- Recommended Practices and Test Methods for Special Conditions and Application Techniques

Steel Structure Painting Council (SSPC), Pittsburgh, Pennsylvania
- Specifications, Technical Reports and Updates
- "Journal of Protective Coatings and Linings" JPCL magazine
- Contractor Certification, Tutorials

ASTM, Philadelphia, Pennsylvania
- Testing Methods and Standards, Committees D1 and D33

International Organization for Standardization, ISO, Norwegian Secretariat, Oslo,
- Specifications and Methods

Swedish Standard Institution SIS
- Visible Standards are available through the SSPC

A comparison of blast cleanliness standards for visible contaminants is given in Table 1.

The requirement for roughness or anchor profile is defined by the coatings manufacturer. The average depth of profile in microns or thousands of inches (mils) is specified in the manufacturer literature and is specific for a particular coatings system. When no abrasive is used in the water cleaning stream, the original profile under the coating is exposed or the profile which was created by the corrosion pattern is exposed. When a soft or soluble abrasive is used such as plastic blasting media, sodium bicarbonate, starch, or sponge, the original profile is exposed. A new surface profile is produced when abrasive is used in the cleaning process.

During the past ten years, the importance of the requirement for the residues or non-visible cleanliness has become recognized as an important factor. The definition of non-visible residues on the substrate is included in the NACE/SSPC Joint Standard on High and Ultra High Water Jetting which is scheduled for publication in 1995. Soluble salts removal may be accomplished by dry or wet methods. Harlan Kline of Ameron estimates that using a wet method to remove soluble salts is four to five times more effective than dry methods. Both low and high pressure water washing techniques will remove the soluble salts.

3. SPECIFICATIONS

A coating system specification is part of the legal procurement document. It defines WHAT final condition is required in respect to degree of cleaning, the impact of environmental regulations, and surface preparation. A coating system engineering work procedure is generally a more detailed in-house document and defines HOW the work will be done. The work procedure forces careful reading of the procurement specification, forces attention to the coatings manufacturers instructions, forces advanced planning, and helps organize the work schedule.

The available specifications for the use of water in surface preparation are recent.

- Interim Guidance for Surface Preparation by Hydroblasting issued by Navy Sea Systems Command, Washington, D.C., Dr. Brenda Holmes, December, 1994.
- Slurryblasting and Hydroblasting Visible Standards, International Coatings, PO Box 4806, Houston, TX 77210-1711, July, 1994.
- Definition of Preparation Grades for High-Pressure Water Jetting, Schiffbautechnisch Gesellschaft Guide No. 2222, Lammersieth 72, 22305 Hamburg, 1992.
- Visual and Written Specifications for Cavitational Blasting, Cavi-Tech, Inc., 2108 Moon Station Dr., Kennasaw, GA, 30144, developed over the past 5 years.
- In Progress- Written Specifications for Carrier Vessels, Navy Sea Systems Command, PERA- CV, Bremerton, WA.
- Wet Abrasive Blast Cleaning, Joint SSPC/NACE TGC Technical Report, in preparation, scheduled date of release, late 1995-early 1996.
- Surface Preparation and Cleaning of Steel and Other Hard Materials By High and Ultra-High Pressure Water Jetting Prior to Recoating, TGD, NACE/SSPC Joint Standard, scheduled for publication in 1995.

3.1 Surface Preparation and Cleaning of Steel and Other Hard Materials By High and Ultra-High Pressure Water Jetting Prior to Recoating (referred to as the TGD document)

Surface preparation with water includes methods which range from 0.2 MPa to 280 MPa (30 to 40,000 psi) water pumps, with flow rates from 1.9 li/min to 83 li/min (0.5 gpm to 22 gpm), with and without abrasive entrained in the stream, and traditional sand blasting compressor systems to which water is added just for dust suppression. While the specification for the final result is presumably independent from the method used to obtain the result, there is much confusion among project managers as to how to get to that result. To reduce this confusion, the TGD document provides basic definitions to the coatings industry for cleaning without the addition of abrasives.

- Water Jetting (WJ). Use of Standard Jetting Water at high or ultra-high pressure to prepare a surface for Recoating using pressures above 70 MPa (10,000 psi, 700 Bar).
- Low Pressure Water Cleaning (LP WC). Cleaning performed at pressures less then 34 MPa (5,000 psi).
- High Pressure Water Cleaning (HP WC). Cleaning performed at pressures from 34-70 MPa (5,000- 10,000 PSI).
- High Pressure Water Jetting (HP WJ). Cleaning performed at pressures from 70-170 MPa (10,000- 25,000 psi).
- Ultra-High Pressure Water Jetting (UHP WJ). Cleaning performed at pressures above >170 MPa (> 25,000 psi).

Surface cleanliness (SC) is the condition of the substrate after water jetting has removed partial or total residues of chloride, soluble ferrous salts, and sulfates contaminants. The TGD Joint Standard has two requirements for surface preparation. The first requirement defines four conditions of surface cleanliness for visible contaminants such as is found for the abrasive blast cleaning methods. These visible conditions range from WJ-1 for the "best" condition to correspond to the concept of "white" metal through WJ-4 for the condition to correspond to the concept of "brush off" blast cleaning. See Table 1.

The second requirement in TGD defines the non-visible surface preparation conditions. This is new to the coatings industry. In addition to the requirement for a visual surface cleanliness, a surface shall be prepared to one of the three non-visual conditions prior to recoating, when deemed necessary. For non-visible surface preparation, the chloride, ferrous, and sulfate ions are included as non visual contaminant.

- SC-1. The surface shall be free of all detectable levels of contaminants as determined using available field test equipment with sensitivity approximating laboratory test equipment.
- SC-2. The surface shall have less than 7μg/cm^2 chloride contaminants, less than 10 μg/cm^2 of soluble ferrous ion levels, and less than 17 μg/cm^2 of sulfate contaminants as verified by field or laboratory analysis using reliable, reproducible test equipment.
- SC-3. The surface shall have less than 50 μg/cm^2 chloride and sulfate contaminants as verified by field or laboratory analysis using reliable, reproducible test equipment.

3.2 **Wet Abrasive Blast Cleaning** (referred to as the TGC Document)

The TGC document is a SSPC/NACE Joint Technical Report or Update; it is not a joint standard or specification. Air/water/abrasive blasting is a cleaning method in which water is injected into the air/abrasive stream generated by conventional air-pressurized abrasive blasting equipment. Water helps to remove contaminants from the substrate, to wet the abrasive, and to substantially reduce dispersion of fine particulates (dust). The major disadvantage to this method is that it is practically impossible to recycle or reclaim the wet used abrasive. The wetted abrasive must be removed from the substrate after blast cleaning and prior to recoating.

Air/water/abrasive blasting is referred to as wet blasting. The SSPC/NACE technical report describes different configurations of wet blasting systems. Radial Water Injectors and Coaxial Water Injectors inject the water at or near the nozzle. The abrasive is carried by a dry air stream to the nozzle.

Slurry Blasting is the term used when the water is injected into the air/abrasive stream at some point substantially upstream from the blast nozzle. A wetted abrasive is carried through the delivery system.

Water blasting with abrasive injection is the system in which the propelling force is the water stream, not compressed air. This method is referred to as "abrasive wet jet." This use of the term "Abrasive Wet Jet" is different from the usage within the water jet industry.

Because this cleaning is primarily by the abrasive, the surface preparation specifications SSPC-SP-5, SSPC-SP-10, SSPC-SP-6, and SSPC-SP-7 are used for the visible surface cleanliness. The TGC document further discusses the selection of abrasives, inhibitors, operation of equipment, and minimal safety guidelines.

3.3 PERA-CV

The U.S. Navy has funded a robotics controlled ultra-high pressure water jetting system which was integrated by Pratt and Whitney USBI. The Ship-ARMS™ is being field tested starting in July 1994. The purpose of a July 1994 workshop in Bremerton, Washington, was to increase the Navy awareness of new or different technologies which bear on prominent and costly problems in ship maintenance. Ultra High Pressure Water Jetting (UHP WJ) is thought to be an economical, practical solution for compliance with environmental regulations promulgated by the Federal Clean Air and Water Acts. Open air abrasive blasting will essentially be no longer permitted under the Federal Clean Air Act. The adoption of Ultra High Pressure Water Jetting (UHP WJ) to strip paint decreases or eliminates the used abrasive grit which is the largest waste stream for many shipyards. PERA-CV is the Naval detachment unit tasked with the planning and engineering of carrier vessels. PERA-CV is currently working on an interim specification for water jetting for 1995 approval. The interim specification will cover both visible and non-visual surface preparation.

3.4 Interim Guidance for Surface Preparation by Hydroblasting

The Navy Sea Systems Command, Washington, D.C., material branch has responded to the immediate need for guidance to the shipyards using water jetting by issuing an interim guidance document in December, 1994. This conservative document incorporates the language of the International Coatings Hydroblasting Visual Standards and limits the acceptance of surface preparation to one visual specification- C HB 2.5 L. The hydroblasting method can be used on all areas of the U.S. Navy vessels, but the document specifically addresses underwater hulls as this is a very critical area. An epoxy primer coating system is recommended for the underwater hull area. The level of chloride contamination is limited to 3 $\mu g/cm^2$ Chloride for immersion areas and 5 $\mu g/cm^2$ Chloride for non-immersion areas. A minimum adhesion pull test is specified for the epoxy primer coating system. The amount of flash rusting is limited to light flash rusting.

3.5 Cavi-Tech Specifications

Cavi-Tech Inc. is one of several contractors who have been using water jetting in surface preparation. Cavi-Tech is particularly competitive in maintenance where spot blasting is prevalent or where only part of the existing coating is removed. They have defined seven stages from brush blast cleaning to bare metal. They provide generic written descriptions and visual photographs which are prepared for specific industries. These proprietary specifications are very useful. It is exceedingly difficult to develop industry-wide consensus specifications for situations in which the individual coatings manufacturer has to agree that the new coating will be compatible with existing material on the surface.

The Cavi-Tech blast cleaning specifications are numbered CB-1 to CB-4. Some are closely equivalent to SSPC/NACE surface preparation specifications. Within the "brush -off" Blast cleanliness specification, CB-1, CB-1.5, CB-2, CB-2.5, CB-3, and CB-3.5 vary from

- CB-1. Sweep Off Blast. Removal of loose mill scale, loose rust, and loose paint to the degree hereafter specified. Leaves on tightly adherent material. The surface should be abraded for adhesion. The tight paint is feathered.

to

- CB-3.5. Control Blast and Cutback Cleaning. All old paint is to be removed down to the existing primer. The prime coating shall be removed to a dry film thickness of not more than 0.8 mils.

3.6 **Definition of Preparation Grades for High-Pressure Water Jetting**, Schiffbautechnisch Gesellschaft Guide No. 2222 (referred to as STG 2222)

This guideline is a visual standard for marine application. The STG 2222 Guide was drawn up as part of the research project "Development of a high-pressure water-jetting tool, definition of surface standards for steel surfaces prepared by high-pressure water-jetting and development of coatings systems compatible with that method" and was sponsored by the German Federal Ministry of Research and Technology. STG 2222 provides definition of preparation grades for high-pressure water jetting without addition of solid abrasives, of corroded and coated steel surfaces, and at different initial conditions. STG 2222 consists of a series of photographs taken on the hulls, decks, and tanks of ships. Adherent black iron oxide is left on the surface and it is hard to interpret the photographs. The European marine community uses this visual document and it has been proposed as an ISO method.

3.7 **Slurryblasting and Hydroblasting Visible Standards**, International Coatings

Courtlaulds Company International Coatings has prepared two visual sets of photographs to assist their technical service representatives in assessing the adequacy of surface preparation by slurryblasting and hydroblasting (water jetting) for their coating materials. The world wide community is adopting the use of water in surface preparation faster than consensus standards can be developed. The International Coatings definitions and pictures follow the ISO and Swedish Standards Institute definitions for surface preparation. The visual standards use grade C and D steel surfaces for the photographs. The International Coatings Marine Handbooks provide a very thorough treatment of flash rusting and provide guidance for the use of International Coatings over flash rust.

The four degrees of cleanliness are:

- SB 2- Thorough Slurryblast Cleaning. When viewed without magnification, the surface shall be free from visible oil, grease, dirt, most paint coatings and foreign matter. Any remaining contamination shall be firmly adherent.

- HB 2- Thorough Hydroblast Cleaning. When viewed without magnification, the surface shall be free from visible oil, grease, dirt, and from most paint of the rust, paint coatings and foreign matter. Any remaining contamination shall be firmly adherent.

- SB 2.5 - Very Thorough Slurryblast Cleaning. When viewed without magnification, the surface shall be free from visible oil, grease, dirt, rust, paint coatings and foreign matter except for slight staining. Slight staining shall be limited to light shadows, streaks or minor discoloration.

- HB 2.5 - Very Thorough Hydroblast Cleaning. When viewed without magnification, the surface shall be free from visible oil, grease, dirt, rust, paint coatings and foreign matter except for slight staining. A brownish-black discoloration of ferric oxide may remain as a tightly adherent thin film or corroded and pitted steel.

An important property of the water jetting process is that it can emulsify and remove oil and grease from a surface as it is blasted. However, this does not preclude the need for proper degreasing procedures as specified in SSPC-SP1, prior to water jetting. The gray, brown to black discoloration seen on corroded and pitted steel after hydroblasting cannot be removed by further water jetting. Analysis shows that this thin film consists mainly of ferric oxide, which is an inert material. As it is tightly adherent, it does not present a serious contamination problem.

Steel will rust when water is used in the cleaning process. The International Coatings Marine Handbooks also define flash rusting.

- Light Flash Rusting. When viewed without magnification, small quantities of light tan-brown rust will partially discolor the original metallic surface. This discoloration may be evenly distributed, or in patches, but it will not be heavy enough to easily mark objects brushed against it.

- Moderate Flash Rusting. When viewed without magnification, a layer of light tan-brown rust will obscure the original metallic surface. This layer may be evenly distributed or patch in appearance, but it will be heavy enough to mark objects brushed against it.

- Heavy Flash Rusting. When viewed without magnification, a heavy layer of dark tan-brown rust will completely obscure the original metallic surface. This layer of rust will be loosely adherent and will easily mark objects brushed against it.

The International Coatings definitions have provided the initiative for other coatings manufacturers in the world market to adopt and issue new product material data sheets incorporating these definitions of flash rusting.

4. CONCLUDING REMARKS

The adoption of water by the coatings maintenance industry has been slow to occur and is being driven in the USA from both regulatory environmental issues and the adoption of world wide practices to reduce the soluble salt levels and reduce the waste grit stream. The NACE/SSPC Joint Standard on High and Ultra-High Water Jetting should be published in 1995 barring unforeseen delays. The SSPC/NACE Joint Report on Wet Abrasive Blasting should be completed in late 1995.

Both SSPC and NACE are seeking to adopt the International Coatings visual photographs as joint interim standards until such time as a complete set of visuals can be funded and developed through consensus procedures.

In environmental issues, the contractor must be able to evaluate the economics of control of dust and grit with the collection of water, filtering and disposal. Water Blasting and water jetting are finding acceptance in lead based paint removal projects.

There are other committee activities in the coatings organizations which will assist the adoption of water jetting in surface preparation. The International Organization for Standardization ISO/TC 35/SC 12- Preparation of steel substrates before application of paints and related products has a task group working on "Guidance on Levels of Salt Contamination before Application of Paints and Related Products." The Steel Structures Painting Council has committees involved in "Guide for Containing Debris Generated During Paint Removal Operations" which includes water blasting/water jetting. There are draft Technology Updates in preparation on "Surface Tolerant Coatings," "Retrieval Methods for Use in Determining Soluble Salt Contamination of Steel," and "Chloride Extraction from Corrosion Pits on Steel Surfaces." All these activities emphasize the awareness of the non-visible contaminants.

Water blasting contractors can work in coatings maintenance. The contractor must be aware of the details of the surface preparation specifications. The pump manufacturers must be prepared to provide continuing customer service assistance to the contractor as they enter a market dominated by dry abrasive blasting.

5. ACKNOWLEDGMENTS

The mention of specific products or companies by name does not represent, nor is it to be construed as, an endorsement of any individual company or product. The material is provided for illustrative purposes only. The opinions expressed in this paper are not intended to be, nor should they be interpreted as a replacement for professional legal advice. Data, literature, and examples have been generously supplied by several individuals and companies. Dr. Frenzel extends her thanks to all the industry for their assistance and cooperation.

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7. TABLES

Table 1
Nominal Comparison of Blast Cleanliness Standards for Visual Contaminants

	NACE	SSPC	SIS	NACE/SSPC
"White Metal"	No. 1	SSPC-SP-5	Sa 3	WJ-1
"Near White"	No. 2	SSPC-SP-10	Sa 2.5	WJ-2
"Commercial"	No. 3	SSPC-SP-6	Sa 2	WJ-3
"Brush-Off"	No. 4	SSPC-SP-7	Sa 1	WJ-4
Solvent Cleaning		SSPC-SP-1		
Hand Tool Cleaning		SSPC-SP-2		
Power Tool Cleaning		SSPC-SP-3		
Pickling		SSPC-SP-8		
Power Tool Cleaning to Bare Metal		SSPC-SP-11		
Visual Standards for Abrasive Blast Cleaned Steel		SSPC VIS 1-89		
Visual Standards for Power Cleaned Steel		SSPC VIS 3		

Table 1 (Continued)
Nominal Comparison of Blast Cleanliness Standards for Visual Contaminants

	Navy	NACE/SSPC TGD	Int. Paint		Cavi-Tech
"White Metal"		WJ-1			
"Near White"	C HB 2.5	WJ-2	SB 2.5	HB 2.5	CB 4
"Commercial"		WJ-3	SB 2	HB 2.5	
"Brush-Off"		WJ-4			CB 1 to 3.5

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Paper 10

370 SAPPHIRES FOR TIRE RECYCLING

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ABSTRACT

Already existing recycling methods for tires are not very environmentally friendly and the cleanness of recycled material is rather low. The actual paper presents a mature method to separate the different materials of car and truck tires. In total 370 sapphire nozzles are in alternating use. Two high pressure intensifier pumps supply all nozzle blocks with the required amount of pressurized water. After subsequent cleaning and grinding procedures the recycled rubber could be reused in various technical rubber products.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

The global rubber industry produces approximately 30 million tonnes of rubber product per annum utilizing 12 to 15 million tonnes of raw caoutchouc in the manufacturing process. Some 40 to 50 % of this amount is consumed by tires while the balance is divided between several product groups none of which exceeds 10 % of the total consumption.

2. ACTUAL SITUATION

The annual global production of tires is approximately 900 million. North America produces 260 million tires, Europe around the same number, Japan produces 100 million with the remaining production being focused in Asia and to a much lesser degree South America. The annual number of discarded tires approximately equates to the production figure. The main method of disposal is landfill, followed by incineration, retreading, illegal dumping and finally recycling, including the production of rubber crumb and powder.

Stockpiled scrap tires, estimated at two to three billion tires in the US alone, pose potentially serious health and safety problems since whole tires serve as breading grounds for disease carrying mosquitos and rodents and uncontrolled tire piles are fire hazards. Once ignited, tire piles can burn out of control for months, producing acrid black smoke and a hazardous oily residue.

The caloric value of scrap tires is 28 to 33 MJ/kg which exceeds the highest quality coals. However the volatile zincoxide and the gas fume emitted when scrap tires are incinerated cause great concern for environmental regularity authorities in the developed countries. Furthermore, the thermal value of the waste tires is not favorable from an ecological point of view. Approximately 37 liters of crude oil is needed in the manufacturing of a car tire but the thermal value of this equates to only about 7.1 liters of crude oil.

From 1997 the European community has legislated that, all manufacturers will have to comply with Total Product Responsibility and therefore tire manufacturers such as Michelin and Pirelli will be responsible for the recycling or acceptable disposal of used tires manufactured by them. In the United States more states are banning the use of Tire Derival Fuel (TDF) being burned in cement kilns and power plants and more states are specifying rubber modified bitumen roads. In addition, the US Federal Government has legislated the mandatory use of crumb powder into roads through the International Transport Act of 1991.

Although tires represent less than one percent by weight of industrial, commercial and domestic waste, they possess much greater significance not only as a disposal problem but also as a recycling opportunity in view of their potentially valuable mix of raw materials and the fact that they are already collected and sorted.

As indicated previously current disposal trends and legislative pressure ensure that the key issues for any tire recycling operation do not include sourcing the raw materials, but rather developing end markets for rubber powder and of having the most efficient technology to supply the markets current and potential requirements.

3. THE TASK

Companies involved in the waste tire management and recycling industries are confronted with a number of problems in processing used tires.

Most of the problems have only been partially solved and there has been no approach which addresses them in a comprehensive way. Some of the issues are:

- Complete separation of the tire components of rubber, fibre and steel.
- Production of these components in a form which is of significant market value and which can be varied in accordance with market demand.
- Low handling, transport and processing cost.
- Environmentally friendly method of processing.

4. THE SOLUTION

The Combined Mechanical and Hydro Tire (CMHT) technology effectively addresses all of these issues and delivers the process operator an integrated, economic solution.

The CMHT technology offers numerous advantages over existing mechanical and cryogenic processing methods including the following:

- Lower production cost
- Very fine rubber powder, under 100 μm can be produced in a totally separated way such as:
  a) tread rubber
  b) outside sidewall rubber - truck tires
  c) inner lining (butyl) rubber - truck tires
  d) interlayer rubber material - truck tires
  e) sidewall rubber - passenger cars
- Good particle morphology (surface profile)
- No metallic contamination
- Less than 2% fibre contamination
- Clean steel belt and bead wire
- 100% processing of tires (non-debeading)
- Meets environmental standards
- Small modular processing plant

5. REQUIRED EQUIPMENT

To achieve all these criteria for the supply of recovered resource material into high quality value added products CMHT technology uses High Pressure Water Jetting Technology. The CMHT technology is composed of two sets of equipment used to process waste car and truck tires.

5.1 Overview

The site size requirement for the CMHT plant is approximately 2,000 m^2 including the water treatment processing plant. Plant construction may be divided into several areas:

- Primary tire separation unit
- Water jet processing core equipment
- Ultra high pressure intensifier pumps
- Ancillary processing equipment
- Transporters
- Storage bins and packaging equipment
- Water treatment equipment

5.2 Tire Separation

The Tire Separation Unit separates the sidewalls from the treaded crown by means of a mechanically cutting process. The tread crown and the separated sidewalls are then processed separately within the Dual Tire Processing plant.

5.3 High Pressure Technology

The key to the separation of the rubber from the steel bead and steel belt is the application of ultra high pressure water jet via specially designed nozzle blocks. The nozzle blocks are either in orbiting or transverse vibrating motion to remove the tread rubber from above the steel belting or bead rubber and carcass material from the embedded beadwire.

370 sapphire nozzles with diameters between 0.12 and 0.15 mm are in alternating use. More than 30 high pressure valves are installed for switching on and off the water jets in the different cutting units.

The high pressure water supply is delivered by two high pressure intensifier pumps with 250 kW power supply delivering a 200 MPa (30,000 psi) working pressure with a flow rate of 45 liters per minute each.

An axial piston pump with a hydraulic oil stream of 720 liters per minute is used for the main hydraulic drive unit. Just to have an idea about the size of the high pressure pump - the weight of one single intensifier is 972 kg!

The UHP water system is a closed recycling system of 90 liters per minute flow rate and there are minimal loss rates through evaporation, etc.

One of the benefits of the CMHT technology and its plant design is that the plant separately processes the passenger tire and the truck tire range. The technology has an excellent offer for tire manufacturers to process their own factory rejects and thereby reuse them with the best possible result since they control their own composition.

6. RECYCLED PRODUCTS

Using the CMHT technology to reclaim crude and rubber powder from used tires presents a competitive advantage over competing technologies, since the CMHT technology offers product with three key physical advantages over product generated by other existing technologies. These physical advantages are expected to lead to the development of new markets for recovered rubber crumb and powder in areas which only natural rubber is currently utilized. These advantages relate to the ability to produce rubber crumb and rubber powder:

- Of much smaller particle size
- With virtually no steel or fibre contamination and
- Of differentiated rubber material

With regard to particle size, one can generally categories as follows:

- Corse crumb - most particles above 1.0 mm (1,000 μm) diameter
- Fine crumb - most particles below 1.0 mm (1,000 μm) diameter
- Superfine crumb - most particles below 0.2 mm (200 μm) diameter

The minimum particle size which existing ambient grinding technologies are able to economically produce is around 400 μm. The so called wet grinding process produces only 154 μm (100 mesh) particle size. CMHT technology can produce down to 50 μm, such a fine rubber powder can be used for more exacting purposes than those which are only coarsely ground.

The rubber contained in scrap tires cannot be considered homogeneous for several reasons - the tires themselves are made from many different compositions of rubber, the elastic modules and hardness of each part of a tire varying quite considerably due to the function each part plays within the tire. These differences are more pronounced in the case of steel radial tires. The carbon black that is used, the white filler and softener in the individual parts is also different with respect to quality and quantity.

Because of this, each crumb granual from a whole tire differs from other granules with respect to physical and chemical features. As existing technologies grind whole tires they are unable to segregate those various properties, while CMHT technology segregates the whole truck tire into:

- Tread rubber
- Outside sidewall rubber
- Butyl rubber - inner lining
- Interlayer rubber
- Bead area rubber

7. CAPACITY

The capacity in a three shift around the clock operation is about 7,500 tons of rubber product per day. That means in average a recycling rate of 1.2 million tires per year. For this the required staffing level is eight persons per shift.

8. POTENTIAL MARKETS

Potential end markets for CMHT produced crumb rubber are as follows:

- Rubberized asphalt
- Tires and retreading
- Rubber goods
- Industrial applications
- Composite materials, thermo plastics
- Steel and fibre applications

Rubberized asphalt represents the lowest value market for CMHT produced product. CMHT's competitive advantage is in the value added areas which can be assessed being the superfine crumb, surface modified and composite materials markets, and the thermo plastics industry.

9. CONCLUSION

In the last years the importance of recycling increased tremendously. Especially in our production and consumer orientated industrial society there is a high demand for adequate solutions.

The Combined Mechanical and Hydro Tire (CMHT) technology is an efficient and economic procedure for tire recycling with low production cost. A small modular processing plant meets environmental standards and guarantees a 100% recycling rate for passenger car and truck tires.

8th American Water Jet Conference
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Paper **11**

ANALYSIS OF THE PROCESS OUTPUT IN ABRASIVE WATER JET CUTTING

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ABSTRACT

Abrasive water jets generated by injection systems consist of air, water and abrasive particles, which remove the material and disintegrate during the process.

Aim of this paper is to analyse the output of the cutting process. The major amount of process output is sedimented after a while. The sedimented amount of abrasive material is contaminated with the machined material. Depending on the application the contamination varies in a range from 1% to 5% of the mass of abrasive material.

Tests were carried out to separate the abrasive and removed material for different combinations of abrasives and machined material. The shape and size of the abrasive particles and especially of the removed particles was analysed in relation to the input particle size and the cutting quality.

These investigations provide on one hand fundamental know-how concerning the environmental sociability of abrasive water jet cutting. On the other hand the shape and size analysis of removed particles will help to understand the initial process of abrasive water jet cutting.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

The environmental sociability of abrasive water jet cutting is a subject that has been discussed over the last few years. Extensive investigation concerning the environmental sociability (Lorin et al., 1990) and the recycling capacity of abrasives in abrasive water jet cutting (Guo et al., 1992, 1994; Knaupp and Ohlsen, 1994) lead to the question about the size and shape of the removed particles.

As usually in water jet technology the subject that is investigated is influenced by a variety of parameters. The major investigated combination of abrasives and material to be cut was Barton garnet (AlMgSi0.5) and aluminium. Besides this, olivine and steel were investigated.

Due to the fact that the abrasive material contains after the cutting process only 1 to 5% of removed material, the removed particles had to be separated and concentrated. A special separation technique, using the difference of density of two materials, as well as magnetic separation have offered the opportunity to separate abrasive and removed particles. Optical evaluation was used to determine the size and shape of removed particles.

Besides the question of environmental sociability, the results of these tests may provide another small piece to complete the mosaic of the initial process of abrasive water jet cutting, which is not yet sufficiently investigated.

2. EXPERIMENTAL SETUP AND PROCEDURES

2.1 Experimental Setup

To generate the water pressure, an intensifier pump was used; the maximum pressure level of this intensifier is 400 MPa with a maximum flow rate of water of 4 l/min. For all cutting tests, a self-designed abrasive mixing head was used (Haferkamp, et al. 1991).
To analyse the particle disintegration of different particle ranges, a special catcher was designed to slow down the particles without destroying them any further.
A vibration feeder was used to dose the dry abrasives. The amplitude of vibration and thus the mass flow rate of the abrasives was adjustable.

Separate particle ranges (Table 1) of Barton garnet and olivine were used for the tests. The analysis of the abrasive particle size distributions (psd) of the abrasive material was determined by sieve analysis.

Analysis of the psd and shape of removed particles was carried out by optical evaluation. Due to the fact that the ratio of the mass of removed and abrasive material is usually in the range of 1 to 5%, separation of abrasive and removed material was necessary to concentrate removed material. Depending on the material properties, two methods were used to separate removed particles and abrasive particles.

Magnetic separation was used in the case of cutting ferromagnetic, stainless steel. To neutralise magnetic agglomeration, the removed particles were demagnetised in a decreasing alternating magnetic field.

For the separation of aluminum and garnet particles the difference of the density of the materials was used. The mixture of removed and abrasive material was given into a liquid (1,1,2,2, Tetrabromoethane) with a high density of ρ = 2.96 g/cm^3 which is between the density of the removed and the abrasive material. Garnet particles (ρ = 4.0 g/cm^3) sink to the bottom and the aluminumparticles with a density of ρ = 2.7 g/cm^3 float on the surface. A special separatory funnel, designed by **Sindowski** (Müller, 1964) was used.

Due to the fact that the removed particles separated by both methods were still contaminated with some abrasive particles, photos of the particles were made using counterlight that shines through the abrasive particles, but not through the removed particles. The projection pictures of the particles on the photos were evaluated.

2.2 Experimental Procedure and Presentation of Results

For all tests the jet generation parameters (pressure, massflowrate, nozzle and focus diameter, focus length) were constant. The parameters are given in Table 2.

Two characteristic qualities (different depth of cut for same jet parameters) were defined in relation to the depth of kerf (Figure 1):

- high quality cut = 0.1 x average depth of kerf
- rough cut = 0.8 x average depth of kerf

In case of kerfing the energy of the jet is converted to the max. depth of penetration. A quality cut characterises a surface with a roughness that is mainly caused by the size of the abrasive particles (Guo et al., 1993). A rough cut characterises a quality showing striations and waviness on the bottom of the shoulder of the cut, caused by the jet geometry.

Due to the fact that abrasive particles disintegrate during the acceleration and focusing process, the psd of abrasives that work the material is different to the input particle range. So the psd of the removed particles is always presented in combination with the psd of the abrasive material after the focus, that really affects the material (Figure 2).

The psd´s of abrasive material were determined by sieve analysis, so that the distribution is related to the percentage of mass of abrasive material.

The psd of removed material was determined by optical analysis, so that the distribution is related to the amount of particles that were analysed. Each psd is based on the manual evaluation of 200 to 300 removed particles. The largest dimension of the particle was set to be the particle size.

Carrying out particle shape analysis and psd´s that are related to the amount of particles, it has to be kept in mind, as Guo, et al. discussed in 1992, that the comparison of the appearance of psd´s, that are related to the amount of particles, and psd´s, that are related to the mass of particles, is difficult. Especially when the psd´s cover a wide range of particle sizes.

Reasons are, that the measuring criteria and the analysed amount of particles are different. The analysed quantity of particles is for sieve analysis in the range of 50 to 100 g. In combination with a correct splitting of the specimen the results are representative.

For optical analysis less than a 10^{-5} of this amount is analysed, even when some thousand particles are analysed. The existence of one coarse particle can cause a total change of the psd.

As discussed by Guo et al. (1992), the method of evaluation related to the number of particles rates small particles higher than coarse particles, so that this method results in smaller average particle sizes (aps) than psd´s related to the mass of particles. This effect is caused by the fact, that a reduction in size leads to an increase of the number of particles to the power of three. For example one 100 μm particle has mass of one thousand 10 μm particles.

All average particle sizes were calculated following the momentum based method presented in Guo et al. (1992).

3. ANALYSIS OF REMOVED PARTICLES

Problems concerning the comparison of psd´s, that are based on the mass and the amount of particles, were discussed in section 2.2. Summarised it has to be kept in mind that the figures that show psd´s of abrasive and removed particles can give only a rough idea of the correlation of the particle size of abrasive and removed particles. Due to the fact that particle sizes can be determined by different criteria and methods, the presented method, that is based on the number of particles, is just one possibility. The range of the whole distribution is nearly for both methods of evaluation similar, but the appearance of the distribution can be different, as mentioned above.

But the results of all tests carried out in this investigation can show a tendency concerning the influence of some major parameters on the correlation of the particle size of abrasive and removed particles.

3.1 Size Distribution of Removed Particles

3.1.1 Influence of Abrasive Particle Size and Cutting Quality

For five different particle ranges from 45 to 710 μm (Table 3), tests were carried out where the mixture of water, abrasive and removed particles was completely caught. Removed particles were isolated as described above. The abrasive material was garnet and the material to be cut was AlMgSi0.5.

Two cutting qualities were realised for each particle range, a rough cut (0.8 x k_m) and a high quality cut (0.1 x k_m). The created shoulder of cut is in case of rough cutting 8 times larger than in case of high quality cutting.

It can be assumed, that the intensity of impacts of abrasive particles and the material is quite low in case of high quality cutting compared to rough cutting. Earlier investigations concerning the disintegration behavior (Guo et al. 1992, 1994) showed that the psd of abrasive material is nearly the same after the focus and a quality cut. In case of rough cutting it can be assumed that all particles affect the material intensively and hence significant additional disintegration occurs.

Figure 3 shows three psd´s. The white bars show the material that affects the material (psd of garnet after the focus). The input particle range was 500 to 710 μm. The grey bars show the psd of the removed aluminum particles after quality cutting. The distribution shows one peak in the range of 60 to 120 μm with a negligible amount of particles smaller 45 μm and a high amount of particles coarser than 120 μm. The aps of the distribution is $d_{Sp,m}$ = 113 μm. Especially regarding the fact, that psd related to the number of particles lead to smaller particle sizes, it has to be realised that the removed particles are only a little bit smaller than the abrasive particles.

The black bars show the psd after rough cutting. The distribution shows the same behaviour, but is shifted to larger particle sizes ($d_{Sp,m}$ = 171 μm).

Figure 4 shows psd as described above for a smaller input particle range (45 to 63 μm). As mentioned above high quality cutting causes smaller sizes of removed particles ($d_{Sp,m}$ = 20 μm) than rough cutting ($d_{Sp,m}$ = 31 μm). In the case of rough cutting, even larger particles than the abrasive particles (d_{Pm} = 36 μm) occur, up to the range of 90 to 125 μm.

The tendency, that quality cutting causes smaller particles than rough cutting, was found for all particle ranges that were investigated. Figure 5 shows the aps of removed particles versus the aps of the abrasive material after the focus, that affects the material.

This indicates that the removal mechanism varies from the top to the bottom of the shoulder of the cut.

Figure 5 shows also the tendency, that the aps of removed particles are smaller than the aps of abrasive particles, but the ratio of average particle sizes of abrasive and removed particles increases with decreasing abrasive particle size. Keeping in mind, that the presented psd is based on the number of particles, we have to assume that the particle size related to the mass of removed material might be only a little bit smaller or similar to the abrasive particle size.

3.1.2 Influence of Material to be Cut

Two combinations of abrasive material and material to be cut were investigated. For both tests rough cuts were carried out using garnet in the particle range of 250-355 μm. aluminum and stainless steel that shows higher strength, higher hardness and less ductility than aluminum were investigated.

Figure 6 shows the psd of the abrasive material after the focus and the psd of removed aluminum and steel particles after a rough cut. The psd´s, that are related to the amount of measured particles, shows the tendency that the steel particles ($d_{Sp,m}$ = 42 μm) are smaller than the aluminum particles ($d_{Sp,m}$ = 62 μm).

3.1.3 Influence of Abrasive Material

Two different abrasive materials (garnet and olivine) in the particle range from 250 to 355 μm, were compared concerning their influence on the particle size of removed particles of steel (rough cutting). The abrasives show different densities. Garnet has a density of 4 g/cm^3 and olivine has a density of 2.2 g/ cm^3. Figure 7 shows the psd of garnet and olivine after the focus. The psd show the tendency that olivine disintegrates more than garnet, but concerning the considerations that will follow, it can be assumed that the psd´s are similar. This means that cutting with olivine results in two times more particles than cutting with garnet (same size, same mass flow rate; half of the density).

The psd of steel particles caused by garnet and olivine are presented in figure 8. The psd show the tendency that olivine causes smaller removed particles than garnet. This result seems to make sense, especially regarding the fact that the amount of particles is two times higher than in case of garnet.

3.2 Shape of Removed Particles

Some chiplike particles were found that show at least a part of the surface, that is clearly created by a cut of one abrasive particle and look a little bit like chips that occur in conventional cutting processes, like milling. Most of the removed particles show many furrows on the surface. Further investigations might give an answer if these furrows result from the initial removal process or if they occur in addition to the removal process when the removed particles leave the workpiece with the stream.

In opposite to abrasive particles that commonly show a round and globular shape, removed particles appear in a variety of different shapes. An attempt was made to classify three different categories of shapes (Figure 9).

Two of the categories include particles that show a more or less regular, symmetric shape. One of these categories includes long particles with a length/width ratio of l/w>3 and the other category includes flat particles with a length/width ratio of l/w=1. The third category includes particles that show no regularity or symmetry.

Tests were carried out to determine the influence of the abrasive particle size (garnet) on the shape of the removed particles (aluminum). For all investigated particle ranges (range 2,3,4,7,9 - Table 1) the same ratio of long, flat and irregular particles was found. Less than half (40 to 50%) of the particles showed a regular shape. About 15 to 20% were long particles.

A comparison of removed aluminum and steel particles, both materials cut with garnet with an input particle range of 250 to 355μm, showed that the ratio of long, flat and irregular particles was for both the same as mentioned above.

Summarised it can be said, that no tendency was found concerning the influence of the investigated parameters on the shape of the particles. Further intensive tests may lead to more reliable results.

4. CONCLUSIONS

Particle size distributions can be determined by different methods. In general particle size distributions (psd) which are related to the number of measured particles show different appearance than psd´s which are related to the mass of particles. In case of psd´s which are related to the number of particles, smaller particles are higher rated than coarser particles. This means that the average particle size (aps) of a psd which is related to the number of particles is in generall smaller than an aps which is related to the mass of particles.

Concerning the discussion of the presented results it has to be kept in mind, that the aps´s of removed particles are related to the amount of particles and so smaller than if they were related to the mass of particles. The presented aps´s of abraisve material is related to the mass of particles.

The results of the investigations can be summarised as follows:

⇒ a general result of the investigations is, that the removed particles are quite coarse
⇒ the abrasive particle size has a significant influence on the size of removed particles in the investigated particle range from 45 to 710 μm
⇒ average particle sizes of removed particles are a little bit smaller than the abrasive particles that affect the material (psd of abrasive material after the focus)
⇒ quality cutting causes a little bit smaller removed particles than rough cutting

Some tendencies, which have to be proved by further tests, were found:

⇒ removed steel particles are a little bit smaller than aluminum particles
⇒ olivine causes a little bit smaller removed steel particles than garnet

The authors are members of the working group on water jet technology (AWT).

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6. NOMENCLATURE

a	material thickness	mm
aps	average particle size	μm
d_D	nozzle diameter	mm
d_F	focus diameter	mm
d_P	particle size of abrasives	μm
d_{Pm}	average particle size of abrasives	μm
d_{Sp}	particle size of removed particles	μm
$d_{Sp\ m}$	average particle size of removed particles	μm
h_{ST}	material thickness in case of rough cutting	mm
h_{SQ}	material thickness in case of quality cutting	mm
i	particle range number	-
k_m	depth of kerf	mm
k_{max}	max. depth of kerf	mm
k_{min}	min. depth of kerf	mm
l_F	focus length	mm
m_P	abrasive flow rate	g/s
p	pressure	MPa
psd	particle size distribution	-
s	stand-off distance	mm
v	nozzle traverse rate	mm/min
x_i	mean particle size of a particle range	μm

Table 1:
Separate Particle Ranges (Bogenschütz, 1973)

i	sieve range [μm]	x_i [μm]	Tyler mesh
1.1	0 - 20	10.0	
1.2	20 - 32	26.0	
1.3	32 - 45	38.5	minus 325
2	45 - 63	54.0	325 - 230
3	63 - 90	76.5	230 - 170
4	90 - 125	107.5	170 - 115
5	125 - 180	152.5	115 - 80
6	180 - 250	215.0	80 - 60
7	250 - 355	302.5	60 - 42
8	355 - 500	427.5	42 - 32
9	500 - 710	605.0	32 - 24

Table 2:
Test Parameters

pressure	$p = 300$ MPa
nozzle traverse rate	depends on cutting quality
nozzle diameter	$d_D = 0.25$ mm
focus	$d_F = 0.9$ mm
	$l_F = 40$ mm
mass flow rate	$m_P = 5$ g/s
stand-off distance	$s = 2$ mm
material	AlMgSi0.5; X 12 CrMoS 17

Table 3:
Investigated Particle Ranges and the Average Particle Size of Abrasive and Removed Particles

abrasive material	input particle range [μm]	aps **abrasive** [μm]	aps **aluminium** [μm]		aps **steel** [μm]
		after focus	quality cut	rough cut	rough cut
garnet	45-63	36	20	31	-
	63-90	50	27	32	-
	90-125	66	40	51	-
	250-355	172	60	62	42
	500-710	273	113	171	-
olivine	250-355	154	-	-	34

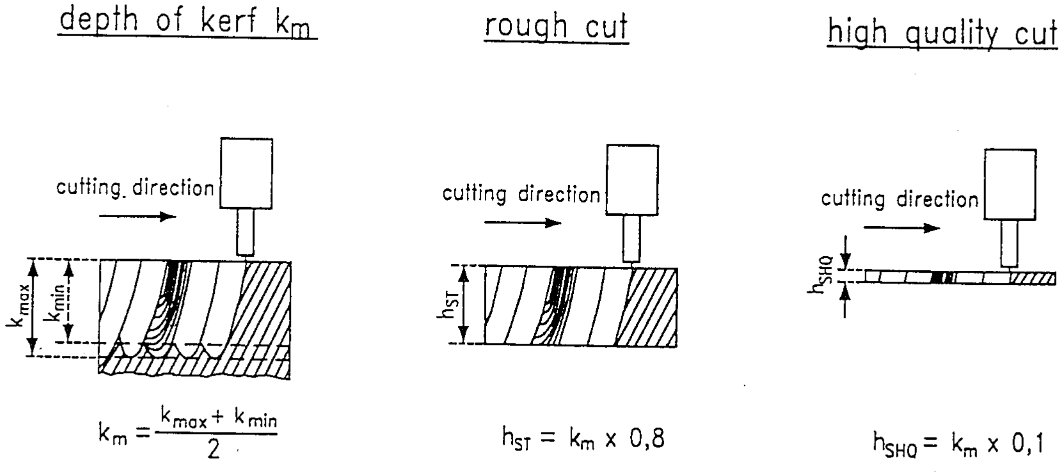


Figure 1: Definition of Cutting Qualities

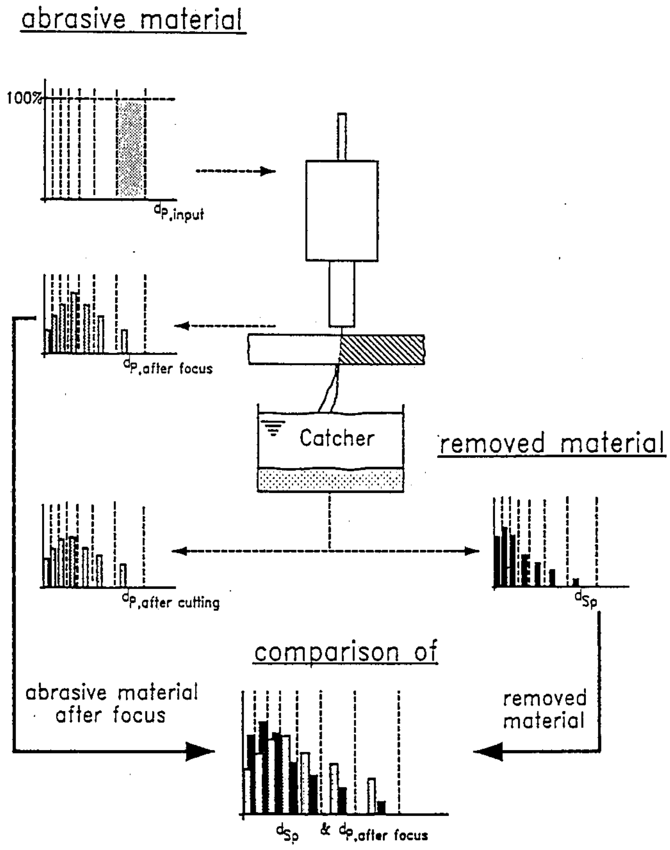


Figure 2: Presentation of Results

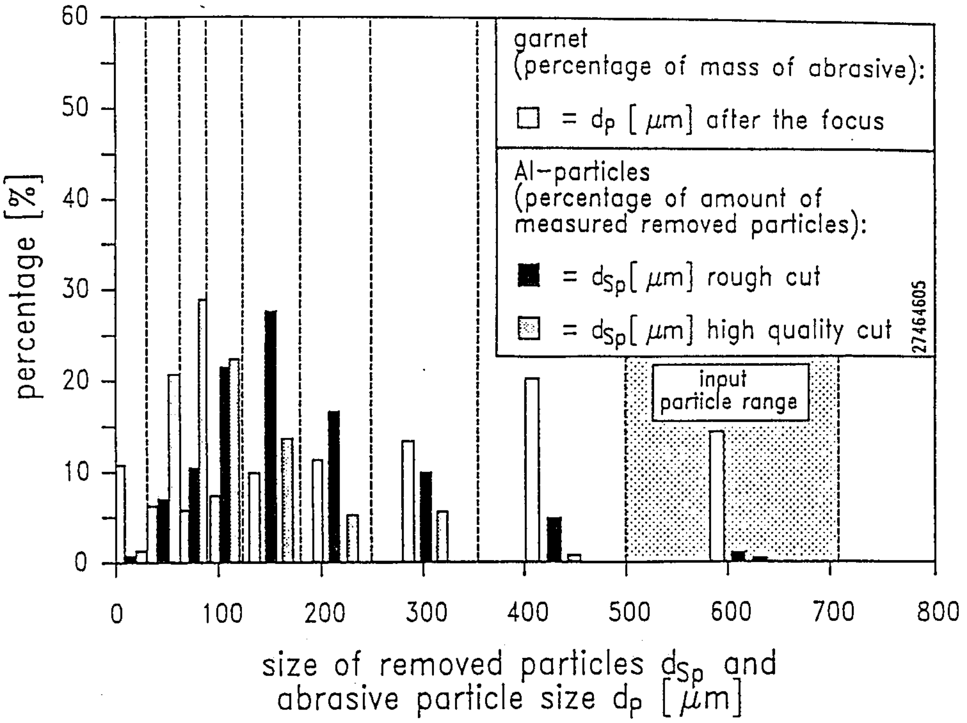


Figure 3: Influence of Abrasive Particle Size on Particle Size of Removed Particles

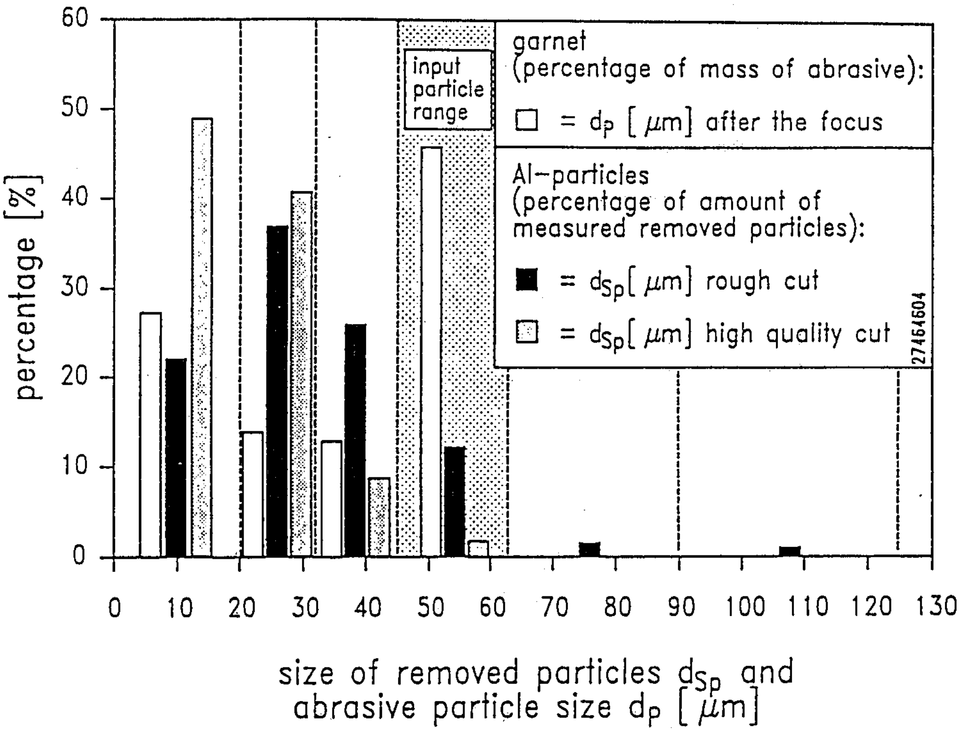


Figure 4: Influence of Abrasive Particle Size on Particle Size of Removed Particles

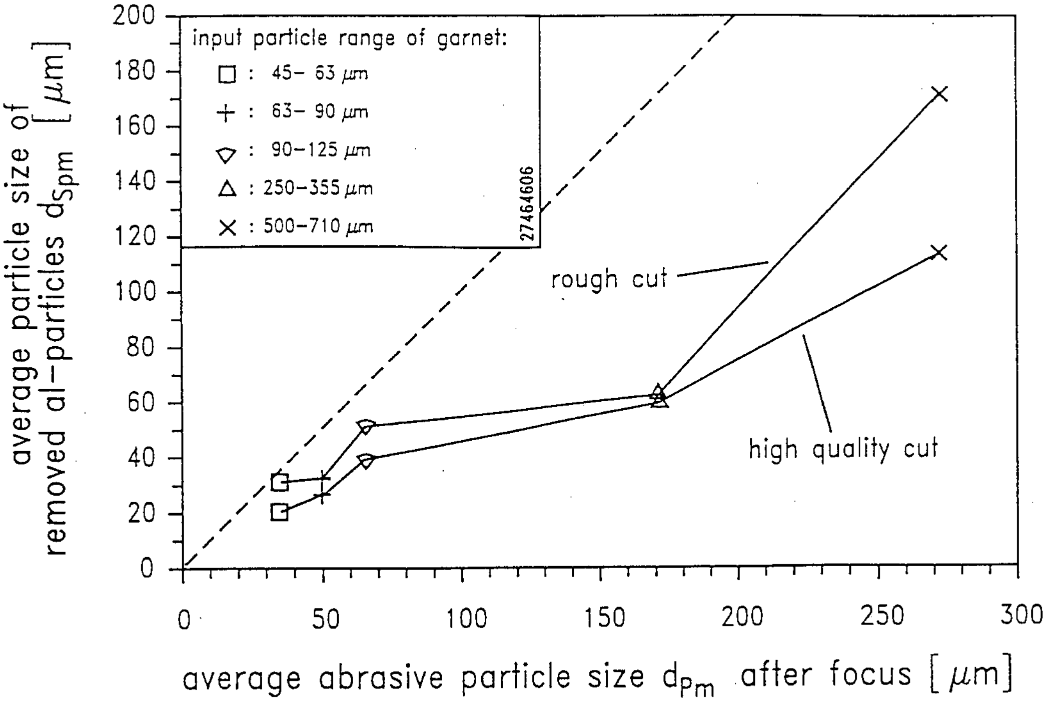


Figure 5: Influence of Average Abrasive Particle Size on Average Particle Size of Removed Particles

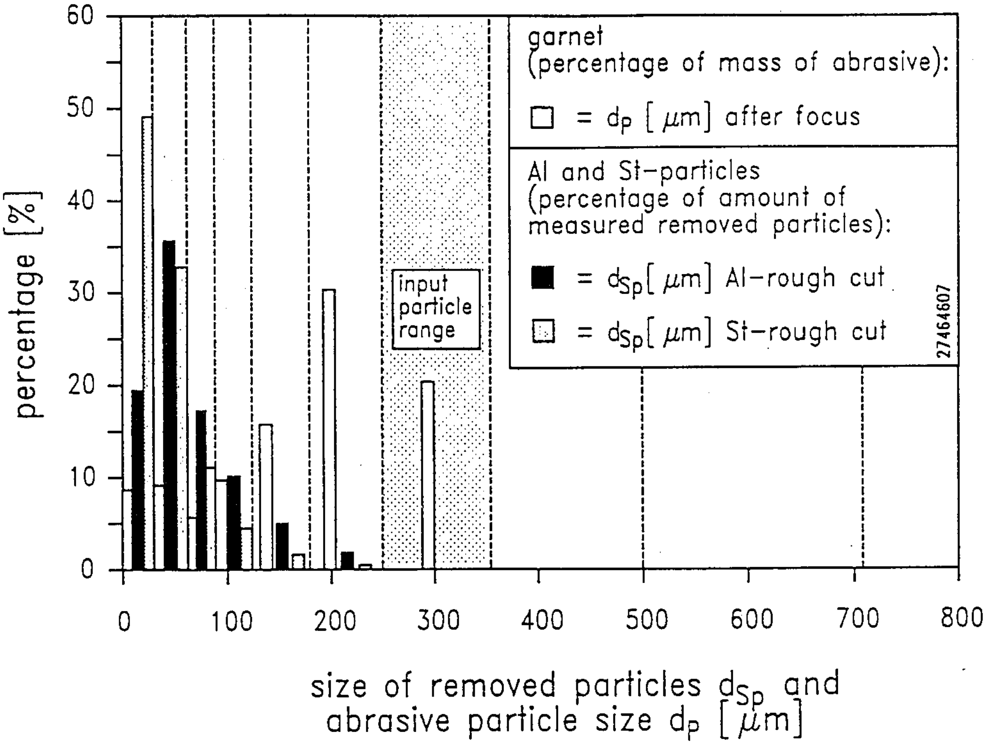


Figure 6: Influence of Material to be Cut on the Particle Size of Removed Particles

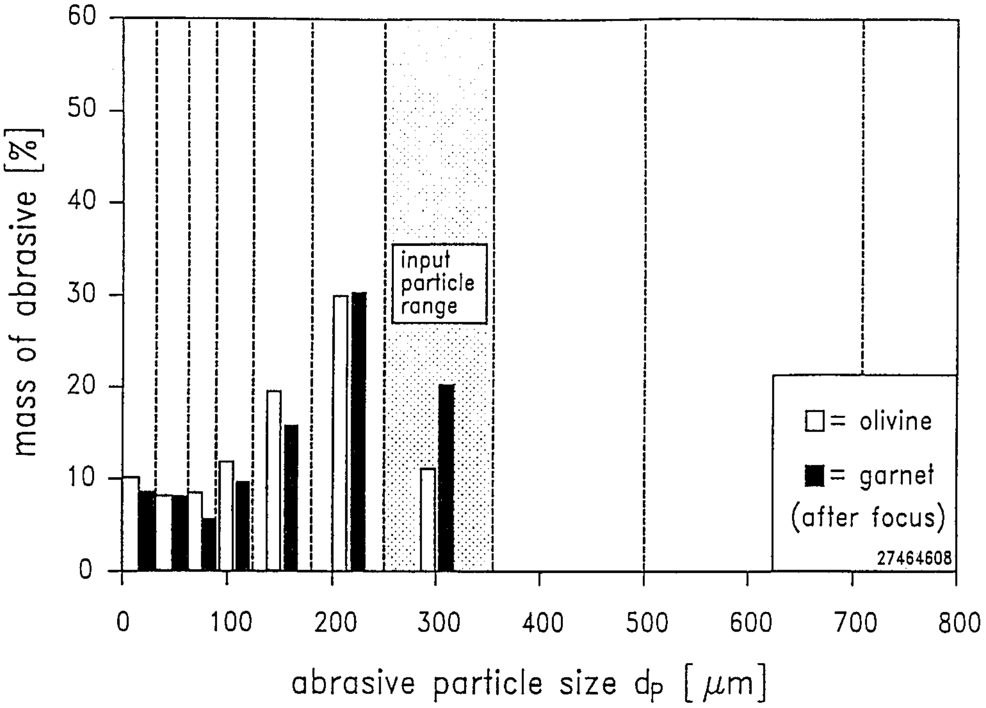


Figure 7: **Particle Size Distribution of Garnet and Olivine after the Focus**

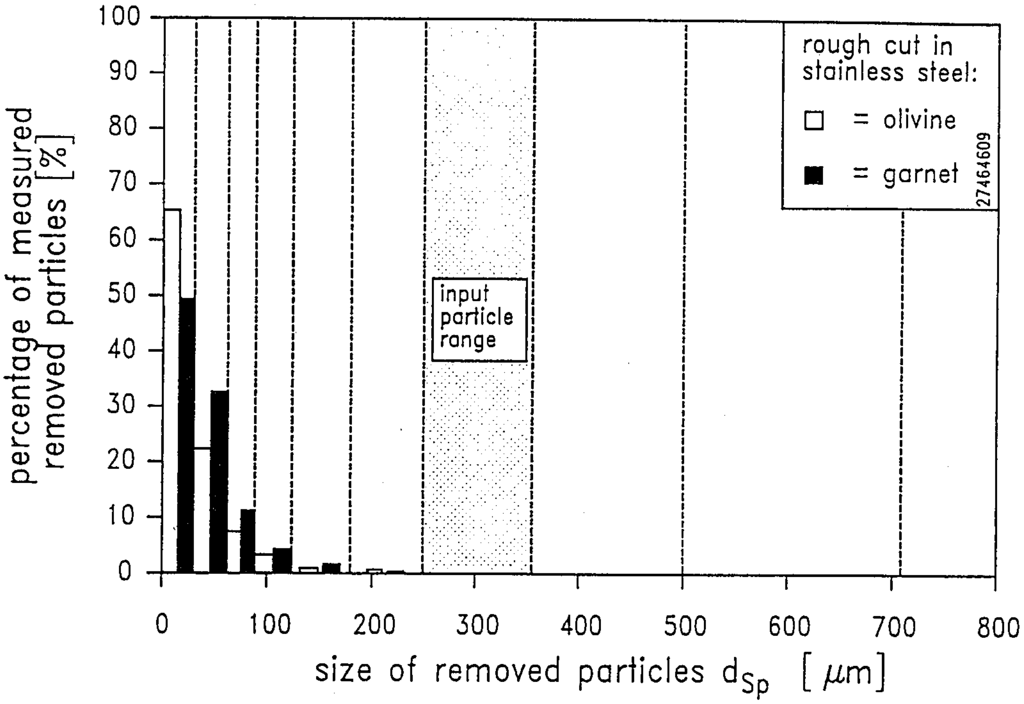
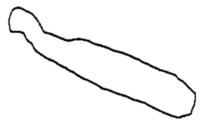
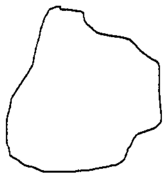
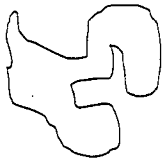


Figure 8: **Influence of Abrasive Material on the Particle Size of Removed Steel**

regular		irregular
long l/w >3	flat l/w ~1	
		

<u>Figure 9:</u> Classification of Shapes of Removed Particles

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Paper 12

ABRASIVE AIR WATER JET MODELIZATION

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ABSTRACT

The development of improved cutting head design (including mixing chamber and mixing tube parts) needs a sufficient knowledge of abrasive particle behavior inside this cutting head. The objective of this study is to present a method to calculate the abrasive air water jet flow in both mixing chamber and mixing tube. All collected information will help for cutting head optimization and Abrasive Jet Cutting investigations (enable an accurate prediction of both depth of cut and traverse rate).

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1. INTRODUCTION

Some of the previous theoretical work conducted in abrasive water jet technology has been concerned with investigations of abrasive acceleration by water jet. The authors aim, through these investigations, was to know particle velocity and behavior ; many models have been built for calculating abrasive acceleration, with the following assumptions:

- air influence on the flow is neglected
- no particle interaction
- no turbulence effect

When we started working in the field of water jet technology, our goal was to design a new abrasive cutting head. In fact, it is in the cutting head that abrasive water jet formation occurs ; thus, abrasive particles velocity and distribution at the mixing tube outlet depend on the internal head shape. For better understanding of particles behavior and optimal definition of internal head geometrical configuration, we decided to build a new abrasive air and water jet flow model more realistic than the existant ones. This model gives informations along abrasive flow, from inlet to outlet : abrasive informations inside the cutting head are helpful for its optimization, while abrasive informations at mixing tube outlet are indispensible for further development of Abrasive Jet Cutting and enable an accurate prediction of both depth of cut and traverse rate.
Our paper presents a method for calculating the abrasive acceleration in the cutting head under real operating conditions of cutting, taking into account:

- presence of air in the cutting head(90% volume occupation)
- flow turbulence
- particle interactions
- internal cutting head shape including mixing chamber and foccusing nozzle

A two phase flow program called "Melodif" was used to carry out computations of the abrasive air water jet flow in two steps :

1- Flow in the mixing chamber
2- Flow in the mixing tube

2. WORKING OF THE CUTTING HEAD

The abrasive air water jet is created by exhausting the high pressure water through a primary sapphire nozzle to form a pure water jet, which passes through a mixing chamber, where air and abrasives are drawn into the mix. The three-phase mixture is then focused through a mixing tube. Using a conventional cutting head will produce a flow whose composition on a volume basis is about 90 to 95% air, 4 to 9% water and up to 0.8% abrasive (Figure.b).

3. FLOW ANALYSIS

In the cutting head, three phases are mixing up to constitute the abrasive air water jet flow. Therefore, we have a three phase flow. Generally, the most important characteristic for such flows is the "elementary volume Ω" configuration, to which we will apply fluid mecanic equations. For a three phase flow, this "elementary volume Ω" consists of three phases. Its configuration must be identical over all the flow field, from inlet to outlet. The configuration commonly studied is the fluid-inclusions one ; at the interface,between phases, the momentum transfer modeling in such configuration is possible, while for other configurations, interfaces instability prevents any modeling.
The definition of abrasive-air-water jet "elementary volume Ω" configuration will not be easy because of water jet structure changing. This changing produces an instability of interfaces

separating the three phases. In fact, the water jet breaks up in droplets after a certain length (Shimizu, 1984) and creates two flow regions in the cutting head (Figure.a) :

- In the mixing chamber - first region-, the flow is a particular one.
- In the mixing tube -second region-, the flow is a fluid-inclusions one.

3.1 FLOW IN THE MIXING CHAMBER

In the mixing chamber, the flow is particularly complicated. Near the axis, the flow is one phase flow ; its "elementary volume Ω" consists of a fluid phase (water). Far from the axis, near the wall, the flow is two phase flow ; it consists of a fluid phase (air) and inclusions (abrasive). At the interface between air and water, the flow is three phase flow (Fig.c). Under such conditions, the definition of an "elementary volume Ω" for this region is not possible. To allow flow analysis in the mixing chamber, we need to propose another "elementary volume Ω". For this, we assume that the water jet break up occurs near the sapphire nozzle implying that the flow configuration is a fluid (air)-inclusions (droplets-abrasives) (Fig.d).

Up to now, we have no numerical means to compute **three phase-flows** because of their complexity. Only two-phase flow programs, which are built particularly for predicting fluid-inclusions flows, are available. Therefore, to compute the abrasive air water jet we need to reduce the flow component number from three to two. Generally, this reduction is achieved thanks to a method called "**homogenization**". In multi-phase flow, when two phases present almost the same velocity -relative velocity equals zero-, we can use a simplified (homogenized) model which considers the global state of the mixture (Simonin, 1990). From densities, pressures and velocities of both phases (phase 1 and phase 2), we define a density ρ_m, a pressure P_m and a velocity U_m for the mixture as :

$$\rho_m = \alpha_1 \rho_1 + \alpha_2 \rho_2$$

$$P_m = \alpha_1 P_1 + \alpha_2 P_2$$

$$U_m = \frac{\alpha_1 \rho_1 U_1 + \alpha_2 \rho_2 U_2}{\rho_m}$$

Following this definition, comparisons between "water-air", "water-abrasives" and "abrasives-air" velocities show that the relative velocity is different from zero, meaning that in the mixing chamber no homogenization is possible. Thus, we are in front of a three-phase flow with no alternative for simplification. Therefore, we decide :

- to compute the Water Jet and air flow in the mixing chamber using a two-phase flow program.
- to make an analytic study of abrasive particles flow in the mixing chamber.

3.1.1 The water jet and air flow

The Water-air flow is a two-phase flow. Its "elementary volume" has a fluid-inclusions configuration (Figure.e). To compute this flow, we use a two-phase flow program called "Melodif". It is a two-dimensional separated two-phase flow model, developed for predicting fluid-inclusions -bubbles, drops or particles- turbulent recirculating flows. Its governing equations have been derived directly from the local instant conservation equations in single-phase flow by density-weighted averaging with in addition local balances of mass, momentum at the interface (Delhaye, 1974 ; Ishii, 1975).

a- Basic equations

<u>Mass balance :</u>

$$\frac{\partial}{\partial t} \alpha_k \rho_k + \frac{\partial}{\partial t} \alpha_k \rho_k U_{k,i} = 0$$

where:

- $U_{k,i}$ is respectively the mean velocity for the continuous (k=1) and dispersed phases (k=2),

• ρ_k the mean density, α_k is the volumetric fraction,

$$\sum_{k=1}^{2} \alpha_k = 1$$

Momentum balance :

$$\alpha_k \rho_k \frac{\partial}{\partial t} U_{k,i} + \alpha_k \rho_k U_{k,j} \frac{\partial}{\partial x_j} U_{k,i} = -\alpha_k \frac{\partial P_1}{\partial x_i} + \alpha_k \rho_k g_i + I_{k,i} - \frac{\partial}{\partial x_j} \alpha_k \langle \rho U''_i U''_j \rangle_k$$

where:

• P_1 is the mean pressure of the gaseous phase,

• U''_i is the fluctuating part of the local instantaneous velocity and $\langle . \rangle_k$ the averaging operator associated to phase k,

$$U_i = U_{k,i} + U''_i \quad ; \quad \alpha_k \rho_k U_{k,i} = \alpha_k \rho_k \langle U_i \rangle_k \quad ; \quad \langle U''_i \rangle_k = 0$$

• $\langle \rho U''_i U''_j \rangle_k$ is the turbulent Reynolds stress tensor

• $I_{k,i}$ is the part of the interfacial momentum transfer rate between phases which remains after substraction of the mean pressure contribution and complies with the local balance equation,

$$\sum_{k=1}^{2} I_{k,i} = 0$$

Interfacal momentum transfer :

In dispersed two phase flows, inclusions are assumed to interact only slightly. Therefore, interfacial transfer terms in the basic equations can be obtained from the analysis of the behaviour of an isolated inclusion in function of the surrounding fluid characteristics. The analysis of local balance of forces acting on an isolated inclusion leads to the following expression :

$$I_{2,i} = -I_{1,i} = \alpha_2 \rho_1 F_D V_{r,i} + \alpha_2 \rho_1 C_L [\, \mathrm{ro}\vec{U}_{1,i} \wedge \vec{V}_{r,i} \,]_i + \alpha_2 \rho_1 C_A [\, \frac{\partial V_{r,i}}{\partial t} + U_{2,j} \frac{\partial V_{r,i}}{\partial x_j} \,] + \frac{\partial}{\partial x_j} \alpha_2 \rho_1 C_A \langle U''_{2,j} V''_{r,i} \rangle_2$$

where:

• F_D is the average dragg coefficient

• $V_{r,i}$ is the average of the local relative velocity $v_{r,i}$

$$V_{r,i} = \langle U_{2,i} - U_{1,i} \rangle_2 = [\, U_{2,i} - U_{1,i} \,] - V_{d,i} \quad ; \quad V_{d,i} = \langle U''_{1,i} \rangle_2$$

$V_{d,i}$ the drifting velocity accounts for the dispersion effect due to the particle transport by the fluid turbulence.

Turbulence model :

In our approach, all the correlations are computed with the help of the eddy vicosity concept:

$$\langle \rho U''_i U''_j \rangle_k = \rho_k \nu_k^t [\, \frac{\partial}{\partial x_j} U_{k,i} + \frac{\partial}{\partial x_i} U_{k,j} \,] + \frac{2}{3} \delta_{ij} [\, \frac{1}{2} \langle \rho U''_m U''_m \rangle_k + \rho_k \nu_k^t \frac{\partial}{\partial x_m} U_{k,m} \,]$$

where the eddy vicosity ν_k^t is written in function of the turbulent kinetic energy q_k^2 and a characteristic time τ_k^t:

$$\nu_k^t = \frac{2}{3} q_k^2 \tau_k^t \qquad \rho_k q_k^2 = \frac{1}{2} \langle \rho U''_i U''_i \rangle_k$$

b- Boundary conditions (Figure.f)

The chosen boundary conditions are conventional for abrasive water jet cutting.

• *Geometrical conditions :*

sapphire diameter:	$\varnothing_S$ =	0,30 mm
mixing chamber diameter:	$\varnothing_C$ =	4,40 mm
mixing chamber length:	L_S =	0,30 mm

•*Water jet :*

droplet diameter:	**d** =	0,05 mm	(K-J. Wu, 1983)
water pressure:	**P** =	2500 bars (V = 700m/s)	

•*Air:*

air flow rate:	Q_2=	20,4 l /mn	(Raissi, 1994)

c- Results and discussion (see **Figure.1** to **Figure.4**)

In figure.1, the water jet spreading, which is necessary for abrasive incorporation into the air-water flow, is due to air recirculation. Air recirculation depends on internal mixing chamber geometry. In fact, large mixing chamber diameter produces excessive air suction (Raissi, 1994). Because of the mixing tube small diameter and of high air flow rate, reciculation occurs in the mixing chamber. This induces excessive water jet spreading which dissipates jet energy. Therefore, we need to design the mixing chamber in a such way that the sucked air flow rate is optimum. Figure.2 shows the water mass-flow stream lines loosening from the cone wall. This induces loss of energy near the axis due to particle-particle and fluid interactions. When designing the mixing tube, we have to avoid such deviation reducing the cone angle to an optimum value.

3.1.2 Abrasive particles in the mixing chamber

To "air water jet flow" presented before, we add abrasive particles. Directly after the inlet, these particles hit the water jet below a particular velocity. Because of high water energy, particles rebound. They then collide with the inner wall of the mixing chamber and hit the jet again. This phenomenon may be repeated in the mixing chamber until jet penetration. A series of experiments (Raissi, 1994), carried out to verify the abrasive particle distribution near the mixing chamber outlet, shows that the greatest part of abrasive particles deposit in the narrowing between mixing tube cone and the water jet before being accelerated (Figure.a).

3.2 FLOW IN THE MIXING TUBE

After a certain length (L_b = 25mm), the jet breaks up in droplets and mix up with air (Shimizu, 1984). When abrasive particles penetrate the air water stream, the flow becomes three phase flow. Its "elementary volume Ω" has a fluid-inclusions configuration. As for the mixing chamber, we need to homogenize this flow to make abrasive air water jet calculations possible using the same two phase flow program. The observation of abrasive air and water accelerations in the mixing tube shows that only the relative velocity between air and water approachs zero (Raissi, 1993). Therefore, we can consider the global state of air and water as a mixing phase. Finally, the homogenized "elementary volume Ω" looks like a "fluid (mixing phase) - inclusions (abrasives)" one.

3.2.1 Boundary conditions (Figures.g, 5)

• *Geometrical conditions :*

mixing tube diameter:	$\varnothing_t$ =	1,20mm	
mixing tube length:	L_s =	50mm	
cone angle:	θ =	30°	

•*Water jet* :

water velocity:	V_1=	600m/s	

•*Air:*

flow rate:	Q_2=	20,4 l/mn	(Raissi ; 1994)

•*Abrasive:*

abrasive velocity:	V_2=	350m/s	(Raissi ; 1994)
Abrasive mesh:	d =	0,15mm	(K-J. Wu, 1983)
flow rate:	Q=	250 gr/mn	

3.2.2 Results and discussions (see **Figure.5** to **Figure.10**)

Figure.3 shows initial boundary conditions. The volumic fraction profile comes from an erosion experiment. In this experiment, we found that at tube entrance, abrasive particles are concentrated et the periphery of the jet from 1/2 tube ray to the tube wall (Raissi, 1994). The water and air velocity profile is a standard jet profile (Simonin, 1990) while the abrasive profile comes from calculation of abrasive acceleration by air-water jet flow (Raissi, 1994).
Figure.4 shows the abrasive mass flow stream lines. We note here that after a first impact on the tube cone and the violent stream lines deviation, particles migrate towards the axis and come back after near the inner tube wall. Impact angles on the tube wall are very high near the inlet and less near the outlet. This is in total concordance with the actual mixing tube wear. Figure.5 and figure.6 present the volumic fraction and velocity of abrasive near the wall. Presence of abrasive particles near the wall under these velocities is dangerous for tube life. We have to reduce particle impact angle and presence near the wall to increase mixing tube life.
Figure.7 and figure.8 show the evolution of both abrasive volumic fraction and velocity along the tube axis.These informations will help investigations about Abrasive Jet Cutting and will enable an accurate prediction of both depth of cut and traverse rate.

4. CONCLUSIONS

The abrasive air water jet was calculated in the cutting head using a two phase flow program. It appears from obtained results that this numerical tool is very interesting for cutting head design. Informations collected at the mixing tube outlet will help investigations about Abrasive Jet Cutting and will enable an accurate prediction of both depth of cut and traverse rate.

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•Shimizu, M., Arai,M., "Measurements of Breakup Length in High Speed Jet", Bulletin of JSME, Vol. 27, No. 230 August 1984.
•Simonin, O., 1990, "Introduction à la modélisation des écoulements constitués d'une phase continue contenant des inclusions dispersées", Ecole Nationale des Ponts et Chaussées, Paris

Figure 1 : Water and Air stream lines in the mixing chamber

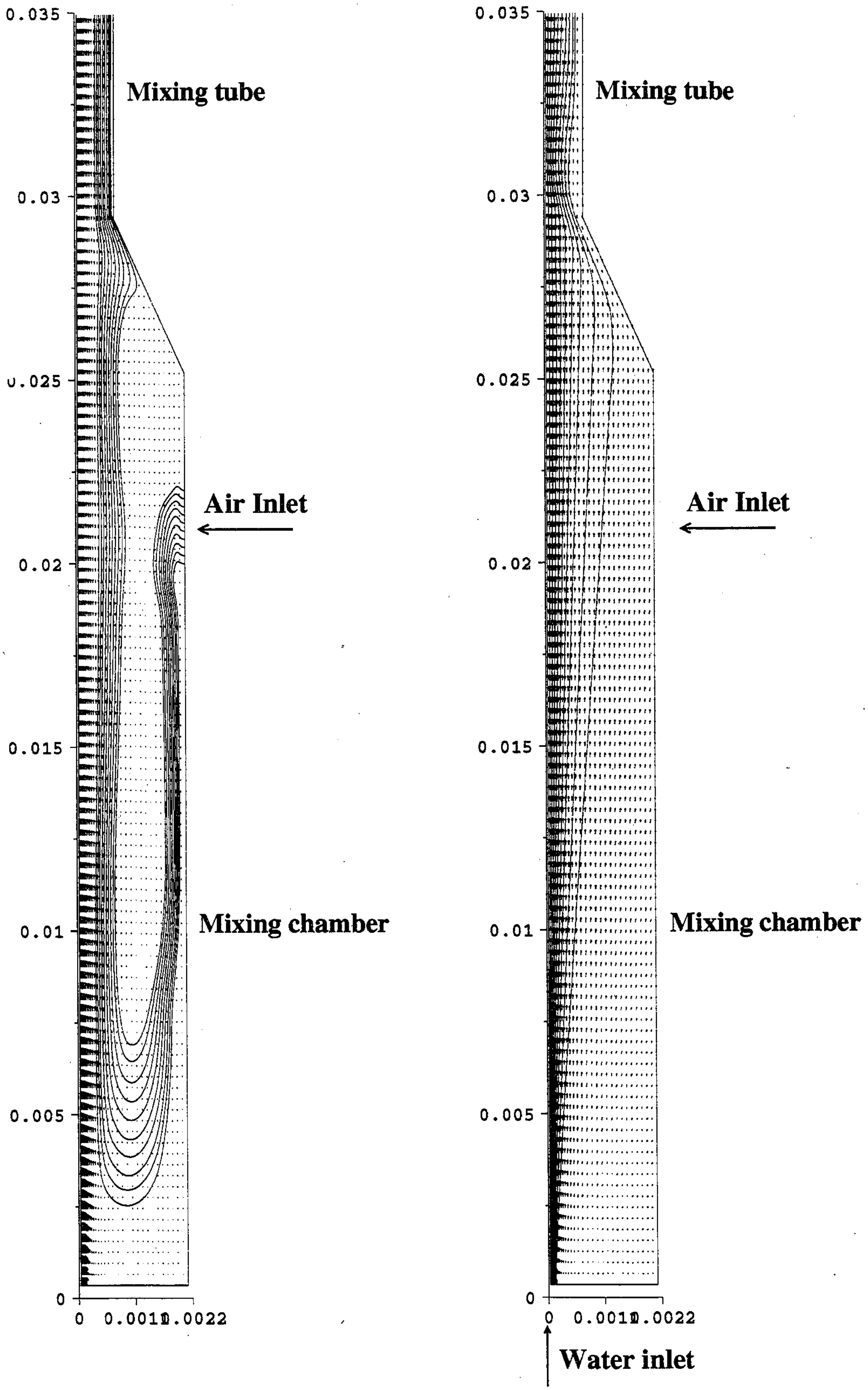
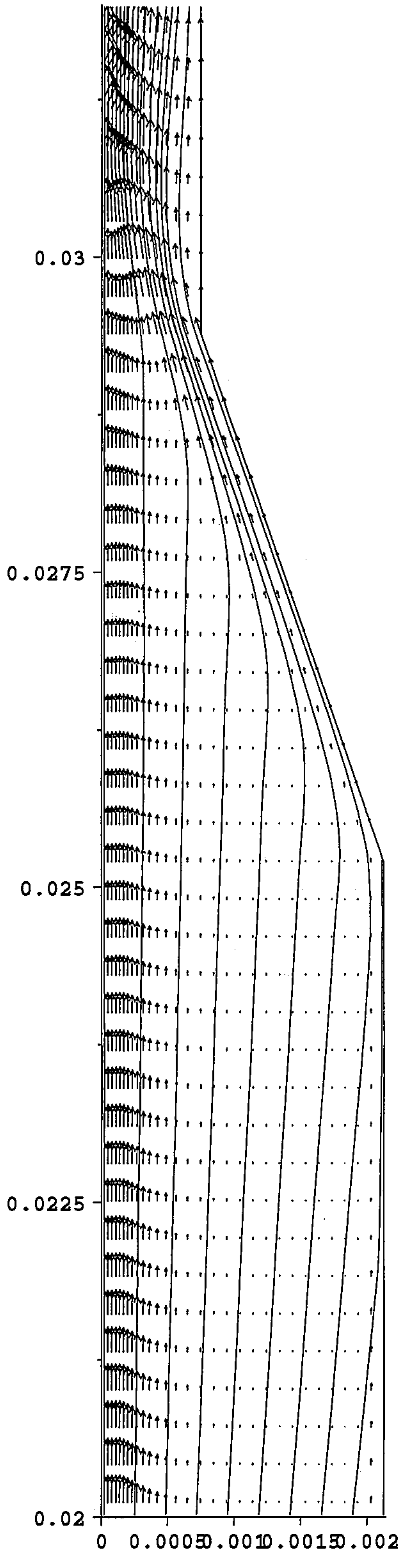
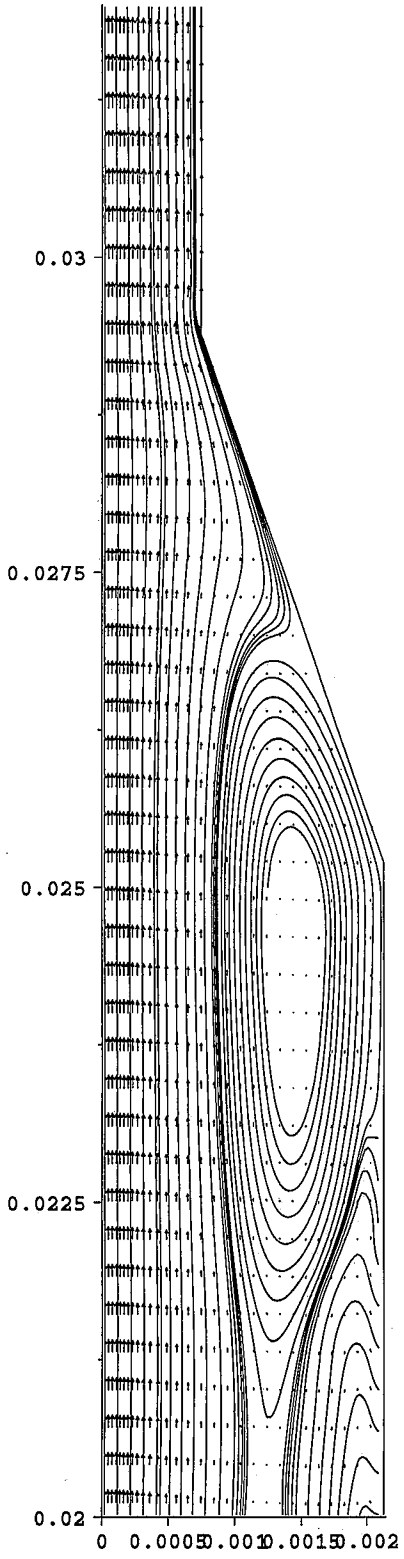


Figure 2 ; Water and air mass-flow in the mixing chamber



Water stream lines



Air stream lines

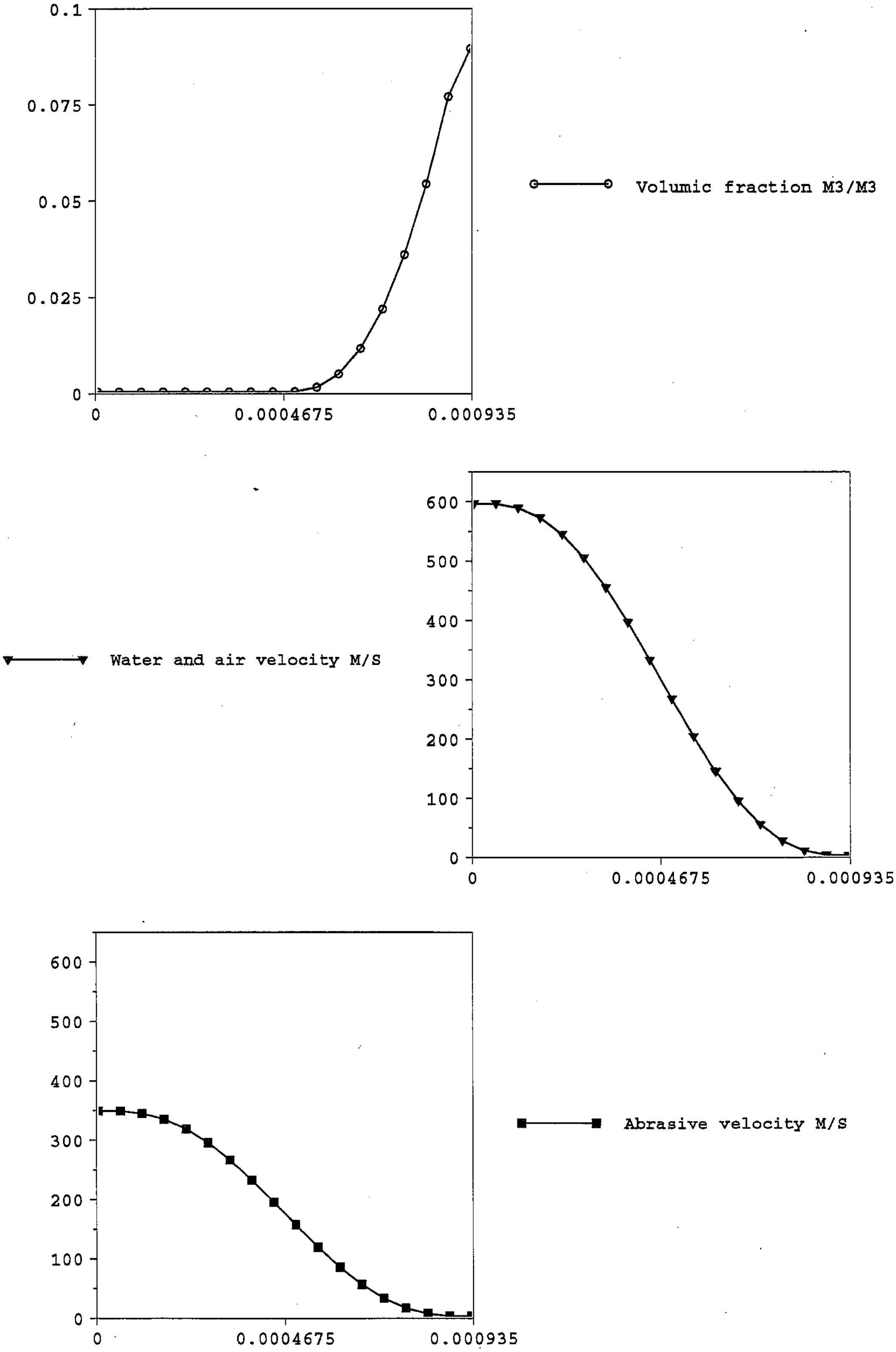


Figure.3: Initial boundary conditions

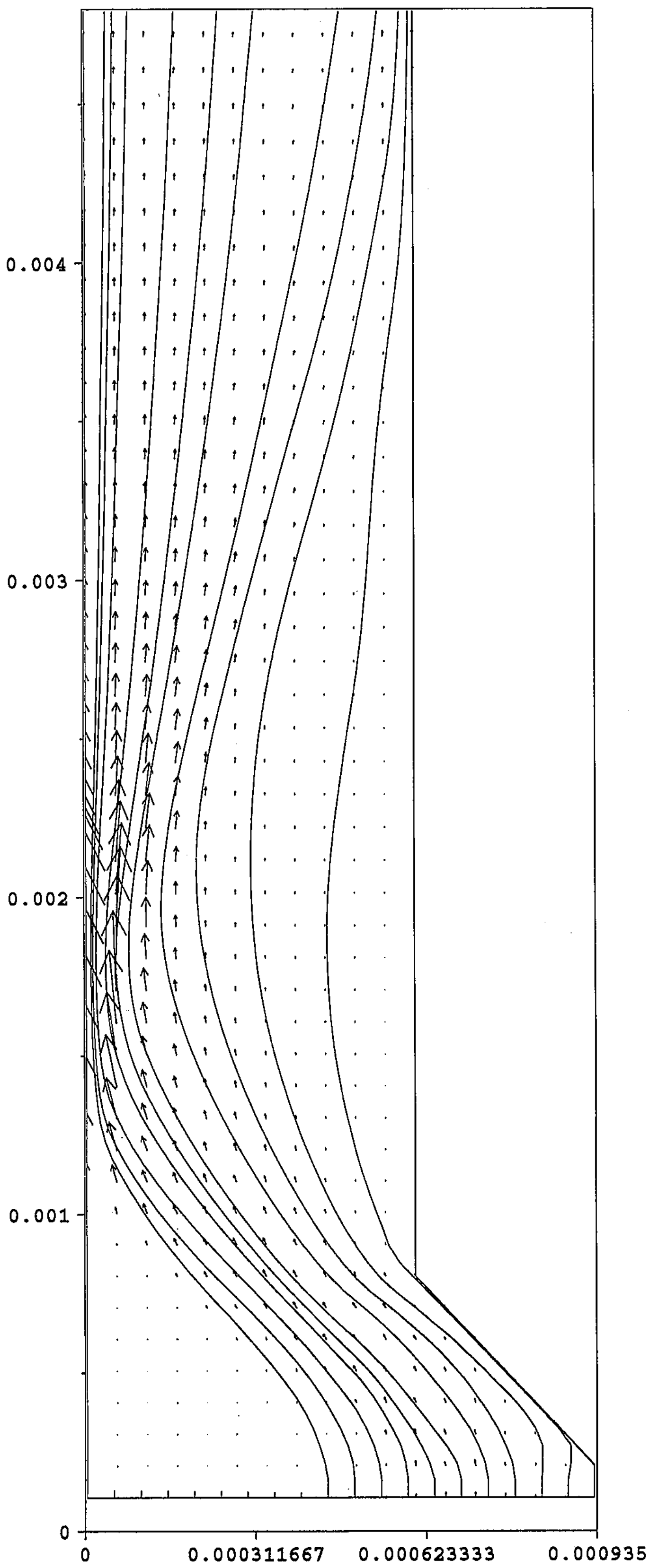


Figure.4: Abrasive mass flow in the mixing tube

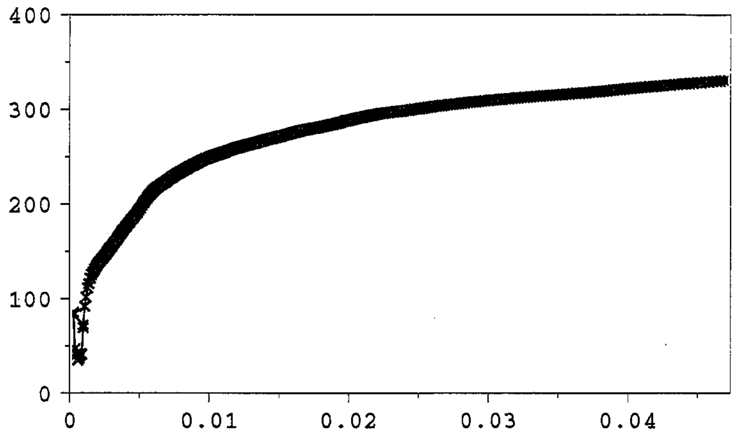


Figure.5: Abrasive velocity near the tube wall

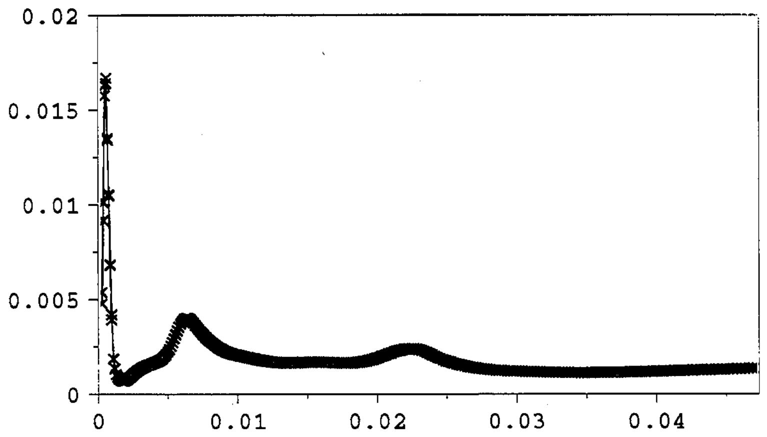


Figure. 6: Abrasive Volumic fraction near the tube wall

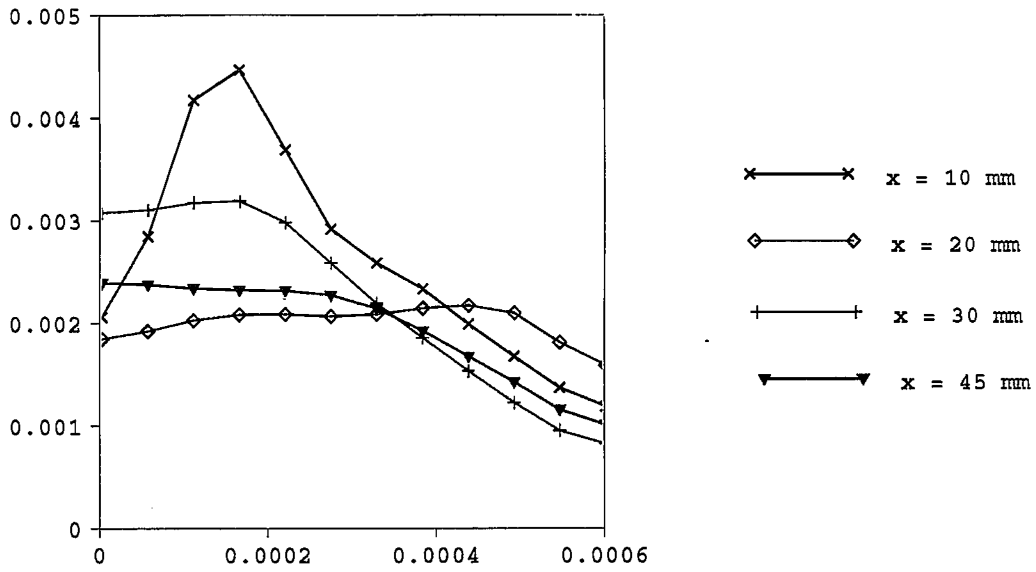


Figure. 7 : Abrasive Volumic fraction along the flow

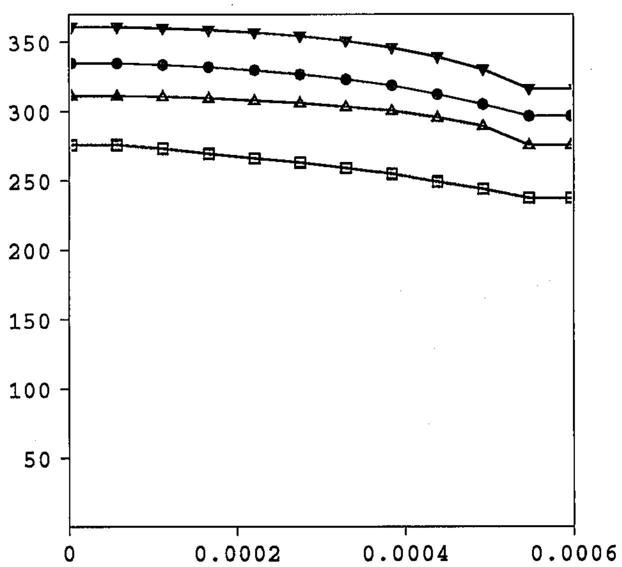


Figure. 8 : Abrasive velocity along the flow

6. FIGURES

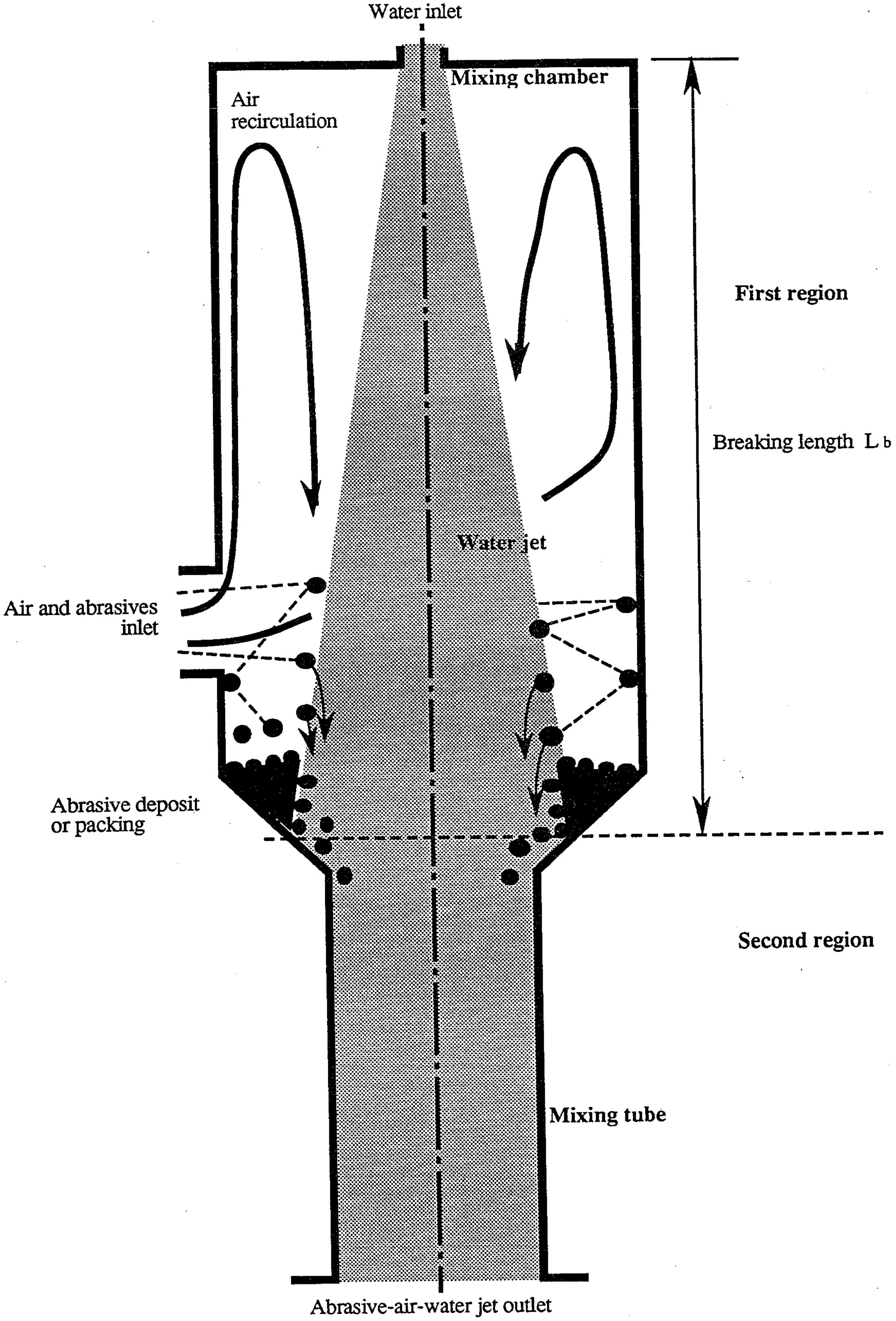


Figure.a : Abrasive air water jet cutting head

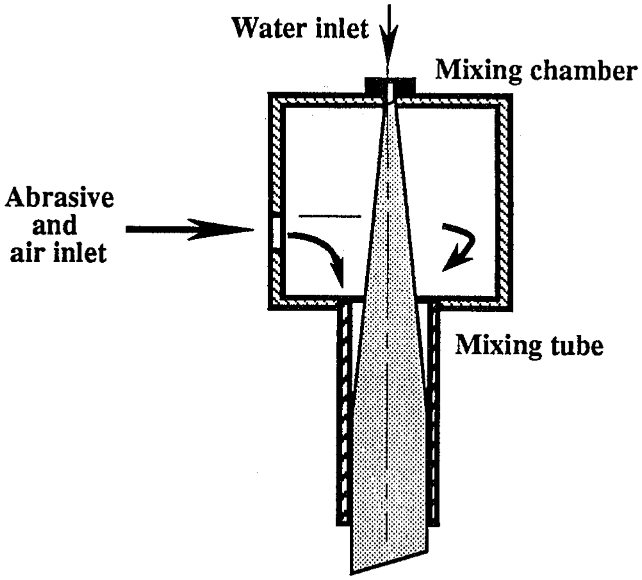


Figure.b : Abrasive air water jet cutting head

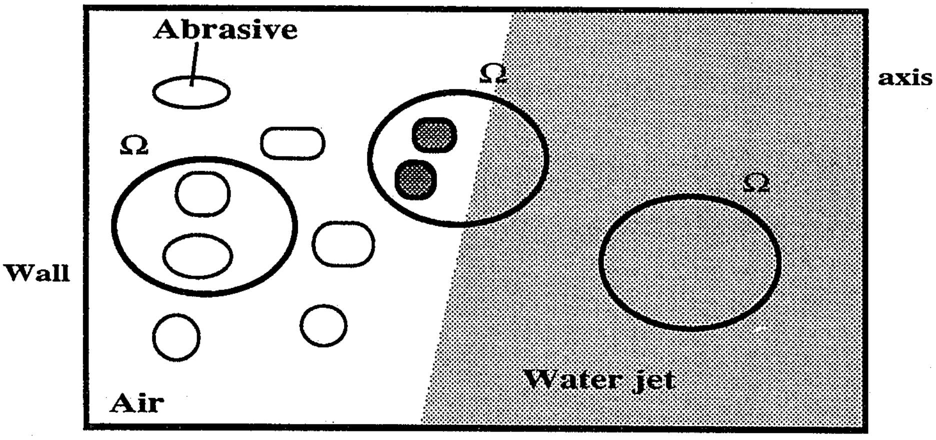


Figure.c : "Elementary volume" Ω in the mixing tube

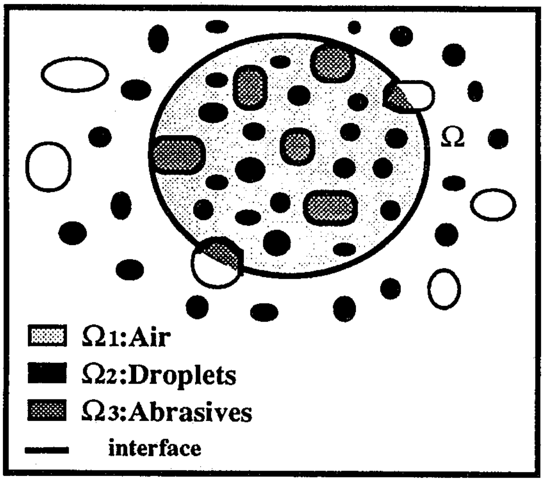


Figure.d : A fluid-inclusions "Elementary volume Ω"

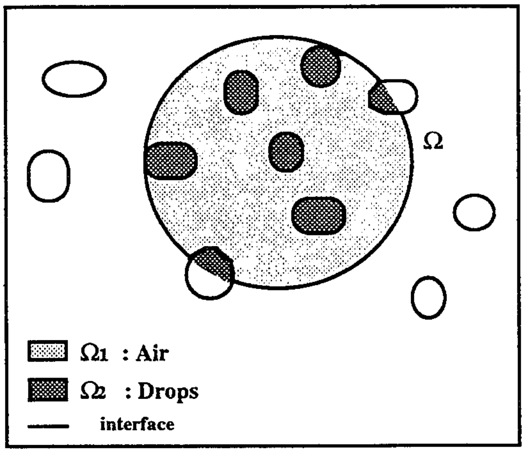
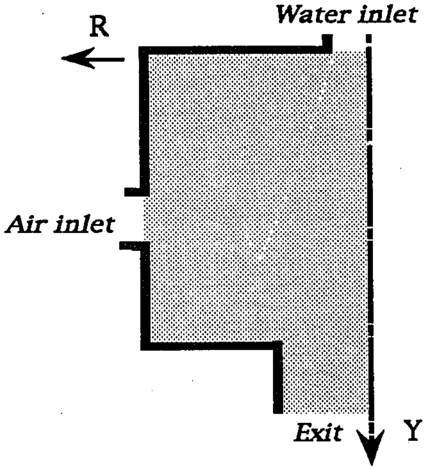


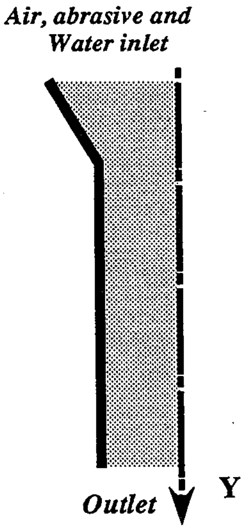
Figure.e : "Elementary volume Ω" of the air water jet flow



Boundary conditions :
continuous phase(air)
*velocity profile
*volumetric fraction
dispersed phase(water)
*velocity profile
*volumetric fraction

Exit Condition :
atmospheric pressure

Figure.f : Calculations in the mixing chamber



Boundary conditions
continuous phase(water-air)
*velocity profile
*volumetric fraction
dispersed phase(abrasive)
*velocity profile
*volumetric fraction

Outlet Condition :
atmospheric pressure

Figure.g : Calculations in the mixing tube

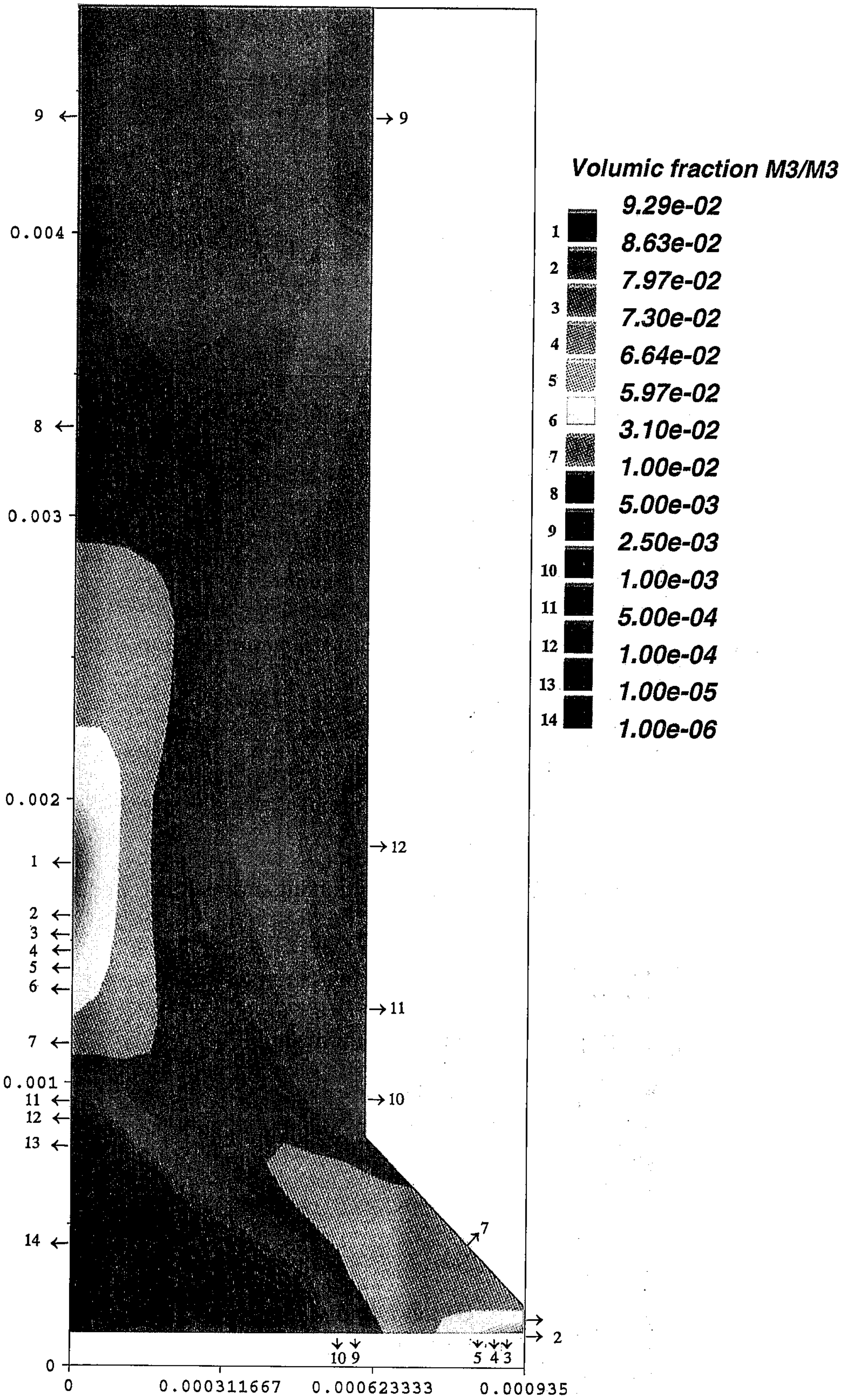


Figure.9 : Abrasive volumic fraction in the mixing tube

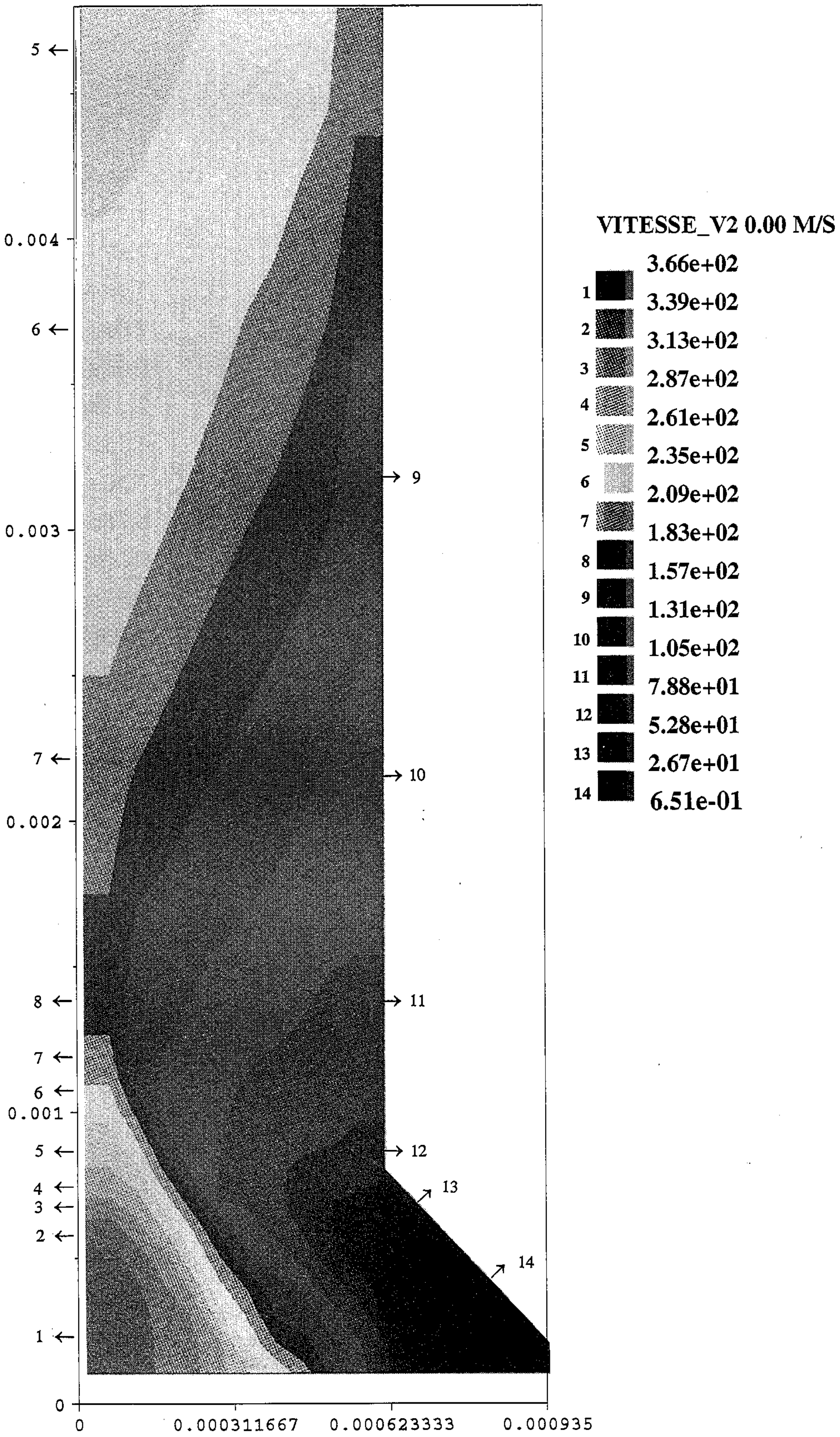


Figure10: Abrasive velocity in the mixing tube

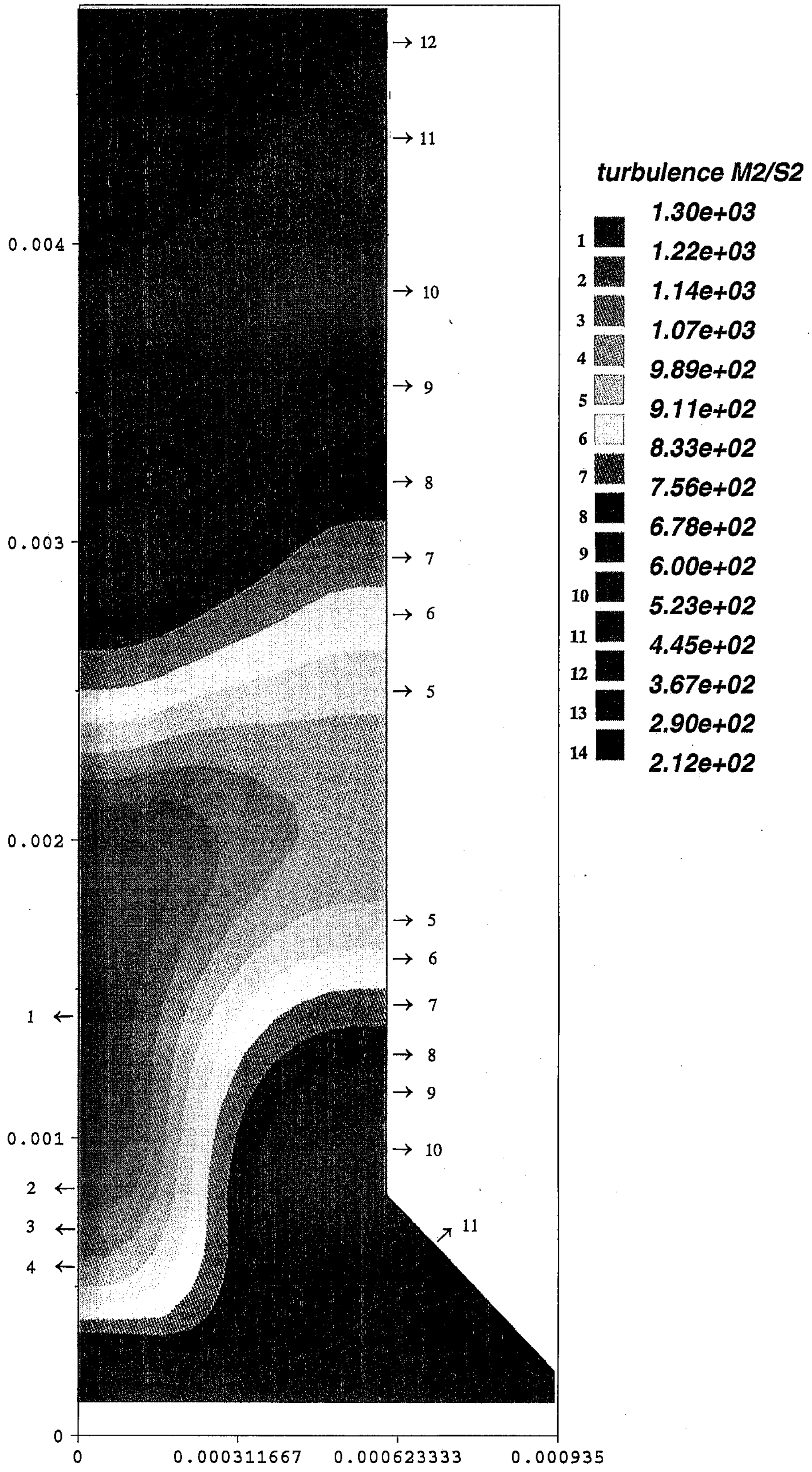


Figure 31: Abrasive turbulence energy in the mixing tube

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Paper **13**

INTERACTION OF ABRASIVE WATER JET WITH CUT MATERIAL AT HIGH VELOCITY OF IMPACT — DEVELOPMENT OF AN EXPERIMENTAL CORRELATION

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ABSTRACT

In this study, some theoretical and experimental investigations on the interaction between a cut material and Abrasive Water Jet (AWJ) tool, are presented. As a result, we have obtained an important general equation which is called by an *experimental correlation.* For some given working parameters (hydraulic pressure, abrasive mass flow rate, traverse rate of cut...), this equation represents a variation of a removal mass flow rate (experimental parameter) of cut material as function of abrasive particle velocity (theoretical parameter) at impact. From the expression of the experimental correlation, we have, afterwards, set a relation between depth of cut and particle velocity at impact. However, that velocity is estimated by a theoretical acceleration modelling which was established in a previous and separate work.

The present modelling is available for a large range of cut materials and, for ductile steel, experimental trials showed a good concordance between the predicted depths of cut and the experimental results.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

The Abrasive Water Jet technology is used for cutting several materials by erosion under the impact of accelerating particles on the material. This leads to consider that the amount of eroded material should be proportional to kinetic energy of abrasives then to their velocity at impact. The control of this parameter is of a great importance for cutting and optimization process, but this fact is a troublesome operation, since the penetration of low velocty particles into the high velocity of water jet is not easily accomplished in either the mixing chamber or mixing tube. However a theoretical acceleration process is established in (Tazibt, 1995) for estimating a particle velocity at impact in some conditions of jet formation such as hydraulic pressure of water, abrasive mass flow rate, nozzle diameter...

This paper presents the results of a theoretical development for cutting process which takes place in the cut wear zone (Hashish, 1984) also called by the linear zone of cut (Nadeau, 1991). This development is based on some experimental considerations in which the particle velocity is estimated theoretically at a practical distances of impact and also where effect of air is considered (Tazibt, 1994). It describes a new method of modelling concerning the cutting process without considering any micro-erosion theory. The theoretical data consists on that abrasive velocity estimated in (Tazibt, 1995) at impact, while others parameters are given experimentally. As a result, the depth of cut and the traverse rate are estimated in the linear zone of cut as functions of the estimated particle velocity at impact and of some others working parameters.

2. BASIC IDEA

One can see that experiment (Finnie, 1978), (Hashish, 1984) and (T, 1995) leads to a linear dependance between hydraulic pressure and removal volume flow rate, Figure 1. As shown in Figure 2, the curve is characterised by two remarkable points (A) and (B) which translate a partial cutting phenomenon. The first point corresponds to a *threshold pressure* and the second one designes a *specific amount of removal material.*

Hydraulic pressure times removal volume flow rate of cut material gives a physical quantity which is compatible with power. The way in which that power should be considered as a cutting one consists to take a pressure as an internal variable (section 3) like the removal volume flow rate of cut material. Cutting power represents a part of the kinetic power of abrasives at impact and the difference is lost by the inpingment of some particles on the upper surface of the workpiece. This consideration allows us to assume that, ideally, all of particles kinetic power is used for cutting so abrasive particle velocity must be linked with removal flow rate of cut material by means of an experimental correlation which leads a predicted depth of cut.

Threshold pressure represents a minimum hydraulic pressure that waterjet should have to provide particles a minimum kinetic power which is required for starting the cutting process. This correspends to the pressure $P0$ for which removal flow rate remains equal to zero. Therefore, when hydraulic pressure is equal to zero, the corresponding removal flow rate of cut material is equal to a *specific removal flow rate* which has not a physical signification. This new parameter is virtual and remains available as much as a cut material does not present any resistance against particles impacts.

3. EQUIVALENT INTERNAL CONSTRAINT

Experimental results on cutting show that for each abrasive mass flow rate m_{1a}, it corresponds a specific removal mass flow rate m_{1r0}, Figure 2. This constatation translates the interaction between the internal characteristics of the cut material and the accelerating particles. This aspect leads to introduce an internal parameter which is denoted, here, by the *equivalent internal constraint* σ instead of hydraulic pressure P, in the following equations. While the explicit expression of σ is still unknown, its foundamental knowledge is not required in this study. Then from a previous experimental constatation, one can write the global (or macroscopic) expression of the equivalent internal constraint, as follows :

$$\sigma = \frac{V_{1a}}{V_{1r0}} P = \eta . P \qquad (1)$$

where

$$\eta = \frac{V_{1a}}{V_{1r0}} = \left(\frac{\rho}{\rho_a}\right)\left(\frac{m_{1a}}{m_{1r0}}\right) \qquad (2)$$

4. CUTTING POWER

4.1 Complete Mathematical Formulation and Definition

The elementary cutting power dE_{1r} is defined mathematically, here, as the product of the equivalent internal constraint differential $d\sigma$ and the total virtual volume flow rate $(V_{1r} + V_{1r0})$ which is removed by the action of $d\sigma$. Then the expression of E_{1r} can be writen as follows :

$$E_{1r} = \int_0^{\sigma} (V_{1r} + V_{1r0}).d\sigma \qquad (3)$$

then

$$E_{1r} = \frac{1}{\rho}\int_0^{\sigma} (m_{1r} + m_{1r0}).d\sigma \qquad (4)$$

Considering relation (1) since V_{1a} and V_{1r0} are constant as well as η, the expression (4) can be writen as

$$E_{1r} = \frac{\eta}{\rho}\int_0^{P} (m_{1r} + m_{1r0}).dP \qquad (5)$$

Therefore, experiment deals a linear dependance between m_{1r} and P, so as it is shown in Figures 1 and 3, the equation of a such experimental curve can be consistent to

$$m_{1r} = \alpha_p . P - m_{1r0} \tag{6}$$

Considering relation (6), equation (5) becomes :

$$E_{1r} = \frac{\eta}{\rho} \int_0^P \alpha_p . P . dP \tag{7}$$

then

$$E_{1r} = \frac{\eta}{2\rho} \alpha_p . P^2 \tag{8}$$

and if we consider again relation (6), expression (8) becomes :

$$E_{1r} = \frac{\eta}{2\rho} (m_{1r} + m_{1r0}) P \tag{9}$$

Equations (8) and (9) represent the complete mathematical definition of the cutting power. They translate geometrically the sum of three areas specified by 1, 2 and 3 in Figure 3.

4.2 Linearizattion

The representative parabolic curve of the equation (8) of cutting power is very open and positive. So its opproximation by means of a straight line, which is determined following the "lesser squares" method for $P \in (0, P_m)$, leads to a less important error. The equation of a resulting straight line is then derived by linearization as specified previously and it is found :

$$E_{1r} = \alpha_1 . P - \beta_1 \tag{10}$$

where $\alpha_1 = \frac{\eta}{2\rho} \alpha_p . P_m$ and $\beta_1 = \frac{\eta}{12\rho} \alpha_p . P_m^2$

One can see that the new expression (10) of cutting power has the advantage to translate the linear dependance between hydraulic pressure and power according to the literaure review. According to experimental results of kerfing, the linear function between removal mass flow rate m_{1r} and hydraulic pressure P leads to write the following expression. So from equation (6) and after simplification, expression (10) becomes

$$E_{1r} = \left(\frac{\alpha_1}{\alpha_p} \right) . m_{1r} + \left[\left(\frac{\alpha_1}{\alpha_p} \right) . m_{1r0} - \beta_1 \right] \tag{11}$$

It is clear that the new relation (11) reveals that cutting power is depending only of experimental parameters, nevertheless this expression is derived mathematically. In addition, this realtion represents the equation of a straight line of the cutting power E_{1r} verus removal mass flow rate m_{1r}, Figure 4. While the knowledge of the variable m_{1r} is always accessible experimentally, cutting power E_{1r} can be estimated consequently.

5. ADDED POWER

It is called, here, by added power E_{1r0} the area of the triangle which is drawn under the abscisses axis of Figure 5. In fact, added power translates a kind of material resistance against the abrasive particles impacts. That is to say, matrial starts to be eroded by wear when the added power is overpassed. As a first important result, added power can be calculated analytically considering either removal mass flow rate m_{1r} as equal to zero or the hydraulic pressure P as equal to threshold value $P0$, respectively, in the expressions (11) and (10) of cutting power.

We obtain, in the first case, the following expression of added power E_{1r0} of cut :

$$E_{1r0} = \left(\frac{\alpha_1}{\alpha_p}\right).m_{1r0} - \beta_1 \qquad (12)$$

The relation above represents approximatively the area of the triangle 1 drawn in figure 3.

6 EFFECTIVE POWER

Effective power, E_{1rE} , is defined as that part of cutting power which is drawn in a positve triangle area 3, Figure 3. While its physical signification is still ignored, the knoweledge of this power is of a great importance for calculations. Following the geometrical representation and for $P > P0$, a mathematical expression of effective power is given by :

$$E_{1rE} = \frac{\eta}{2\rho} m_{1r} (P - P0) \qquad (13)$$

7. TRANSITIONAL POWER

When added power is consumed, a cut material reactive changes suddenly; that is represented by the rectangle area 2, Figure 5. A such resulting power is called by Transitional power E_{1rT} because it makes a bridge between added power and effective one. For $P > P0$, its mathematical expression is derived geometrically as

$$E_{1rT} = \frac{\eta}{\rho} m_{1r0}(P - P0) \qquad (14)$$

8. SPECIFIC ENERGY

It is called by specific energy ε, the amount of energy that is required to remove a unit of mass of material when this last is subject to erosion by abrasive particles impacts. Specific energy represents geometrically the slope of the straight line of cutting power variation as function of removal mass flow rate, which is drawn in Figure 4 using equation (11). So, it follows the analytical expression of a specific energy ε :

$$\varepsilon = \frac{\alpha_1}{\alpha_p} = \frac{E_{1r1} + \beta_1}{m_{1r} + m_{1r0}} = \frac{1}{2\rho_a}\left(\frac{m_{1a}}{m_{1r0}}\right) P_m = \frac{\eta . P_m}{2\rho} \tag{15}$$

If we put : $e_{1r} = E_{1r} + \beta_1$ and $M_{1r} = m_{1r} + m_{1r0}$,

then

$$e_{1r} = \varepsilon . M_{1r} \tag{16}$$

e_{1r} and M_{1r} are, respectively, the global cutting power and the total virtual removal mass flow rate.

9. EXPERIMENTAL CORRELATION

Since a material is cut by wear when the accelerated abrasives hit the workpiece, the origin of cutting power should be necessary from kinetic power of particles at impact. However, a part of kinetic power must be lost by inpingment on the top surface of workpiece. Nevertheless, in first approach, it seems logical to assume that the entire kinetic power of abrasives at impact is wasted to remove material in the linear zone of cutting wear. In others terms, the kinetic power becomes as cutting one, after attack. This assumption makes possible to consider that these two forms of power are the same.

So :

$$E_{1r} = E_{ac} = \frac{1}{2} m_{1a} . V_{ac}^2 \tag{17}$$

after substituting $E1r$ by its expression (11) in (17), one can write :

$$\left(\frac{\alpha_1}{\alpha_p}\right) . m_{1r} + \left[\left(\frac{\alpha_1}{\alpha_p}\right) . m_{1r0} - \beta_1\right] = \frac{1}{2} m_{1a} . V_{ac}^2 \tag{18}$$

According to experiments (Tazibt, 1995), slope of the experimental line of removal mass flow rate as function of hydraulic pressure, is changing proportionally following abrasive mass flow rate, Figure 1. Then :

$$\alpha_p = \frac{m_{1a}}{m_{1ap}} \alpha_{ap} \tag{19}$$

Considering relation (2) and (19) , we obtain from (18) :

$$m_{1r} = \frac{\rho.m_{1a}}{\eta.P_m} V_{ac}^2 - \frac{\rho.m_{1a}}{\eta.\rho_a} + \left(\frac{m_{1a}}{6}\right)\left(\frac{\alpha_{ap}}{m_{1ap}}\right).P_m \tag{20}$$

The relation above represents the ***experimental*** ***correlation*** between the removal mass flow rate m_{1r} of cut material and abrasive particle velocity V_{ac} which is estimated theoretically, in (Tazibt, 1994), at impact for hydraulic pressure P and others fixed conditions of abrasive water jet formation.

10. CORRELATING VELOCITY OF PARTICLE AT IMPACT

An interesting result that can be gathered from equation (20) consists to express a correlating velocity V_{ap} of a particle at impact for a given experimental removal mas flow rate m_{1r} , as follows :

$$V_{ap} = \sqrt{\frac{\eta.P_m}{\rho.m_{1a}}\left[m_{1r} + \frac{\rho.m_{1a}}{\eta.\rho_a} + \left(\frac{m_{1a}}{6}\right)\left(\frac{\alpha_{ap}}{m_{1ap}}\right).P_m\right]} \tag{21}$$

Equation (21) is used for the comparison between the theoretical particle velocity V_{ac} at impact with V_{ap} in the same and real conditions of jet foramtion and operating.

11. CORRELATING DEPTH OF CUT

The first important consequence of the experimental correlation consists on that possibility to express depth of cut from the removal mass flow rate because depth of cut is a cutting parameter which is accessible experimentally and translating some important informations about the interaction between the abrasive water jet and a cut material.

Before expressing a correlating depth of cut H, it seems obvious to set a relation between this experimental parameter and the removal mass flow rate. This procedure needs the set of the approximative removal volume which is obtained from the shallow kerf performed during the time $(T_f - T_i)$ of cutting operation. Based on these consideration, the examination of several geometrical shapes of experimental shallow kerfs leads to the following reasoning : If $\Omega 3$ is the cross sectional area of a shallow kerf, the volume V_k of a such kerf is given by:

$$V_k = V_{1r}\,(T_f - T_i) = u\,(T_f - T_i).\Omega_3 \tag{22}$$

where T_f and T_i are, respectively, the final and initial time of kerfing.

The real cross sectional area of a kerf is approximated by considering the medium between rectangular and triangular areas, respectively, $\Omega 1$ and $\Omega 2$. So as it is shown in Figure 5, it follows :

$$\Omega_3 = \frac{\Omega_1 + \Omega_2}{2} \tag{23}$$

but all kerfs presented widths D that are *20 %* less than jet or mixing tube diameter d, so the substitution of D by $(0.8\, d)$ makes :

$$\Omega_3 = 0.6 H d \tag{24}$$

The removal volume flow rate V_{1r} is gathered from relation (24) as follows :

$$V_{1r} = u\,\Omega_3 = u(0.6 H d) \tag{25}$$

The removal mass flow rate m_{1r} is then given by :

$$m_{1r} = \rho V_{1r} = \rho u (0.6 H d) \tag{26}$$

then

$$H = \left(\frac{1}{(0.6\rho d) u} \right) m_{1r} \tag{27}$$

The expression of a correlating depth H of cut is immediatly gathered from relation (20) by substituting m_{1r} and, after simplification, one can write

$$H = \frac{1}{(0.6\rho\, d)\, u} \left[\frac{\rho . m_{1a}}{\eta . P_m} V_{ac}^2 - \frac{\rho . m_{1a}}{\eta . \rho_a} + \left(\frac{m_{1a}}{6} \right) \left(\frac{\alpha_{ap}}{m_{1ap}} \right) . P_m \right] \tag{28}$$

The expression (28) provides more practical informations about cutting process and control in a such cutting system. In addition, a simplified number of parameters involved makes easy a mathematical representation of depth of cut, since theoretical abrasive particle velocity V_{ac} at impact is estimated accuratly by the acceleration model.

12. CORRELATING TRAVERSE RATE OF CUT

Among the greatest number of parameters involved, traverse rate is one of the most important for operating because its control provides accuracy in cutting process. That is to say, for given parameters concerning the mixing and acceleration process (pressure, abrasive mass flow rate, nozzle diameter...) and those of cut material, kerfing must be successfull until a wellknown depth while traverse rate is fixed correctly. A depth of cut H and traverse rate u are linked together by relation (27), then

$$u = \left(\frac{1}{0.6\rho\, d\, H} \right) m_{1r} \tag{29}$$

Then, from expression (28), we can write also the expression of traverse rate u, as follows :

$$u = \frac{1}{(0.6\rho\, d) H} \left[\frac{\rho . m_{1a}}{\eta . P_m} V_{ac}^2 - \frac{\rho . m_{1a}}{\eta . \rho_a} + \left(\frac{m_{1a}}{6} \right) \left(\frac{\alpha_{ap}}{m_{1ap}} \right) . P_m \right] \tag{30}$$

The expression (30) deals a correlating traverse rate of cut for some fixed conditions of abrasive water jet formation and type of cut material.

13. EXPERIMENTAL INVESTIGATIONS

Experiments consist on making shallow kerfs in steel material specimens. The depths of all of the kerfs did not exceed *7 mm* in order to minimize the friction along the cut surface of the kerf. Hydraulic pressure of waterjet was supplied from a system which is built from a standart Flow Systems Inc. The component of a such system included a filtering unit, a hydraulic cylinder pump, an intensifier and an accumulator which provides a constant high pressure water supply to the nozzle fom which waterjet exits with a high velocity. The range of hydraulic water pressure was of *140* to *240 MPa* and velocity of water at the nozzle exit was about *400* to *700 m/s*.

Each kerf was performed for given hydraulic pressure of water and traverse rate. The depth of cut so obtained was measured and the value compared to that one estimated by the relation (28) of a correlating depth of cut. Experimental results were obtained for some specimens which were placed at a distance of *4 mm* downstream of a carbide mixing tube of *70 mm* long. Figure 1 shows some experimental results of the evolution of removal volume flow rate as function of hydraulic pressure.

A complete presentation of experimental device and experimental data are in (Tazibt, 1995). Nevertheless, a range of an important experimental results are reported in this study and that should be widely sufficient to give a proof of the present modelling's capability to predict either traverse rate or depth of cut for given conditions of working. In fact, experimental results of depth of cut are near theoretical ones. However, the accuracy of modelling is influenced by the amount of abrasives that takes place in the jet. This fact can be explained by the efficiency phenomenon which is detailed in (Tazibt, 1995) : *great is the number of particles in the jet, less is the proportion of active particles which are able to erode a material because of their collision between themselves at impact.* This aspect is available while the abrasive mass flow rate is greater than the optimum. In the present case, the optimum of abrasive mass flow rate is found experimentally around *250 g/mn*.

14. NUMERICAL SIMULATIONS AND DISCUSSION

In Figure 6, one can see that cutting power is drawn under kinetic power of particles at impact. The difference between these two forms of power is of *25 W* providing a lag of *30 m/s* between theoretical and experimental velocity of particles at impact. This value is not important compared to the range of higher velocities that are used in a such cutting system. The constatation above is confirmed in Figure 7 where a curve of a correlating velocity of particles is approaching asymptotically theoretical one. The simulation allows us, also, to quantify an important parameter which consists on that Specific energy, ε, of cut. This parameter is found sensitively near 1.1×10^6 *J/Kg* for the real conditions of jet formation and operation. In addition, a minimum possible power is required for erosion process; that is represented also by the added power which is equal, respectively, to *39.2 W* and *90.2 W* for *146 g/mn* and *298 g/mn* of abrasive mass flow rates.

On the other hand, the experimental results show that for an abrasive mass flow rate of *146 g/mn* , it must be developed a threshold pressure of *90 MPa* and removed a specific mass flow rate of *3.8 g/mn*. Also, for an abrasive mass flow rate of *298 g/mn*, it must be developed a threshold pressure of *107 MPa* and removed a specific mass flow rate of *7.7 g/mn*. However, a predicted curve is drawn between the previous two experimental ones; so for an abrasive mass flow rate of *250 g/mn*, it is expected both threshold pressure of *103 MPa* and a specific removal mass flow rate of *6.8 g/mn*.
As a conclusion, both threshold pressure and specific removal mass flow rate are increasing when abrasive mass flow rate increases. This fact can be explained as follows : when abrasive mass flow rate becomes greater, the amount of particles is increasing in the jet, so a velocity of each particle will decrease for a given hydraulic pressure of water and consequently more threshold pressure should be required for starting cutting process. This consideration translates the increasing removal specific mass flow rate of cut material.

The expressions (28) and (30), respectively, of depth of cut and traverse rate provide plotted results for dicussion. In fact, for some fixed working conditions and for abrasive mass flow rate of *146 g/mn*, Figures 8 and 9 show that the variation of these two parameters as function of hydraulic pressure is linear according to those results obtained in the literature. Obviously, only positive field is considered in these two figures.

15. CONCLUSION

Based on this original and simple approach, a general experimental correlation is established from which both correlating depth of cut and traverse rate expressions are derived. The resulting cutting modelling accuracy is improved since a particle velocity at impact, a foundamental parameter, is estimated by a theoretical accurate acceleration model which is developed in (Tazibt, 1995). In addition, the present work allowed us to define new parameters and notions such as specific removal flow rate of cut material, abrasive optimum mass flow rate, added power, transitional power, effective power and a global equivalent internal constraint. These new notions should make rich a vocabular encountered in the field of cutting by Abrasive Water Jet system.

Finally, the present study provides more control for cutting operation in the linear (cut wear) zone of cut so the optimization of working and operating parameters is improved. Therefore, a work to make in the future consists on the establishment of an experimental correlation which includes a large range of materials and types of abrasives in the linear zone of cut, and also initiate a similar work for analysing cutting process which occurs in the non-linear zone of cut or transition zone.

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NOMENCLATURE

D	kerf width
d	mixing tube or jet diameter
Eac	particles kinetic power at impact
E1r	cutting power
E1r0	Added power
E1rE	Effective power
E1rT	Transitional power
H	depth of cut
m1a	abrasives mass flow rate of working
m1ap	abrasives mass flow rate used experimentally
m1w	water mass flow rate
m1r	removal mass flow rate of cut material
P	Hydraulic pressure of water
u	traverse rate of cutting
V	volume of abrasive particle
Vac	abrasive particle velocity at impact
V1r0	specific removal volume flow rate of cut material
σ	equivalent internal constraint
αp	slope
αap	slope used experimentally
β	volumic fraction of void
ε	specific energy
η	Coefficient of abrasive-material interaction
ρ	volumic mass of cut material
ρa	volumic mass of abrasives
ρw	volumic mass of water

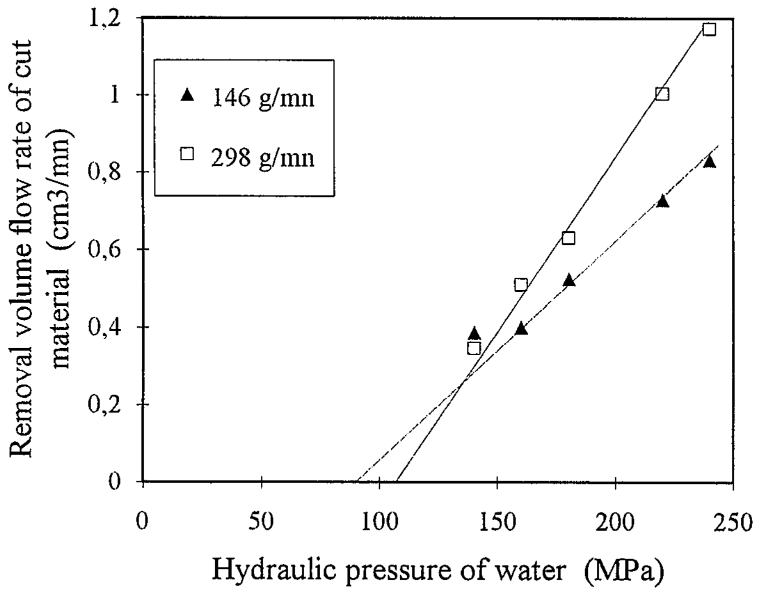

Figure 1 : Some experimental results on the evolution of removal flow rate of cut material as function of hydraulic pressure of water for the real conditions of jetformation.

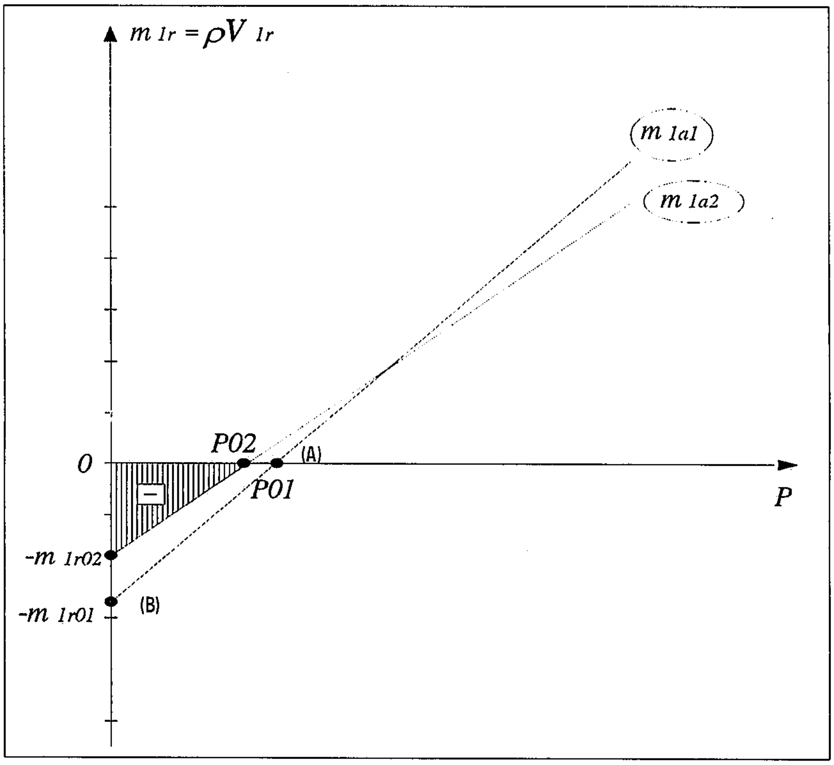

Figure 2 : Extrapolated representation of the evolution of removal mass flow rate of cut material as function of hydraulic pressure of water for different abrasive mass flow rates.

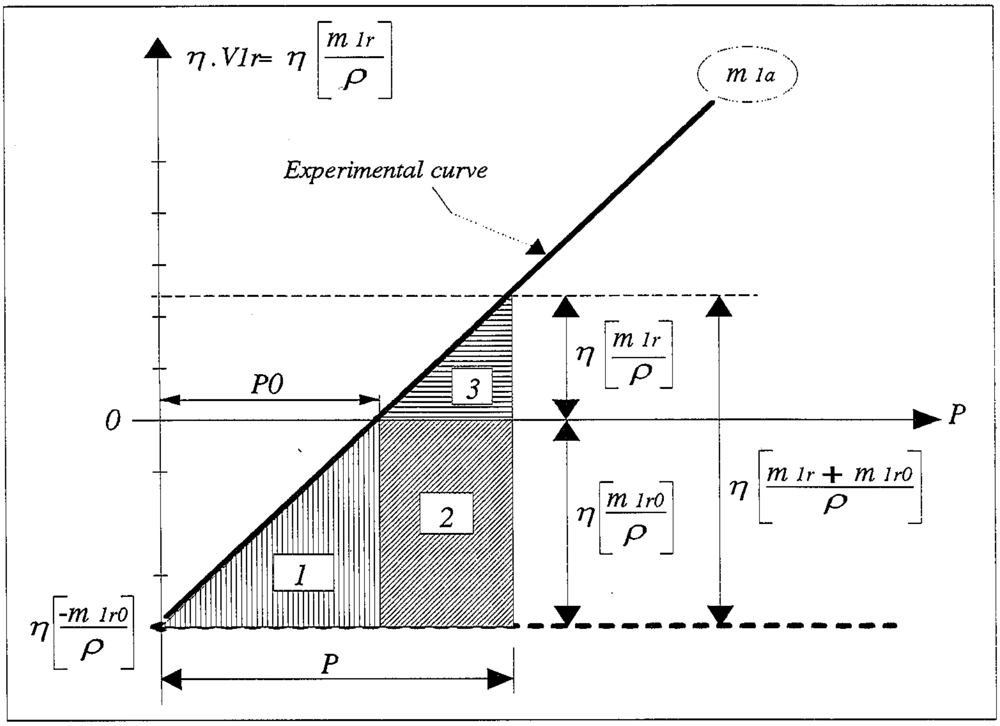

Figure 3 : Geometrical representation of cutting power and identification of both added (area 1) and transitional (area 2) and effective (area 3) powers.

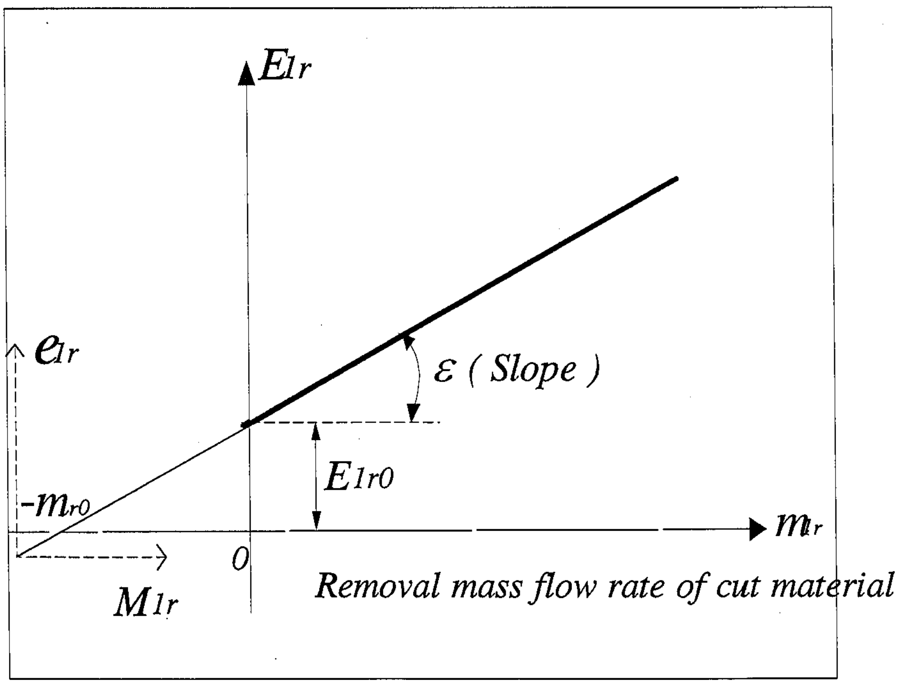

Figure 4 : Schematization of the evolution of cutting power as function of removal mass flow rate of cut material and identification of a specific energy ε.

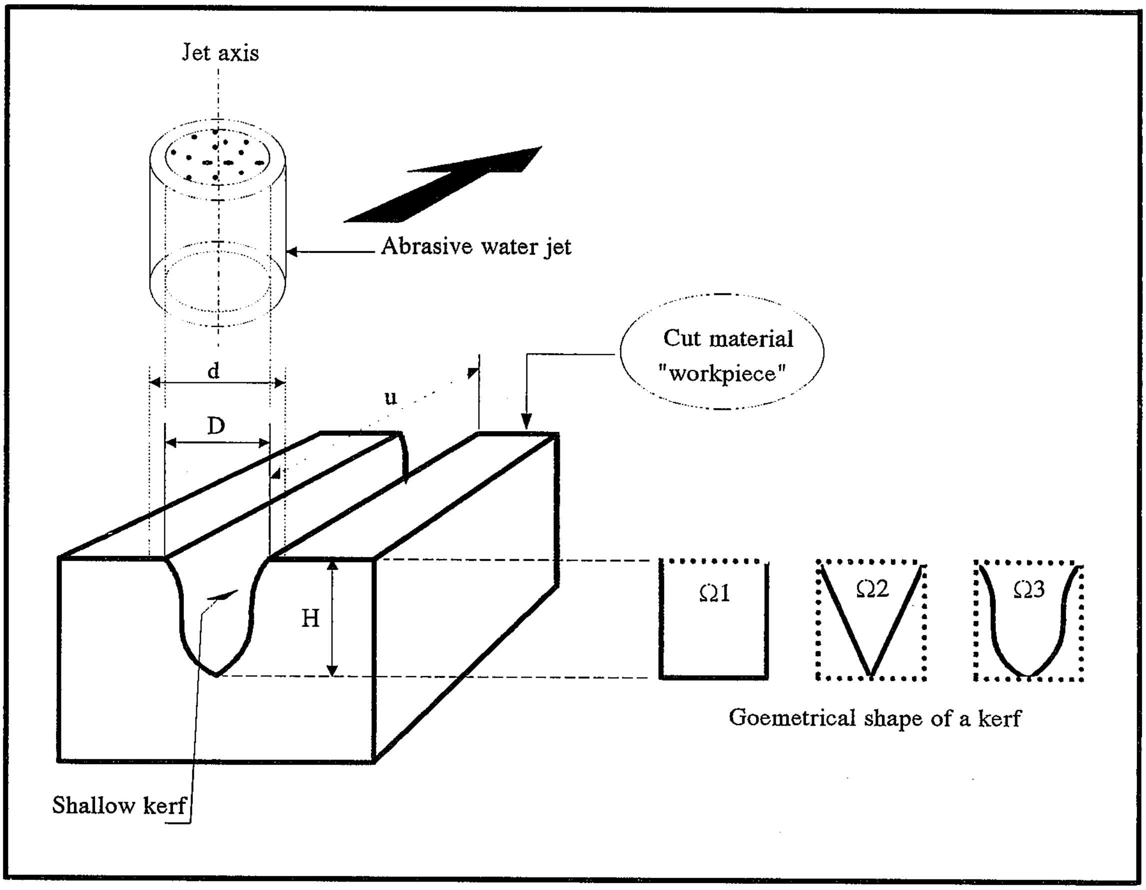

Figure 5 : Approximated experimental shape of a shallow kerf.

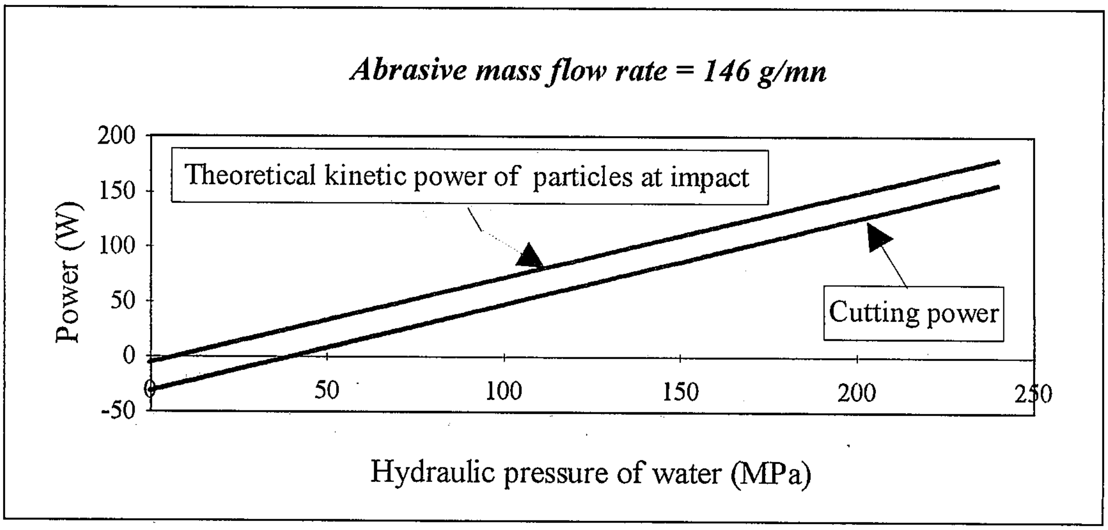

Figure 6 : Estimation of evolution of both theoretical particles kinetic power at impact and cutting power as function of hydraulic pressure of water, for the real conditions of jet formation.

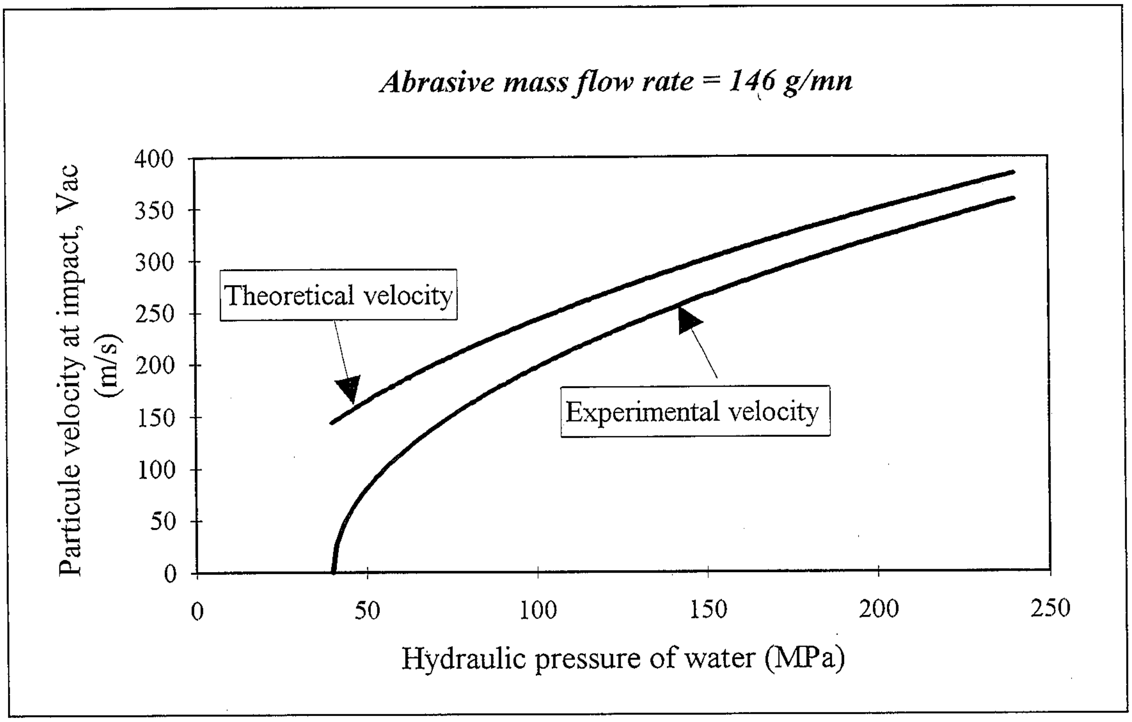

Figure 7 : Comparison between estimated theoretical particle velocity at impact and experimental one estimated by the experimental correlation for some real conditions of jet formation.

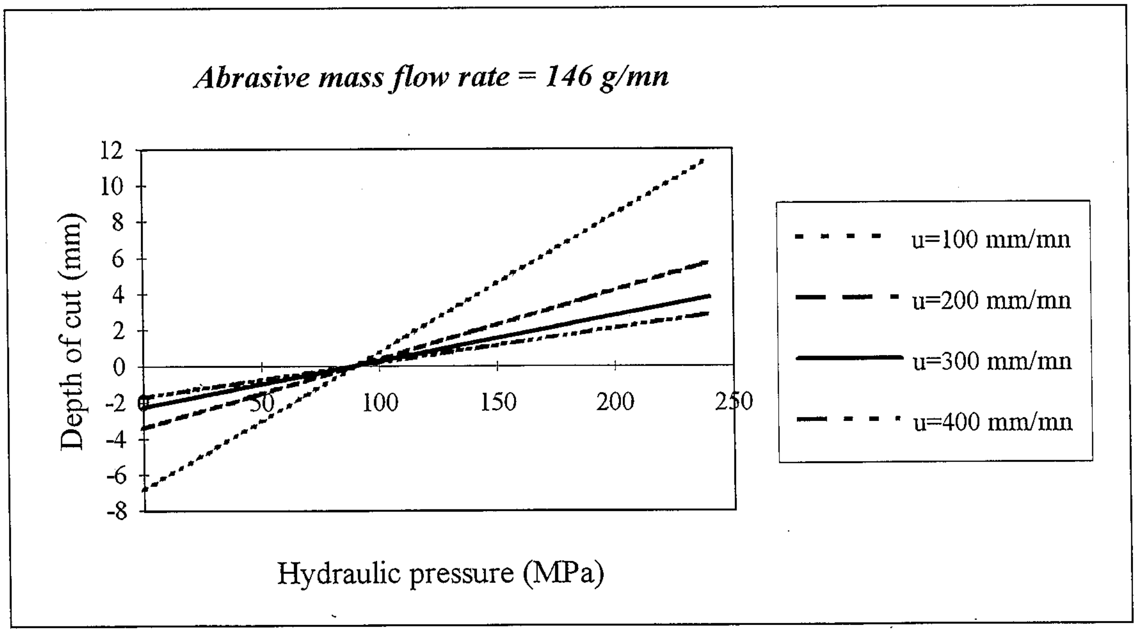

Figure 8 : Estimated evolution of depth of cut as function of hydraulic pressure.

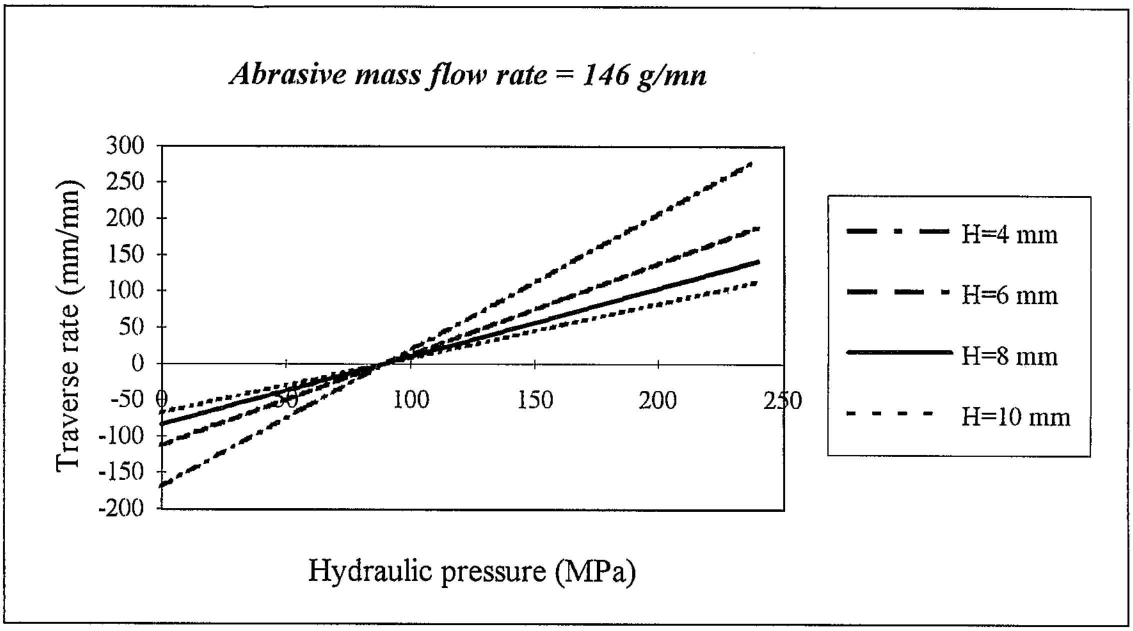

Figure 9 : Estimated evolution of traverse rate as function of hydraulic pressure.

P (MPa)	variable	distance of impact, *Xc (mm)*	68
m_{1a} *(g/mn)*	variable	traverse rate, *u (mm/mn)*	variable
D_a *(mm)*	0.25	depth of cut, *H (mm)*	variable
Nozzle diameter *(mm)*	0.3	ρ *(Kg/m³)*, ductile steel	7800
d (mm)	1.2		
ρ_a *(Kg/m³)*	4140		
ρ_w *(Kg/m³)*	1000		

Table 1 : Data used in simulations.

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Paper 14

EXPERIMENTAL ESTIMATION OF ENERGY DISSIPATIVE PROCESSES IN WORKPIECES DURING ABRASIVE WATER JET CUTTING

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ABSTRACT

Energy dissipative processes play a key role in abrasive water jet machining of materials. They influence the economical and qualitative parameters of the process, such as specific energy and striation formation. This paper describes experimental methods developed by the authors to detect and evaluate energy dissipative processes in workpieces cut by abrasive water jets. A physical model is introduced to define and separate the different portions of the energy dissipation process, such as heat generation, erosion debris generation, water and solid mixture film damping, and wall friction. In the second part of the paper, the experimental methods and preliminary results obtained by using them are reported. The application of infrared thermography, impact force measurements of abrasive water jets and single particles, erosion debris size analysis, and fracture mechanics experiments are described in detail.

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1. INTRODUCTION

The application of abrasive water jets to process materials is one of the most recently introduced machining methods. Using this method it is possible to cut all technical materials, including ceramics (Hochheng and Chang, 1994), alloys, and composite materials (Momber, 1994). As shown by Laurinat et al. (1993) abrasive water jets also have the capability for milling and 3-D machining of materials. The tool is formed by accelerating abrasive particles, usually garnet and aluminum oxide, with diameters typically between 100 µm and 500 µm, through contact with a high velocity plain water jet. The mixing between abrasives, water, and air takes place in a mixing chamber, whereas the acceleration process happens in an acceleration tube, or abrasive waterjet nozzle. The abrasive particles leave this nozzle with velocities of several hundred meters per second. A high number of abrasives (about 10^5 per second) leads to a high frequency impingement on the processed surfaces (Momber, 1993). Because of the small diameter of the acceleration nozzle (typically 0.5-2 mm) the abrasive water jet acts like a streamlike tool, similar to a laser or an electron beam, which is characterized by an unsteady material removal process in regard to the depth of cut. So the most pronounced characteristics of surfaces generated by abrasive water jets is the presence of striation marks which transpire below a relatively smooth region as shown in Fig. 1. The origin of these striations is a controversial issue. Based on high speed photographs taken of transparent materials, the idea of two different material removal mechanisms, called "cutting wear" and "deformation wear," is introduced (Hashish, 1988, and Blickwedel, 1990). In the zone of the "cutting wear" the solid particles strike the material surface at shallow angles producing a relatively smooth cutting surface. In the "deformation wear" zone, unsteady removal with striation marks results from erosive wear due to particles impacting at large angles of attack. In contradiction to these findings, Chao et al. (1993) discussed the unsteady removal process as a result of external disturbances, such as machine vibrations. But this concept does not cover observations on hard to machine materials (Hashish, 1992). The idea of two different material removal modes is also rejected by Arola et al. (1993) who found that the removal mechanism is independent of the depth of cut for a given material. The mechanisms may be different for different materials. These authors define a "smooth cutting" zone at the upper part of the cutting area and a "rough cutting" zone at the lower part. They suggest that a critical kinetic energy of the high-speed slurry flow exists which has to undercut to produce striations on the cutting surface. A similar idea is introduced by Zhou et al. (1991), based on roughness measurements. Raju and Ramulu (1994) have shown that in fact a relation exists between the kinetic energy of the abrasive water jet kinetic energy and the transition point between smooth cutting to rough cutting.

A major contribution to this discussion may be the quantification of the different energy dissipation processes in the workpiece during the abrasive water jet cutting, which would allow the evaluation of the energy distribution in the workpiece at any depth of cut. This paper presents a physical model and experimental methods which were developed to quantify the energy dissipation during the cutting of materials by abrasive water jets.

2. MODELING OF THE ENERGY DISSIPATION IN A WORKPIECE

The kinetic energy of the abrasive water jet entering the workpiece can be estimated using Eq. (1).

$$E_S = \tfrac{1}{2} \cdot m_S \cdot v_S^2 \tag{1}$$

With $m_S = (\dot{m}_P + \dot{m}_W) \cdot t$ and $t = \frac{d_F}{v}$ one obtains

$$E_S = \frac{d_F}{2 \cdot v} \cdot (\dot{m}_P + \dot{m}_W) \cdot v_S^2 . \tag{2}$$

Using a momentum transfer between the water jet in the mixing chamber and the incoming solid particles, the velocity of the abrasive water jet after mixing can be expressed by

$$v_S = \alpha \cdot \frac{v_W}{1 + \frac{\dot{m}_P}{\dot{m}_W}} . \tag{3}$$

Here, α is a mixing efficiency coefficient which can be estimated by force measurements. Typical values measured by the authors are between α = 0.6-0.7. They depend on the applied pump pressure and the abrasive flow rate. The velocity of the plain water jet, which is formed in an orifice can be approximated by applying Bernoulli's law of pressure constancy which yields

$$v_W = \varphi \cdot \sqrt{\frac{2 \cdot p}{\rho_W}} . \tag{4}$$

Here, the parameter φ characterizes the energy transfer in the orifice and can be estimated by measuring the water jet impacting forces, too. A combination of Eqs. (1)-(4) leads to Eq. (5).

$$E_S = \frac{\alpha^2 \cdot \varphi^2 \cdot d_F \cdot (\dot{m}_P + \dot{m}_W) \cdot p}{\left(1 + \frac{\dot{m}_P}{\dot{m}_W}\right)^2 \cdot v \cdot \rho_W} \tag{5}$$

This energy is supplied into the erosion process and is dissipated by different mechanisms. Primarily, this energy dissipation is due to the generation of debris particles, E_M, the friction on the cutting front, E_F, the damping of the slurry due to a water-solid film on the cutting front, E_D, and the heat generation, E_H. A simple expression for the amount of the abrasive water jet input energy which contributes directly to these processes in the workpiece is based on the assumption that part of the abrasive water jet input energy leaves the material after the cutting process as shown in Fig. 2. The difference between input energy and exit energy which is given by

$$E_{Diss} = E_M + E_F + E_D + E_H = E_S - E_{ex}, \tag{6}$$

is identical to the energy which is dissipated in the workpiece during the cutting process. By keeping the input energy constant the value of this energy depends only on the depth of cut. This is expressed by

$$E_{Diss}(h) = \chi(h) \cdot [E_S - E_{ex}]. \tag{7}$$

It is shown in many abrasive water jet cutting experiments that the cutting process is characterized by a critical process parameter, the threshold pressure, p_{thr}, which has to be exceeded to initiate the material removal process (Momber, 1993). It is assumed here that this critical pressure can characterize the exit energy of the abrasive water jet because the jet leaves the workpiece only if it is not able to remove more material. The threshold pressure can be estimated experimentally by plotting the depth of cut versus the applied pump pressure. Combining this assumption with Eqs. (5) and (7) one can write

$$E_{Diss}(h) = \chi(h) \cdot \frac{\alpha^2 \cdot \varphi^2 \cdot d_F \cdot (\dot{m}_P + \dot{m}_W)}{v \cdot \left(1 + \frac{\dot{m}_P}{\dot{m}_W}\right)^2 \cdot \rho_W} \cdot [p - p_{thr}] = \chi(h) \cdot K \cdot [p - p_{thr}]. \tag{8}$$

This equation gives the amount of energy which is dissipated in the workpiece during the cutting process at any particular depth of cut, h. The parameter χ is assumed here to describe different mechanisms of energy dissipation:

- energy dissipation due to erosion debris formation, M,
- energy dissipation due to friction on the cutting front, F,
- energy dissipation due to water-solid particle film damping on the cutting front, D, and
- energy dissipated in heating the workpiece, H.

Thus, $\chi(h)$ can be written:

$$\chi(h) = M(h)+F(h)+D(h)+H(h) \quad \text{or} \tag{9a}$$

$$\chi(\Phi) = M(\Phi)+F(\Phi)+D(\Phi)+H(\Phi), \tag{9b}$$

where Φ is the relative depth of cut, $\Phi = h/h_{max}$, as illustrated in Fig. 2. The relative depth of cut is used here to unify the results. For $\Phi = 1$ one obtains $\chi(\Phi) = 1$ which means that the entire energy E_{Diss} is dissipated during the cutting process and the maximum possible depth of cut is achieved. The following chapters contain different experimental methods developed by the authors to estimate the functions $\chi(h)$, $H(\Phi)$, $M(\Phi)$, $D(\Phi)$, and $F(\Phi)$.

3. EXPERIMENTAL ESTIMATION OF THE ENERGY DISSIPATION FUNCTION χ(h)

The idea of using the geometry of the cutting front to estimate the energy dissipation functions $\chi(h)$ and $\chi(\Phi)$ is introduced by Momber et al. (1994). The basic assumption of this concept is given in Fig. 2. The cutting front can mathematically be modeled by a parabolic function (Zeng et al., 1991, and Momber et al., 1994). The area A_0 in Fig. 2 can be calculated using Eq. (10).

$$A_0 = [b \cdot c] - \int_0^b [a \cdot (x-b)^2 + c] dx \tag{10}$$

Here, c = h_{max}. It is assumed that A_0 characterizes all energy losses up to the maximum possible depth of cut, h_{max}, under the given cutting conditions. This area is defined as A_0 = 1. The energy dissipated in the workpiece up to any other certain depth, h, is simply given by the occupied area A(h), with $0 \leq A(h) \leq 1$. The energy dissipation function is now given by

$$\chi(h) = \frac{A(h)}{A_0} = \frac{A(h)}{A(h_{max})}. \tag{11}$$

It can be seen that $\chi(h) = 0$ for h = 0, and $\chi(h) = 1$ for h = h_{max}. The mathematical and experimental methods to solve Eq. (11) are discussed by Momber and Kovacevic (1995) and Momber (1995). Fig. 3 shows the relation between the relative depth of cut, $\Phi = h/h_{max}$, and the energy dissipation parameter, χ, calculated using Eq. (11). For $\Phi = 1$ ($h = h_{max}$) one obtains $\chi(\Phi) = 1$ which means that the entire energy E_{Diss} is dissipated during the cutting process and the maximum possible depth of cut is achieved. Between $\Phi = 0$ and $\Phi = 1$, the relation is non-linear and progressively increasing. The energy dissipation function follows a second order polynomial according to Eq. (12a)

$$\chi(\Phi) = A_1 \cdot \Phi^2 + B_1 \cdot \Phi + C_1, \tag{12a}$$

or, alternatively,

$$\chi(\Phi) = C \cdot (\Phi - 1)^2 + 1. \tag{12b}$$

This behavior seems to be realistic considering that the energy dissipated by friction and damping may be very low for shallow depths, but contributes significantly to the dissipated energy with increasing depth of cut. Eqs. (12a,b) do not give information on the particular energy portions dissipated by heating, damping, friction and erosion debris generation. The following chapter contains some methods developed by the authors to estimate these particular energy losses.

4. EXPERIMENTAL ESTIMATION OF THE HEAT DISSIPATED IN THE WORKPIECE, H(F)

A technique is developed using infrared (IR) thermography to determine the heat generated in the workpiece during machining with abrasive waterjet. Few highlights of this investigation are provided here from the jet energy dissipation point of view. The detailed results can be found in Kovacevic et al. (1994). Two different workpiece materials namely aluminum (Al 2024) and titanium (R58640) of similar heat capacities but different thermal diffusivities are utilized for a comparative study. The relevant workpiece properties and process parameters are given by Kovacevic et al. (1994). The experimental setup shown in Fig. 4 consists of an AWJ cutting system, an infrared system, a PC/AT with custom-developed software for thermo-image processing and the workpiece. The IR-system includes the scanner, control electronics and monitor. The test surfaces of the workpiece were coated with black enamel of emissivity 0.99 in order to ensure a constant emissivity of the surface for infrared measurement. The abrasive water jet can be considered as a moving line heat source which increases the temperature of the narrow zone along the cut wall. In order to investigate the influence of the thermal diffusivities on the temperature distribution pattern, IR images of the vertical planes which are at the same distance, d, from the kerf for both the materials are acquired. Figs. 5a and 5b give the isotherms for aluminum at a distance of 2.5 mm and 10 mm from the kerf, and Figs. 5c and 5d give the isotherms for titanium at the same distances, respectively. It can be seen that the temperature gradient and peak temperature on the plane closest to the jet is high, indicating locally concentrated heating along the kerf wall. The temperature gradients in the plane farther from the jet axis have been smoothed by heat conduction through the material. A higher peak temperature of T = 61.9 C was observed for titanium at a distance of 2.54 mm from the cut, whereas for aluminum it was T=59.6 C. However, at a distance of about 10 mm, the peak temperature on the titanium workpiece was only T = 50.4 C compared to that of aluminum which was T = 53.7C. This lower peak temperature of titanium can be attributed to its higher thermal diffusivity. It is interesting to note that in the case of titanium, two peak temperatures are present, one in the upper half and the other in the lower half of the plane under observation, indicating the presence of two different material removal modes. On the contrary, even though both wear modes exist in aluminum, only one peak temperature is observed which is at the transition zone where the second removal mode starts. This could be due to the presence of weaker striations (or better surface finish) compared to that of titanium which was observed visually on the surface. It can also be noted that for titanium, the isotherms of planes even farthest from the cut are capable of revealing the jet flow pattern. Using the two-dimensional moving line heat source model and the inverse heat conduction method as described by Kovacevic et al. (1994), the thermal energy generated per unit time in the cut during the cutting process, P_H, is determined for aluminum workpiece. The heat dissipation parameter, H, can then be estimated by

$$H = \frac{P_H \cdot t}{E_{Diss}}. \tag{13}$$

The variations of heat flux, P_H, with change in pump pressure and traverse rate are plotted in Figs. 6a and 6b, respectively. It can be noted from these figures that the heat flux at the cut increases linearly with increasing pump pressure whereas it remains almost constant with increasing traverse rate. As the pump pressure increases, the abrasive water jet velocity also increases, which in turn increases the jet normal force. This leads to higher frictional forces at the jet-workpiece interface and hence higher heat flux. As a result, the workpiece temperature also starts to increase. Even through the kinetic energy of the water jet per unit length decreases with increase in traverse rate, the heat flux which is the heat input per unit time is the same for a given abrasive material, abrasive flow rate, and pump pressure. Thus, theoretically, the heat flux in Fig. 6b should be the same for various traverse rates as all the other parameters mentioned above are constant. The marginal increase in heat flux can be attributed to the idealized assumptions adopted for the analytical model, and errors in temperature measurements. Thus, infrared thermography can be considered as a good technique to quantify the energy of the jet dissipated as heat at the cutting zone. IR-thermography is found to be a feasible technique to quantify the jet energy dissipated as heat in the cutting zone during abrasive water jet cutting.

5. EXPERIMENTAL ESTIMATION OF THE ENERGY DISSIPATED DUE TO EROSION DEBRIS GENERATION, M(F)

It is assumed that a certain amount of kinetic energy of the abrasive water jet entering the workpiece is necessary to remove a certain amount of material during the erosion. This energy involved in the generation of a certain amount of erosion debris is $E_M = M \cdot E_{Diss}$. To estimate this particular part of the dissipated energy, two different experiments have been carried out.

The first experiment is based on the assumption that the energy which is dissipated during the removal of a certain volume of material is identical to the specific fracture energy, E_{fr}, of the material. The energy E_{fr} is assumed to be the area under the stress-strain curve of the given material under compression. These relations are given by Eq. (14).

$$E_M = E_{fr} \cdot V_M = M \cdot E_{Diss} \tag{14}$$

The removed volume, V_M, can be written as

$$V_M = h \cdot [\beta \cdot f(h)] \cdot L. \tag{15}$$

For small depths of cut it is assumed that f(h) = 1. Combining Eqs. (14) and (15) gives the relation between the relative depth of cut, $\Phi = h/h_{max}$, and the energy dissipated due to material fracture

$$M(\Phi) = \frac{E_{fr} \cdot \beta \cdot L}{E_{Diss}} \cdot \Phi. \tag{16}$$

Eq. (16) suggests a linear relation between the relative depth of cut and the energy dissipated due to erosion debris generation. This enables the estimation of the complete function M(Φ) by one reference experiment on a material with a known stress-strain curve. In this experiment the workpiece is cut to a depth of $h = h_{max}$ which means $\Phi = 1$. The stress-strain curves of engineering materials are complex and, as abrasive waterjet cutting experiments on rocks have shown, a simplification of the curves yields unsatisfactory results (Matsui et al. 1991). In the present paper, the authors used concrete samples for the investigations. The stress-strain curves were estimated during eleven loading cycles under compression and fitted by a second order regression. By integrating these functions between $\varepsilon = 0$ and the ultimate strain $\varepsilon = e_{ult}$, the specific fracture energies, E_{fr}, were estimated. The energy dissipation parameter, M, was calculated using Eq. (16) for the case $h = h_{max}$, which means $\Phi = 1$. Some results are shown in Fig. 7a. The estimated values are between $M(\Phi = 1) = 0.0005\text{-}0.0045$ and depend on the material properties.

The second experiment is based on the assumption that the energy required for creating the surfaces of the erosion debris, S_M, for a material is proportional to the work of fracture, Γ. Then, the energy which is dissipated during the generation of the erosion wear particles is approximately

$$E_M = 2 \cdot \Gamma \cdot S_P = M \cdot E_{Diss} . \tag{17}$$

Under the assumption that the particle distribution of the removed erosion debris follows a RRS(B)-distribution (Kiesskalt et al., 1951), Eq. (18) enables the estimation of the energy dissipation parameter M for the case $h = h_{max}$, $\Phi = 1$, by using the distribution parameters d' and n (Momber et al., 1995)

$$M(\Phi = 1) = \frac{\Gamma \cdot 11.62 \cdot \exp\left(\frac{1.769}{n^2}\right) \cdot V_M}{d' \cdot K \cdot \left(p - p_{thr}\right)} \tag{18}$$

The authors used cast iron samples with a work of fracture $\Gamma = 4{,}500\ J/m^2$ for the cutting experiments (Waterman, et al., 1991). The removed erosion particles were collected, separated and analyzed by sieving. The distribution parameters d' and n were estimated graphically using a special RRS(B)-distribution paper (Momber et al., 1995a). Some examples for calculated M-values are plotted in Fig. 7b. For the given process conditions values between $M(\Phi = 1) = 0.005\text{-}0.0085$ were found. This is in good qualitative agreement with the results obtained by Eq. (16).

6. EXPERIMENTAL ESTIMATION OF THE ENERGY DISSIPATED DUE TO DAMPING

6.1 Damping at Single Particle Impact

It is assumed in this part of the experimentation that part of the kinetic energy of an impacting abrasive particle is dissipated by damping effects due to layers from water and wet abrasive fragments. It was shown for low impact velocities (about 5 m/s) by Zu et al. (1991) that the presence of water may improve the erosion process because the water flow removes embedded abrasive fragments as well as removed target material particles. On the other hand, Clark et al. (1992) found that the pressure required to exude a fluid from between an impinging solid particle and the target is of sufficient magnitude to reduce the impact velocity of the abrasives. For glass or quartz particles suspended in water they estimated an energy loss in the kinetic energy of about 33%. Both references cited above studied only the influence of a plain fluid film on the impact characteristics and did not consider the possible influence of layers from broken abrasive fragments and target material debris. To investigate these effects impact force measurements were carried out on single free-falling objects, such as spheres and cones with different front angles. For the impact contact analysis for spherical objects, Eq. (19) is used (Yong et al., 1995).

$$F_P(l,h_F) = K_0^{\frac{2}{5+\gamma}} \cdot \left[\frac{5+\gamma}{2} \cdot \left(M - c \cdot \sqrt{\frac{\gamma \cdot l}{h_F^{\nu}}}\right) \cdot h_F \cdot g\right]^{\frac{3+\gamma}{5+\gamma}} \tag{19}$$

The force ratio between dry and dampened impact, r_F, is given by

$$r_F = \frac{F_P(l=0)}{F_P(l,h_F)}. \tag{20}$$

Figure 8 shows the ratio, r_F, plotted versus the falling height, h_F, which may express the kinetic energy of the impacting bodies. Two features can be seen from this figure. First, the influence of the damping effect is significantly reduced at high impact energies. It can be assumed that for very high particle velocities the energy dissipated due to damping approximates a saturation value. Second, the amount of energy dissipated due to film damping depends on the shape of the impacting particles. Based on the presented results an order of sensitivity can be constructed at least for high impact velocities. Under this condition round particles are less sensitive against damping effects compared to sharp edged particles. The discussion of this effect is relegated to further investigations.

6.2 Damping at Abrasive Water Jet Cutting

Paragraph 6.1 enables the estimation of the damping parameter, D, at a given depth of cut which is characterized by a certain film composition and thickness. Global, the film thickness should increase with increasing depth of cut. However, the complete damping function, D(Φ), cannot be evaluated by these experiments. For an alternative experimental estimation, it is stated that in the case of cutting through (characterized by the symbol T) of a specimen damping effects due to a water-solid film can be neglected because the abrasive water jet can leave the workpiece at the bottom exit. The ratio between the energy of the exiting suspension, $E_{ex,T}$, and the energy of the incoming abrasive water jet, E_S, is then an expression of the energy dissipated due to wall friction, due to heating, and due to erosion debris generation. These assumptions together with Eq. (9b) produce Eq. (21).

$$M(\Phi) + F(\Phi) + H(\Phi) = \frac{E_{ex,T}(\Phi)}{E_S} = \chi(\Phi) - D(\Phi) \tag{21}$$

Solving Eq. (21) for D(Φ) gives

$$D(\Phi) = \chi(\Phi) - \frac{E_{ex,T}(\Phi)}{E_S}. \quad (22)$$

Assuming that the abrasive flow rate is constant during the cutting process (the mass flow of the removed material is very low and is neglected here) and considering the kinetic energy of the abrasive water jet according to Eq. (2), the ratio between the exit energy and the input energy can be expressed as a ratio of the square of the velocities and a ratio of the measured forces, respectively. The force of a high-speed jet is given by its impulse flow

$$F_S = \dot{I}_S = (\dot{m}_P + \dot{m}_W) \cdot v_S. \quad (23)$$

A combination of Eqs. (2), (22), and (23) yields

$$D(\Phi) = \chi(\Phi) - \left[\frac{F_{ex,T}(\Phi)}{F_S}\right]^2. \quad (24)$$

For the force measurements a four component piezo-electric dynamometer was used as shown in Fig. 9. The cutting experiments were carried out on aluminum samples. A typical plot of a measured impact force generated by an abrasive water jet during the cutting through process is given in Fig. 10. The cutting through of several samples with different thicknesses (the sample thickness is assumed to be the depth of cut) and measuring the forces of the exiting abrasive water jet can give the relation between the relative depth of cut, $\Phi = h/h_{max}$, and the energy dissipation processes at the left side of Eq. (21). The maximum possible depth of cut can simply be estimated by an additional kerfing test under the given process conditions. Results of such experiments are shown in Fig. 11. The result can be approximated by a second order polynomial. Combined with Eqs. (12a) and (24) this gives

$$D(\Phi) = (A_1 - A_2) \cdot \Phi^2 + (B_1 - B_2) \cdot \Phi + (C_1 - C_2). \quad (25)$$

The value for $D(\Phi = 1)$, ($h = h_{max}$), is obtained by using the regression parameters A_2, B_2, and C_2. Because the function $\chi(\Phi)$ must have a value of $\chi = 1$ at this point (Fig. 3) it can be concluded that about 50% of the dissipated jet energy is involved in damping. This value is higher than that estimated by Clark and Burmeister (1992) for solid particles hitting water covered plain surfaces. This is probably be due to the additional damping by fine broken solid particles distributed over the erosion site. The value of 50% is also slightly higher than the force ratio plotted in Fig. 8, indicating that particle-particle interaction may contribute to the damping process during the cutting process. The function D(Φ) shows only a small non-linearity. It has a progressive increase with the depth of cut which illuminates the fact that the friction area increases with the depth of cut. This observation is supported by the typical parabolic shape of the cutting front generated during the cutting process (Fig. 1). Thus, the damping function, D(Φ), can be estimated by a combination of cutting front measurements and impact force measurements under identical process conditions.

7. SUMMARY

The energy dissipated during the material cutting by abrasive water jets is investigated in this study. It is shown by a simple physical-mathematical model and by experiments, based on the geometry of the cutting front, that the energy dissipation can be expressed as a function of the relative depth of cut, $\Phi = h/h_{max}$, by the equations

$$E_{Diss}(\Phi) = E_M(\Phi) + E_F(\Phi) + E_D(\Phi) + E_H(\Phi) = \chi(\Phi) \cdot K \cdot [p - p_{thr}],$$
$$\chi(\Phi) = M(\Phi) + F(\Phi) + D(\Phi) + H(\Phi) = A_1 \cdot \Phi^2 + B_1 \cdot \Phi + C_1.$$

In order to separate certain physical components of the energy dissipation function, experimental methods were developed and used. To estimate the energy dissipated in heating the workpiece, H(Φ), an infrared thermography technique was applied. For the calculation of the energy dissipated during the generation of erosion debris particles, M(Φ), fracture experiments and particle distribution analyses are introduced. The energy dissipated by damping effects, D(Φ), was evaluated by impacting force measurements on single solid particles hitting surfaces, covered with water and abrasive particles, as well as force measurements on abrasive water jets during the cutting through process.

By combining the mathematical-physical model and the experimental methods discussed in the paper, it may be possible to estimate the complete characteristics of the energy dissipated in the workpiece during abrasive water jet cutting.

8. ACKNOWLEDGEMENTS

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10. NOMENCLATURE

a,b,c	cutting front regression parameters
A,B,C	regression parameters
D	damping parameter
d'	RRSB-distribution parameter
d_F	focus diameter
E_{Diss}	dissipated energy
E_D	energy dissipated due to damping
E_{ex}	AWJ exit kinetic energy
E_F	energy dissipated due to friction
E_{fr}	specific fracture energy
E_H	energy dissipated due to heating
E_M	energy dissipated due to debris generation
E_S	AWJ kinetic input energy
F	friction parameter
F_{ex}	AWJ exit reaction force
F_P	particle impact force
F_S	AWJ reaction force
H	heating parameter
h	depth of cut
h_F	fall height
h_{max}	maximum depth of cut
K	constant
K_n	stiffness parameter
l	layer thickness
L	length of the cut
$\dot{m}_P$	abrasive flow rate
m_S	slurry mass
$\dot{m}_S$	slurry flow rate
$\dot{m}_W$	water flow rate
n	RRSB-distribution parameter
p	water pressure
P_H	heat flux
p_{thr}	critical threshold pressure
S_M	surface of the eroded particles
t	cutting time
v	traverse rate
v_{ex}	AWJ exit velocity
V_M	eroded material volume
v_S	AWJ velocity
v_W	water jet velocity
x	traverse coordinate
α	energy transfer coefficient
β	width of cut
χ	energy dissipation parameter
ε	strain
φ	velocity transfer coefficient
Φ	depth ratio h/h_{max}
Γ	work of fracture
ρ_W	water density

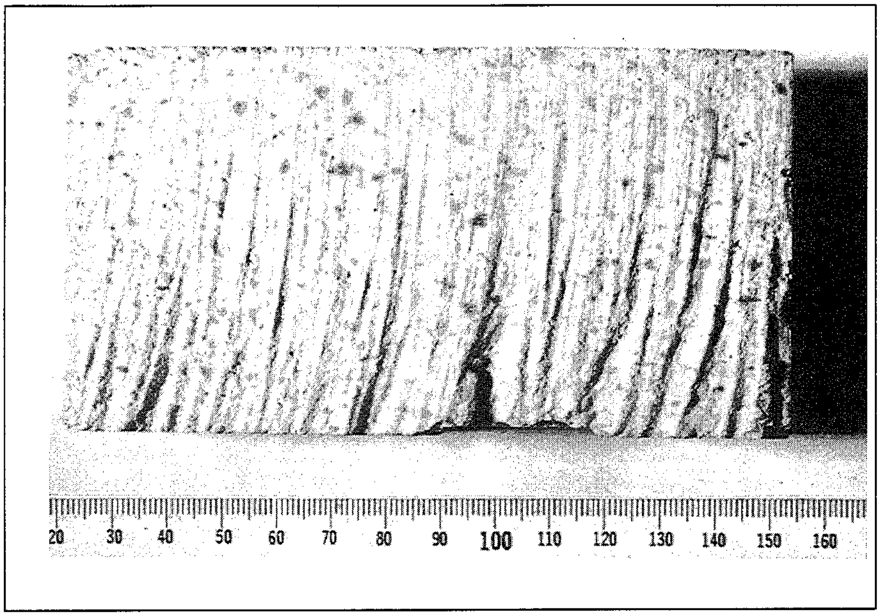


Figure 1. Typical Cutting Front Formed During the Cutting With Abrasive Water Jet. (Material: Bauxite)

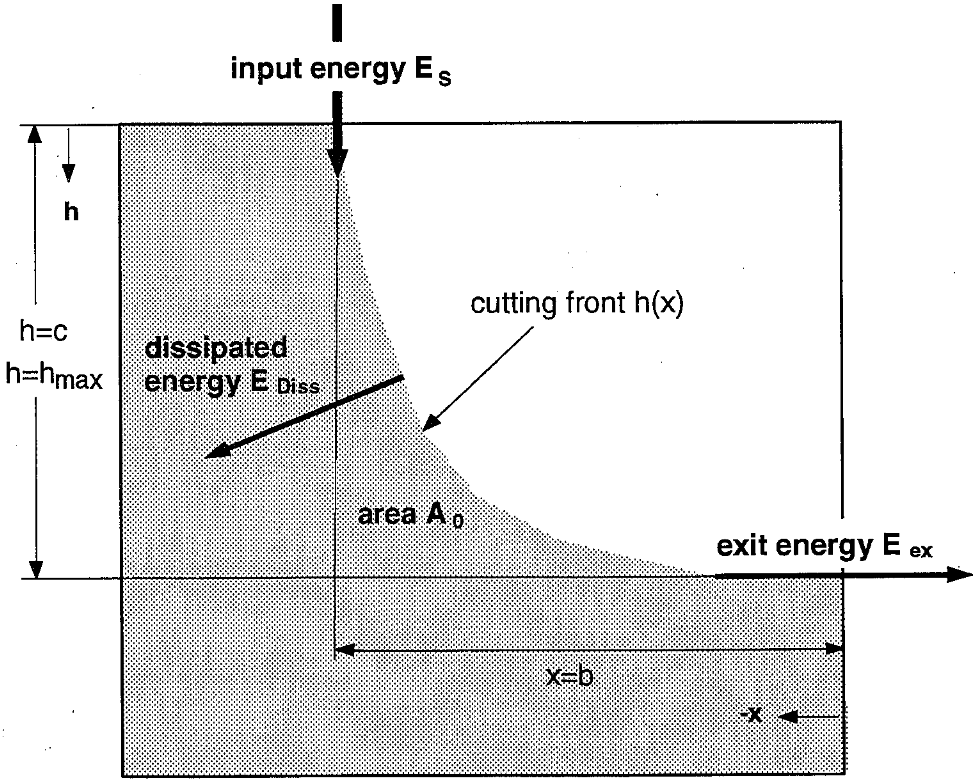


Figure 2. Simplified Energy Balance and Geometrical Situation During the Cutting With Abrasive Water Jet.

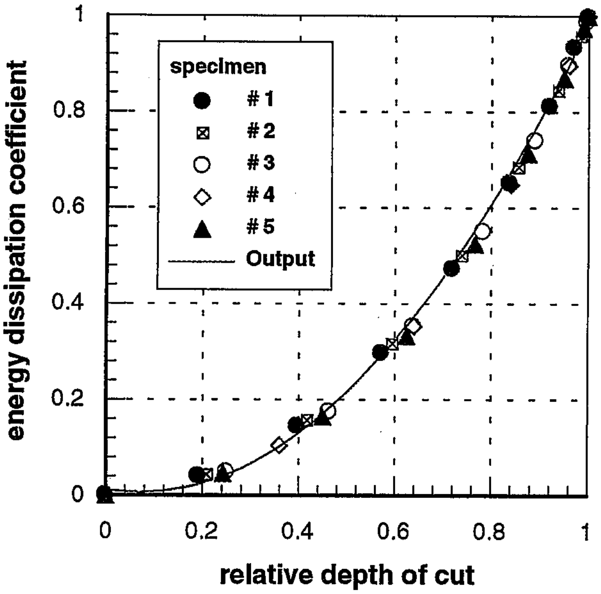


Figure 3. Relation Between the Relative Depth of Cut, $\Phi=h/h_{max}$, and the Energy Dissipation Parameter, χ.

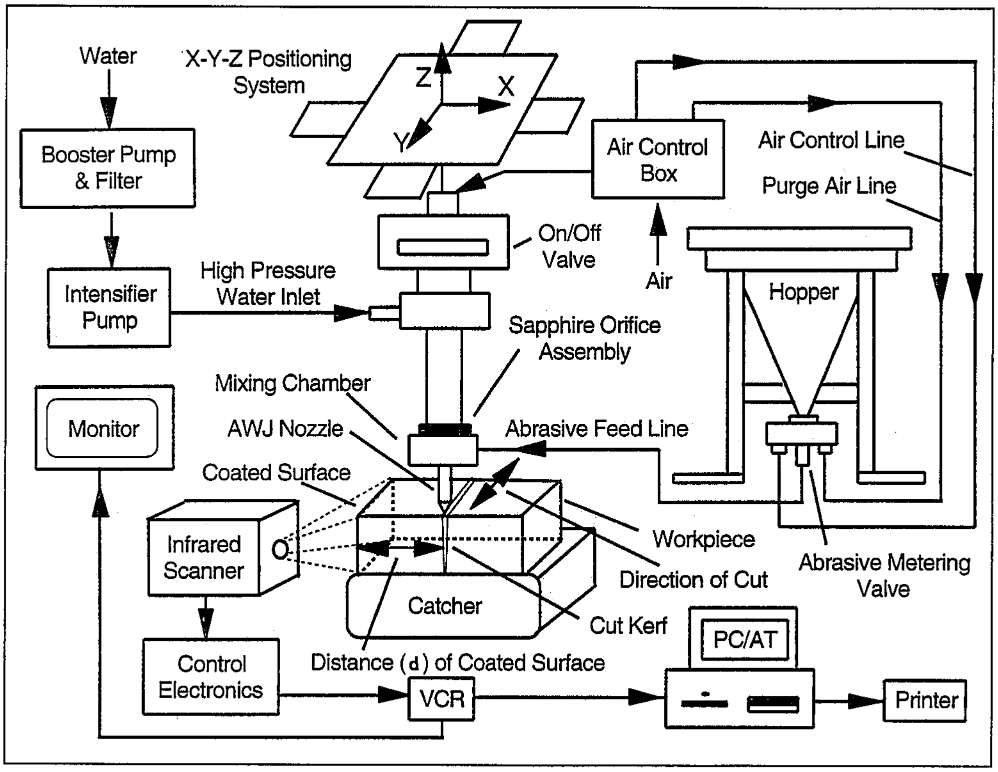


Figure 4. Experimental Setup for the Infrared Thermography Measurements.

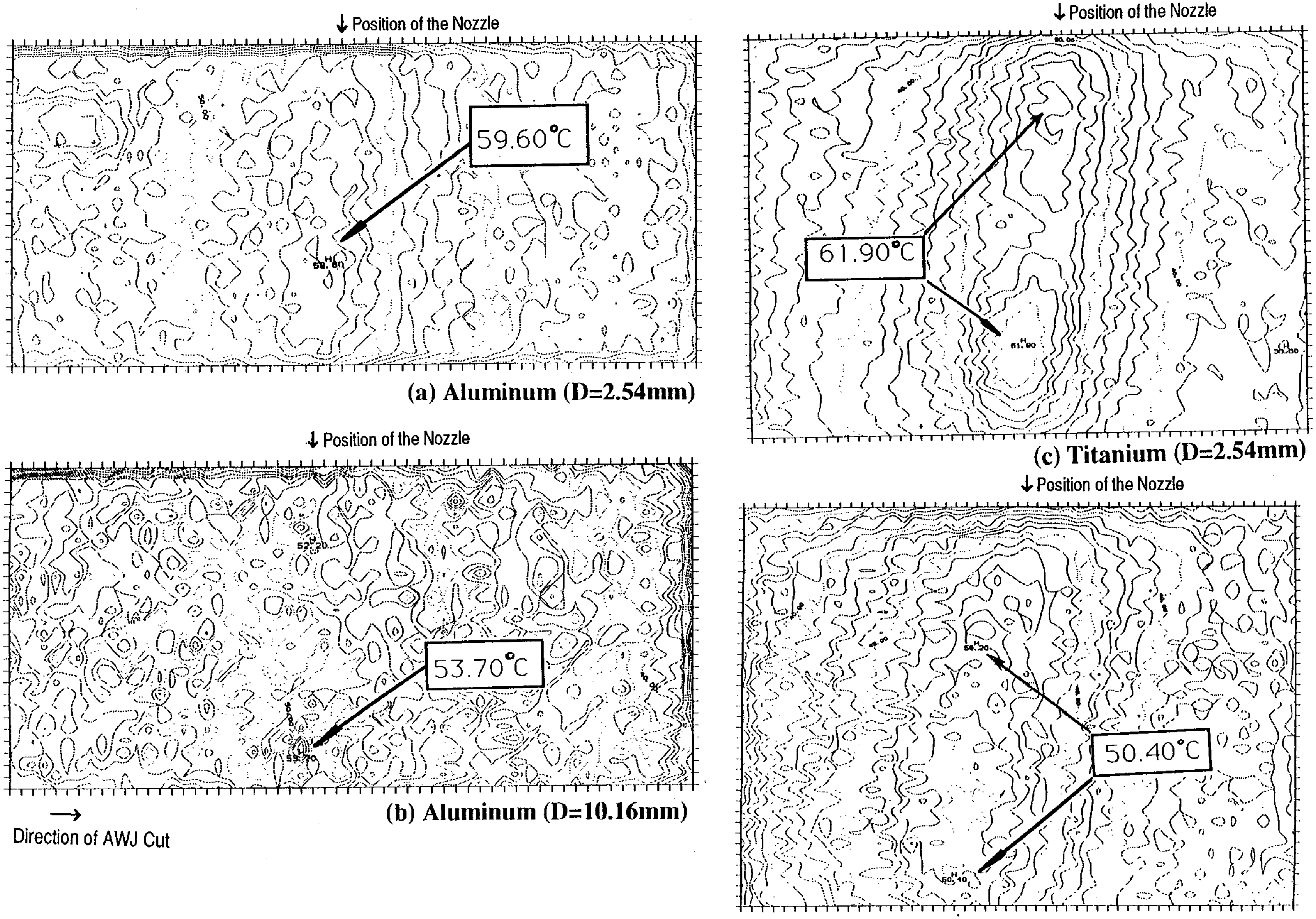


Fig. 5. Typical Isothermes in Aluminum and Titanium Estimated by IR-Thermography Measurements.

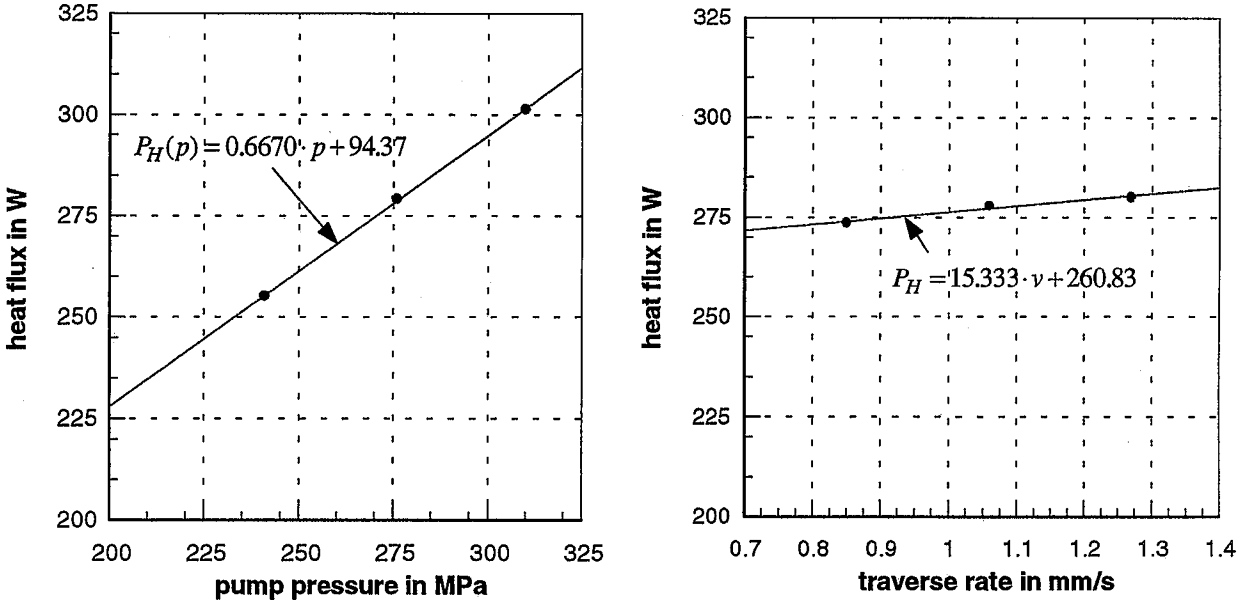
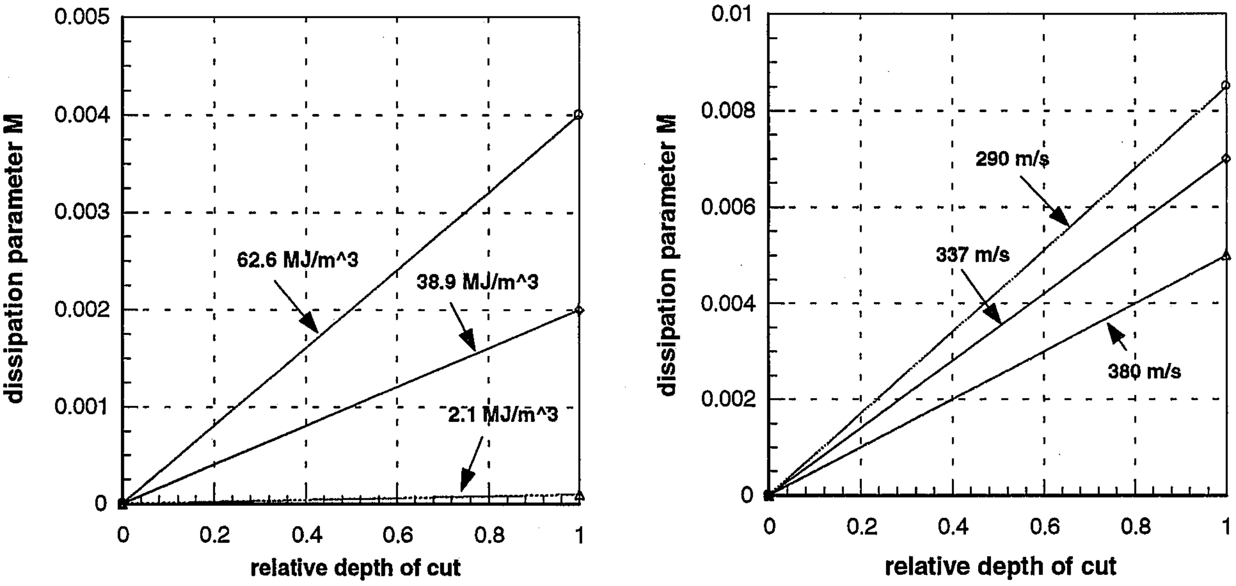


Figure 6. Heat Flux Estimation in Aluminum for Different Pump Pressures (a), and Different Traverse Rates (b).



a - Fracture Experiments

b - Grain Size Analysis

Figure 7. Results of the Material Removal Experiments.

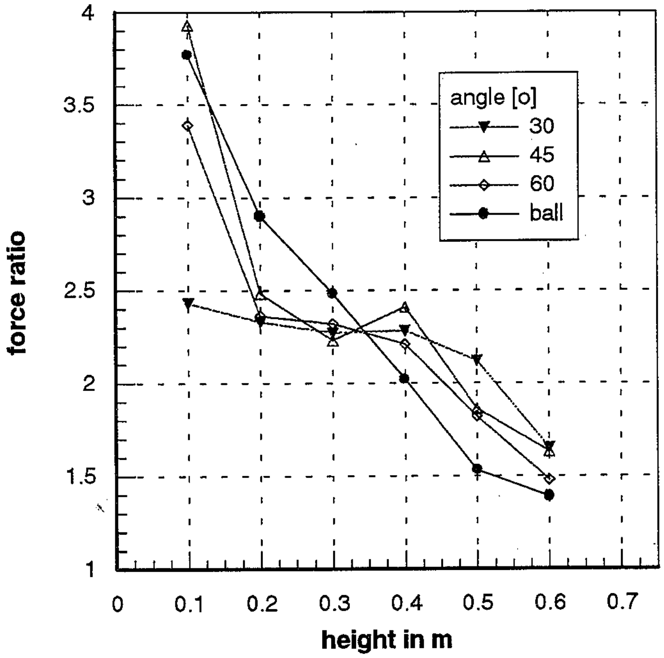


Figure 8. Relation Between the Impact Height, h_F, and the Force Ratio, r_F, for Different Impact Particle Geometries.

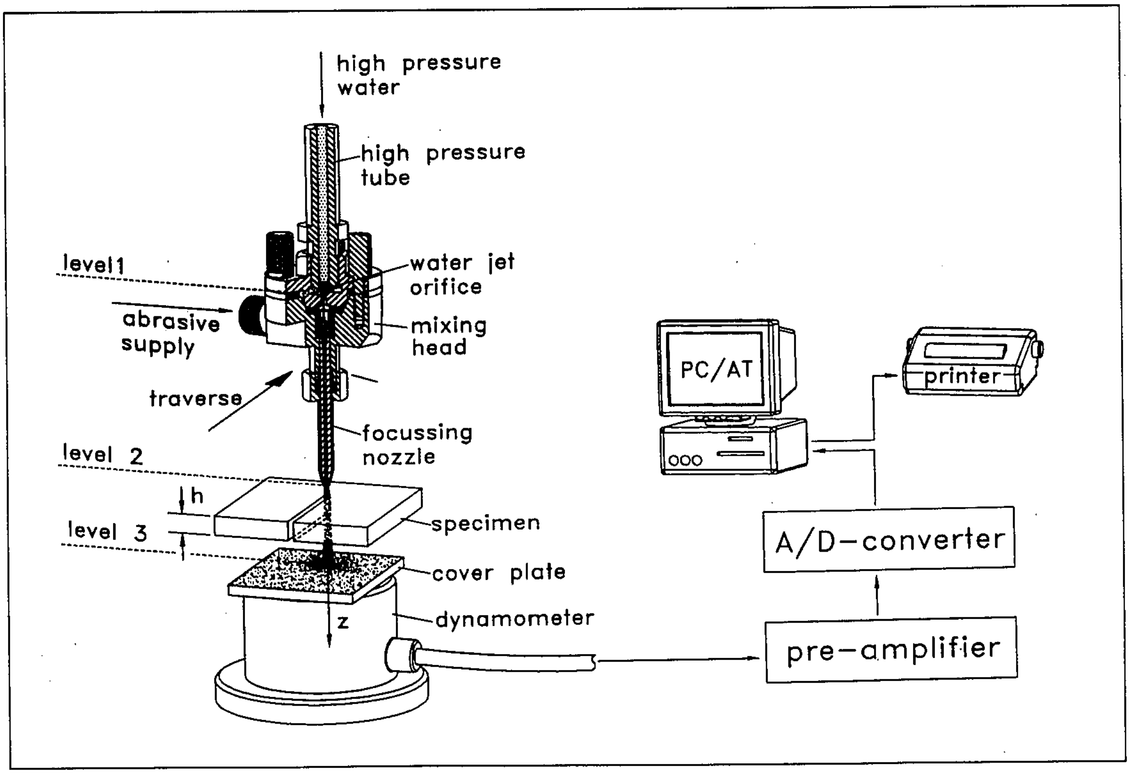


Figure 9. Experimental Setup for the Abrasive Water Jet Impact Force Measurements.

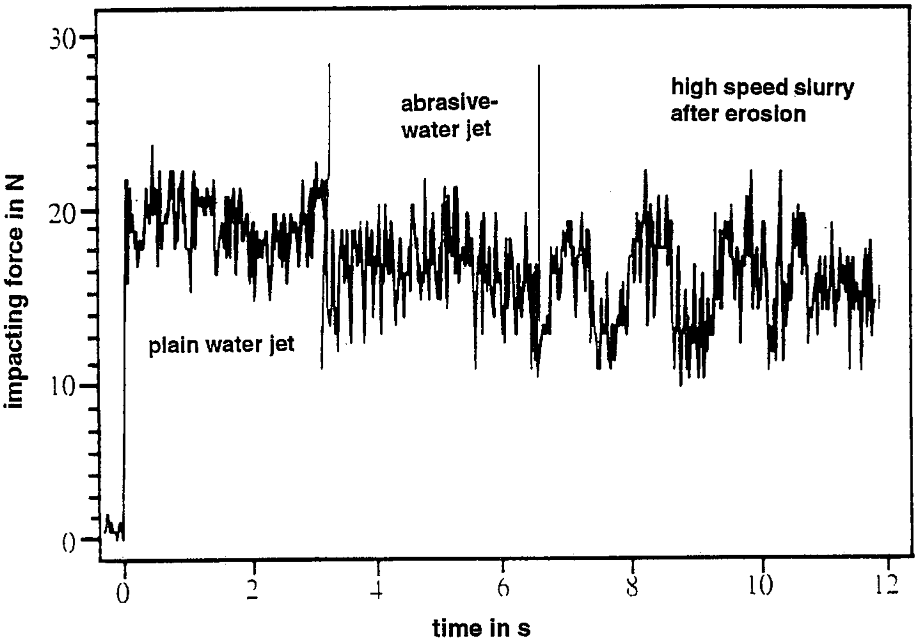


Figure 10. Typical Force Signal Detected During the AWJ Cutting of Aluminum.

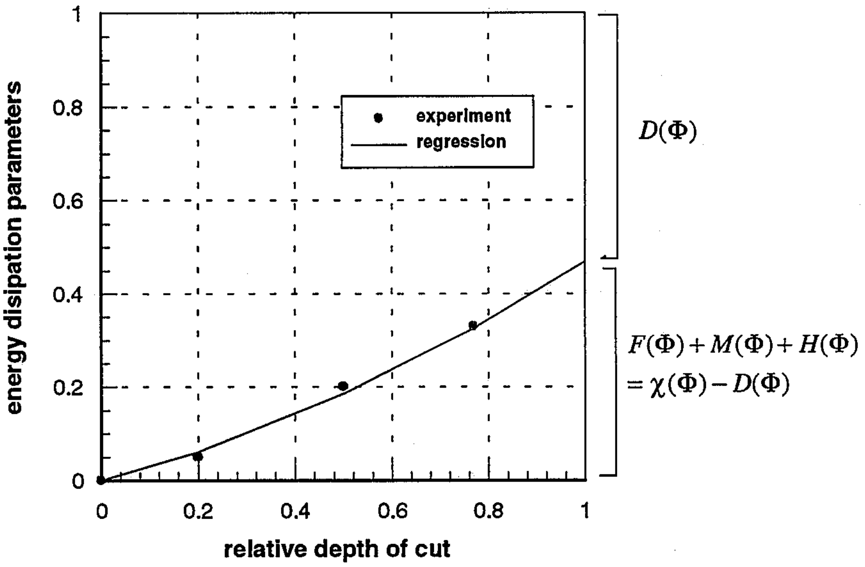


Figure 11. Relation Between the Relative Depth of Cut, $\Phi=h/h_{max}$, and the Energy Dissipation Parameters $D(\Phi)$, $F(\Phi)$, and $M(\Phi)$.

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Paper 15

FIELDS OF APPLICATION FOR ABRASIVE WATER SUSPENSION JETS OF PRESSURES FROM 15 TO 200 MPA

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ABSTRACT

Due to recent developments of the abrasive water suspension jet (AWSJ) technology, especially the steady increase of working pressure, the field of possible applications has been enlarged significantly. Since the hydraulic power of the jet is generated by the pressure and the water flow rate, two different ways of reaching high hydraulic power levels can be followed up.

The first method is to generate a low pressure suspension jet with large flow rates of water and abrasives. Low pressure AWSJ with pressure between 15 and 69 MPa have originally been developed to be used for offshore and onsite purposes.

The target of the second opportunity is the drastic reduction of the used amounts of abrasives and water for manufacturing and decommissioning purposes. This can be realized by increasing the working pressure and reducing the nozzle diameter and hereby minimizing the water and abrasive flow rate.

To evaluate the possible benefit of a pressure increase a 200 MPa prototype suspension jet system (Bypass or DIAJET principle) has been built up. First cutting tests have been carried out with this system at different pressure levels between 50 and 200 MPa (see also Brandt et al., 1994).

The aim of the paper is to delimit the high and low volume flow rate jets related to the pressure level from each other and to give a general idea of the parameter influence. Therefore the effect of the main parameters, such as pressure, abrasive flow rate, traverse rate and nozzle diameter, will be described. The ability of abrasive water suspension jets to cut different materials (concrete, steel, aluminum) and the corresponding cutting efficiency will be evaluated.

A rough matrix of results has been generated to give users a tool to choose the right jet configuration for a given application.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

The first prototype of an Abrasive Water Suspension Jet (AWSJ) called DIAJET was built up in 1984 and was limited to a working pressure of 15 MPa. Today systems with pressures up to 69 MPa are commercially available.

To reach a maximum cutting performance of an AWSJ the hydraulic power of this jet should be as high as possible. The hydraulic power of a jet is given by the product of the working pressure and the water volume flow rate. To generate a high powered jet at a pressure of 15 MPa a large water volume flow rate is necessary.

Also the 69 MPa-systems are characterized by a relatively high consumption of water and abrasives depending on the nozzle diameter. Main advantage of low pressure jets is a high jet stability, which is required for cutting large material thickness. Main fields of insert for low pressure jets are onsite and offshore applications and cutting of large material thickness, for example concrete and steel.

To introduce the AWSJ technique into industrial manufacturing and decommissioning a drastic reduction of the flow rates has to be reached. To reduce the consumption of water by keeping the hydraulic power constant the working pressure has to be increased. Figure 1 compares the required pressure and the water flow rate for different nozzle diameter to reach a hydraulic power of 9.1 kW. This is the hydraulic power which a commercial AWSJ-system generates at 69 MPa with a nozzle diameter of 0.7 mm. All values have been calculated to show the effect of an increase of the working pressure on the reduction of water flow.

With reducing the water flow rate and keeping the hydraulic power constant also the abrasive flow rate can be reduced. As it will be shown later on, a 200 MPa-AWSJ reaches the same depth of cut than a 70 MPa AWSJ, but with only one fifth of abrasives.

2. EXPERIMENTAL SETUP

For the generation of an AWSJ three different principles can be distinguished. Figure 2 shows these principles schematically.

The first principle is called direct pumping. Here a premixed suspension is pumped directly through a nozzle. Until today this principle has only been realized to support drilling applications.

The second principle is called indirect pumping. Main part of this system is an abrasive storage vessel with an isolator inside. The high pressure water from the pump is used to move the isolator downwards so that the premixed suspension is pumped towards the suspension nozzle. With this principle the change of abrasive concentration during the cutting process is not possible. Cutting tests at working pressures up to 345 MPa have been carried out with this system by Hashish (1991). He reported an extreme wear of the nozzle, but also a large increase in cutting performance compared to lower pressure levels and the abrasive water injection jet (AWIJ) technology.

The third principle follows basically the DIAJET-principle developed by BHR Group, U.K. The water stream delivered by the pump is divided into a plain water stream and the so called bypass stream. The bypass stream is used to pressurize the abrasive storage vessel and hereby feed the abrasive particles out of the vessel into the plain water stream. The mixed suspension is pumped through flexible hoses towards the suspension nozzle. A restriction valve is used to control the water flow rate in the bypass line and hereby regulate the abrasive loading ratio of the jet.

The cutting tests reported in this paper have been carried out with two different AWSJ-systems, which have the same technological structure but different inner diameters of tubes and hoses to allow different flow rates. A sketch of both systems structure is given in Figure 3.

3. RESULTS

To evaluate the influence of the important process parameters on the cutting efficiency, kerfing test were carried out. To kerf a sample means to cut a slot into it instead of cutting through. These kerfing tests give the opportunity to get information about the maximum cutting ability of the jet with specific parameters with only one experiment. In all graphs the cutting result is given by the average depth of kerf, which is the average of the maximum and minimum depth along the generated kerf.

3.1 Working Pressure

The influence of working pressure on the hydraulic power was explained in Figure 1. Figure 4 shows the results of cutting tests with three different pressures and a variation of the abrasive flow rate. It can be seen that double the pressure from 35 to 70 MPa results in a more than two times larger depth of kerf using the same amount of abrasives.

Figure 5 summarizes the results of the same cutting tests with pressures from 50 to 200 MPa. Note that the nozzle diameter is different. However, also in Figure 4 the same immense influence of the working pressure is demonstrated.

It has to be mentioned, that cutting deep kerfs results in a lower cutting efficiency than cutting flat kerfs with higher traverse speeds. This effect bases on the energy loss inside the kerf with increasing cutting depth. In this case the kerf takes the function of a second nozzle which focuses the jet on one hand and increases the flow resistance on the other hand. Therefore the effect of working pressure might be even higher when comparing the maximum cutting speed.

3.2 Abrasive mass flow rate

Figure 4 and 5 give also the effect of the abrasive flow rate on the average depth of kerf. Note the significant increase in depth of kerf for an increasing abrasive flow rate in the front part of the curve for 70 MPa. Above 5 kg/min the saturation point is reached, where a further increase of the abrasive flow rate does not increase the average depth of kerf.

The saturation point for the 200 MPa jet is reached at around 3 kg/min which corresponds with a loading ratio of about 20%. The saturation at the 70 MPa system occurs later at almost 40%.

To reach a larger cutting performance it is much more effective to increase the working pressure than to use larger abrasive flow rates. And in addition an increase of working pressure gives the opportunity to reduce the abrasive flow rate and to cut down the amount of abrasives that has to be recycled or disposed.

3.3 Nozzle Diameter

The effect of nozzle diameter on the cutting efficiency has been investigated exemplary for a working pressure of 200 MPa. The results for the given range of nozzle diameters are shown in Figure 6.

For safety reasons the cutting tests with the 0.4 mm nozzle were carried out with Barton Garnet 150W (d_{Pmax} = 125 microns), which has a smaller average particle diameter than HP 120 (d_{Pmax} = 250 microns). Results from Guo et al. (1994) show, that the smaller average diameter of the particles does not result is a loss of cutting performance. Newer tests show, that even the usage of HP 120 with the 0.4 mm nozzle does not lead to frequent nozzle blockages.

The cutting performance increases with increasing nozzle diameter, when keeping the abrasive mass flow rate constant. Note that this results in a decreasing mass loading ratio. The increasing cutting performance is caused by two different effects: On one hand the decreasing loading ratio leads to a small increase of the particle velocity, due to the additional water volume per particle. On the other hand the specific cutting efficiency related to the abrasive flow rate (mm^2/kg), which evaluates the generated surface per used amount of abrasive per time, increases for a decreasing loading ratio.

A similar variation of nozzle diameter has been carried out at 35 MPa. The results are given in Figure 6 and are very interesting for the conclusion drawn above from the results achieved with the 200 MPa system. As obvious in Figure 7 there seems to occur a stagnation, where a further increase in nozzle diameter causes only a small increase in depth of kerf. This would mean, that a certain water volume flow rate is necessary to accelerate the particles to a maximum velocity and that an additional water volume flow is not able to increase the particle velocity. From the given results it is not recommended to use larger nozzle diameters than 1.5 mm since it will lead to waste of water without increasing the depth of kerf significantly.

But there is also a growing number of applications where very narrow kerfs are required, for example the jewelry industry. For these purposes the main advantage of the AWSJ technology is the need of only one nozzle for jet generation. From today's state of art this gives the opportunity to use nozzle diameters down to 0.2 mm and to reach cutting widths down to 0.25 mm.

3.4 Traverse Rate

The general relationship between the traverse rate and the generated depth of kerf is well known. As mentioned above the cutting efficiency of an AWSJ is higher for cutting flat kerf with large traverse rates than for cutting deep kerf with slow speed.

Cutting tests with varying traverse speeds have been carried out with a 70 MPa-AWSJ on different sample materials, to get an idea about the duration of cutting a certain material thickness. The results of these experiments are summarized in Figure 8.

It can be seen that an aluminum sample can be cut twice as fast as a steel sample. This factor has also been proofed at a working pressure of 200 MPa. There is also a factor of 2 between the generated kerf depth of aluminum and concrete.

From first cutting tests on concrete with the 200 MPa-system it is known, that this factor does not occur at this pressure level. The reason for this is the decreasing jet coherence because of decreasing water volume flow rates. This proved to be disadvantageously for cutting inhomogeneous material such as concrete.

From the presented results the low pressure AWSJ with large water volume flow rate is very well qualified to cut inhomogeneous materials like concrete. Due to the high jet stability the cut is straight and with only a view cracks.

4. CONCLUSIONS AND OUTLOOK

The presented results show, that the field of applications for AWSJs is wide ranged. Besides the usage for on- and offshore purposes the increase of working pressure and the reduction of volume flow rates give this technology many advantages to succeed in industrial manufacturing.

One of the main advantages is the very small jet diameter. Cutting width of less than 0.3 mm can be generated. Today's technical limit for the nozzle diameter is around 0.2 mm for nozzle materials with a high wear resistance. Small nozzle diameters require a very small average particle diameter of the used abrasive. Guo et al. recently investigated, that the cutting performance decreases for average particle sizes below 150 microns. For cutting with a nozzle diameter of 0.2 mm an maximum particle size below 150 microns is recommended, but in this case the narrowness of the cut is more important than the maximum depth of cut.

Another important aspect is the reuse of the abrasive material. For the AWSJ technology the recycling of the abrasive is quite easy, since there is no drying process required to feed back the abrasive material into the system. Results about the disintegration behavior of particles in an AWSJ will be presented in the near future. Based on investigations with AWIJ (Guo (1994)) a reuse of abrasives for more than 10 times seems to be possible with an AWSJ.

Problems, which need to be solved in the future, are the control of the abrasive mass flow rate and the on/off-switching of the jet to enable drilling operations. For the abrasive flow rate determination different systems are available and developed, but need to be investigated and improved under real cutting conditions.

Future research work will focus on the increase of working pressure up to 400 MPa with small water and abrasive flow rates and small jet diameters. Additional the handling and control of the system has to be further developed and optimized. Another very important aspect for the application in industrial manufacturing is the influence of the process parameters on the quality of the generated surfaces. Main aspect of this research work will be the optimization of the parameters referring to the cutting efficiency and cutting quality.

5. ACKNOWLEDGMENTS

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7. NOMENCLATURE

d_{Pmax}	microns	maximum particle diameter
d_{Sd}	mm	nozzle diameter
k_m	mm	average depth of kerf
$\dot{m}_P$	kg/min	abrasive mass flow rate
p	MPa	working pressure
s	mm	standoff distance
v	mm/min	traverse rate

8. FIGURES, TABLES AND ILLUSTRATION

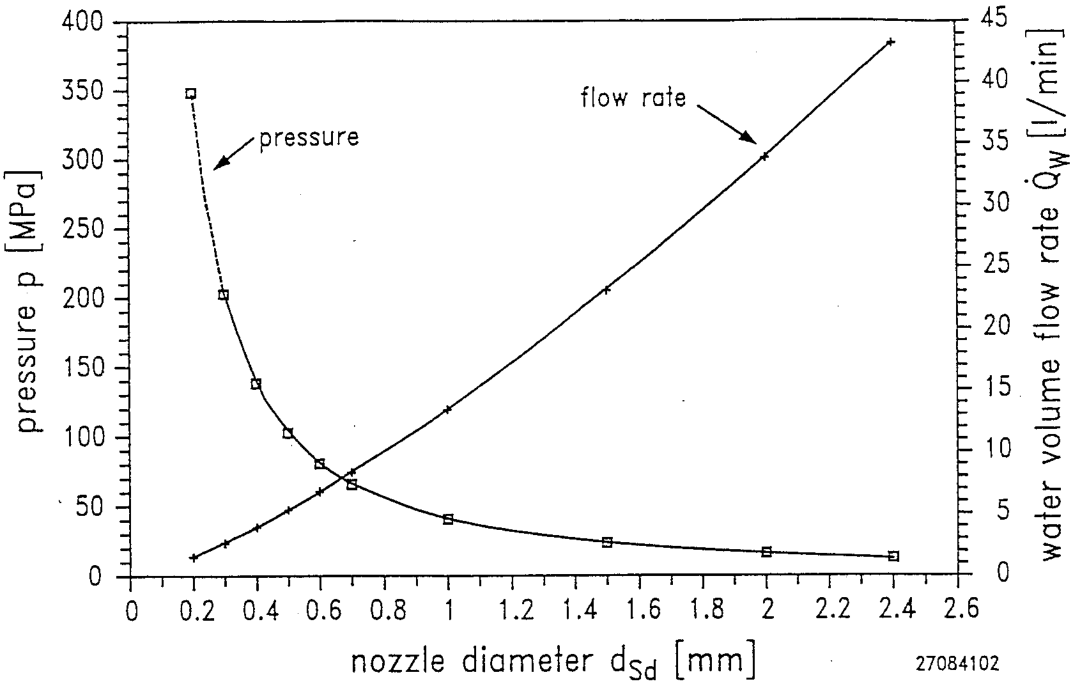

Figure 1: Required pressure and water flow rate for different nozzle diameters to reach a given hydraulic power of 9.3 kW

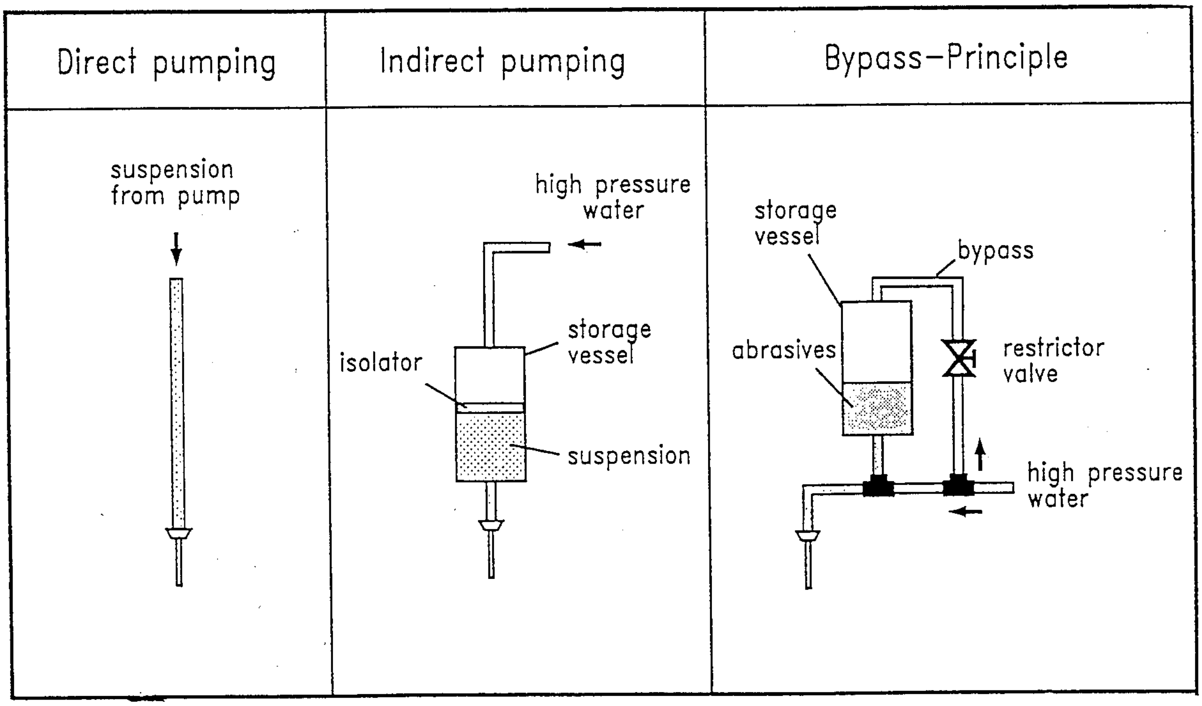

Figure 2: Principles to generate abrasive water suspension jets (AWSJ)

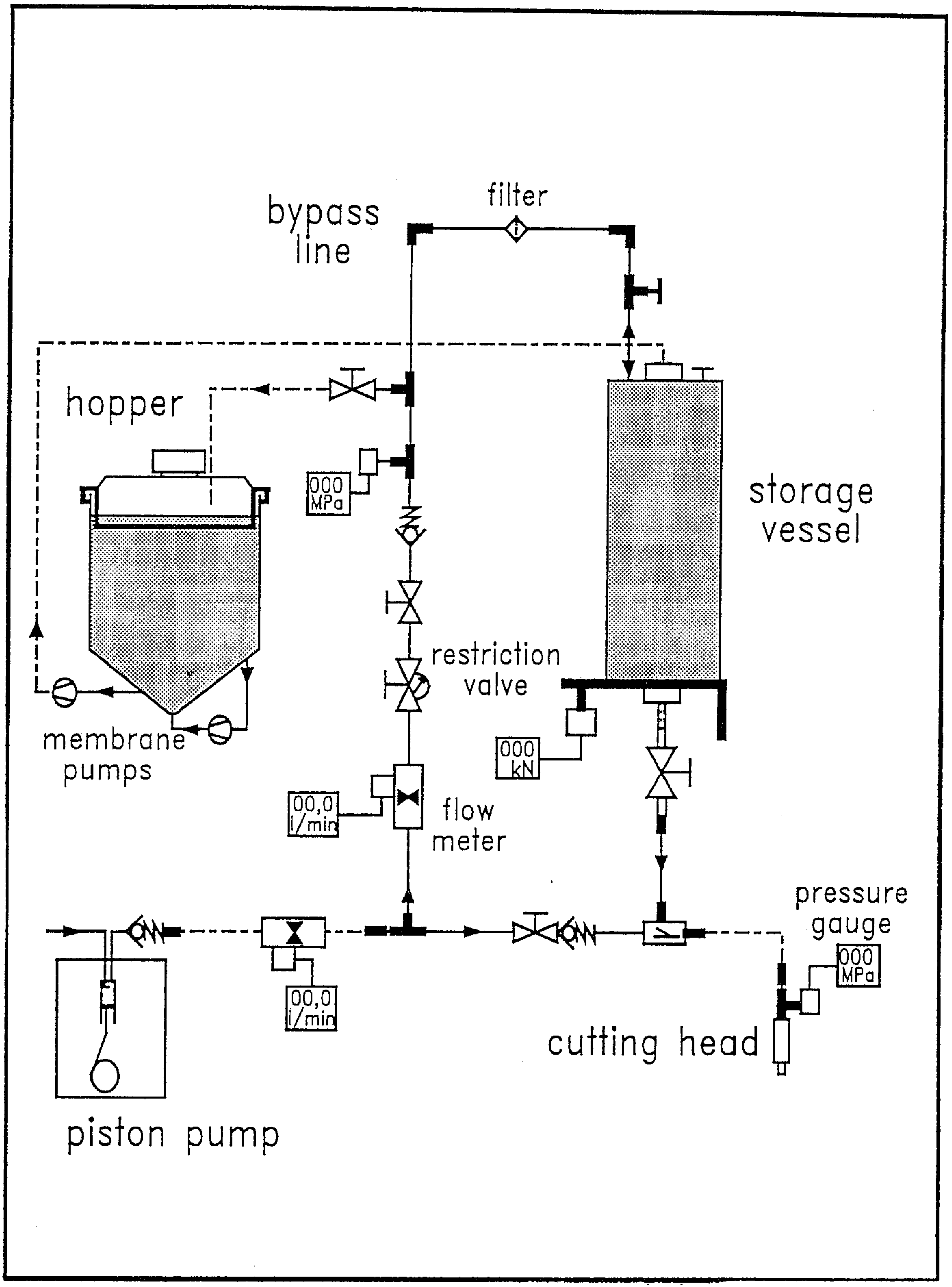

Figure 3: Sketch of the AWSJ cutting units

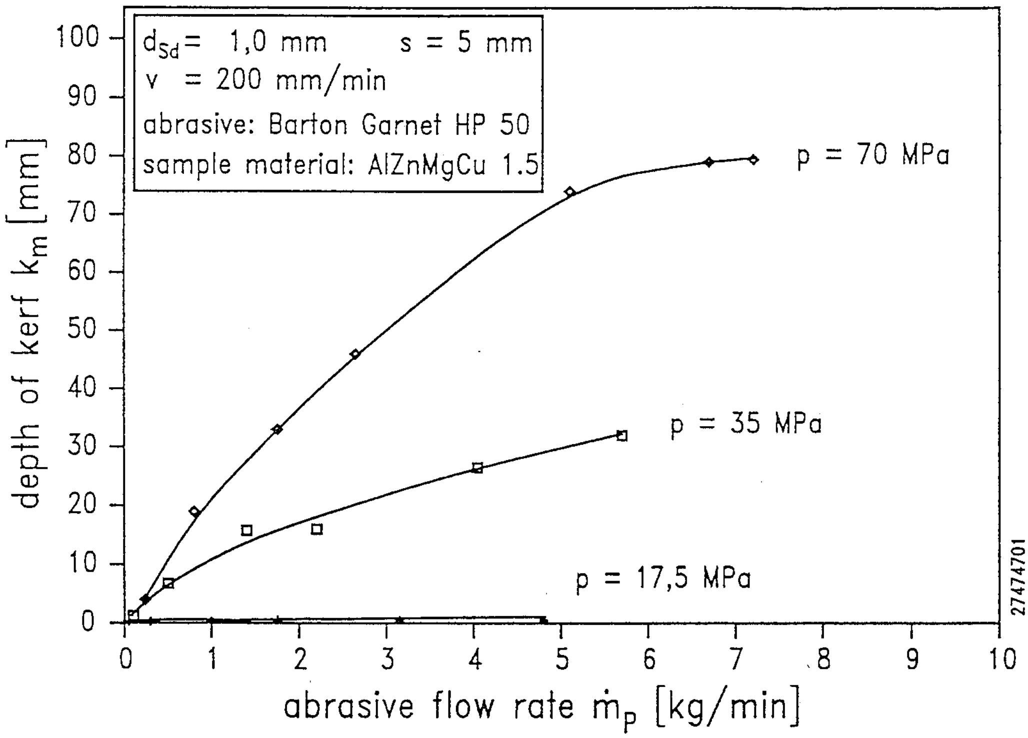

Figure 4: **Influence of abrasive mass flow rate on depth of kerf for pressures from 17.5 to 70 MPa**

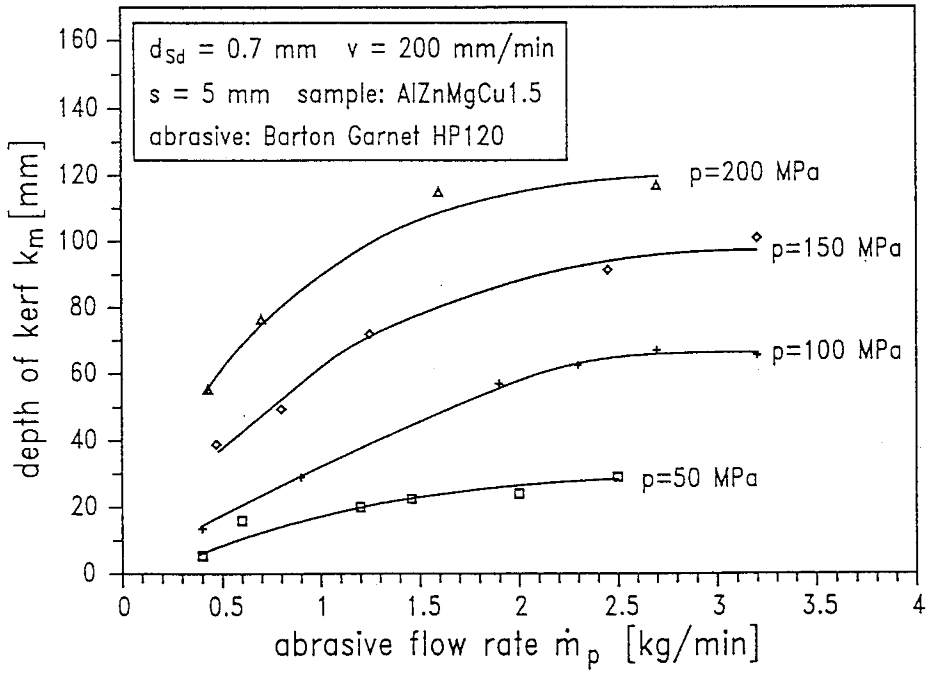

Figure 5: **Influence of abrasive mass flow rate on depth of kerf for pressures from 50 to 200 MPa**

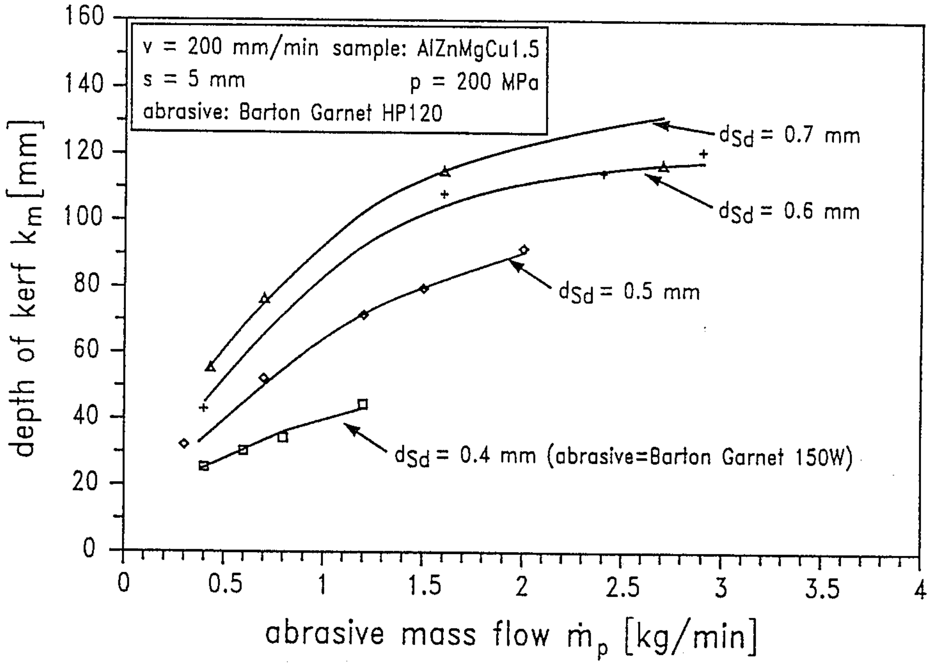

Figure 6: Effect of nozzle diameter on average depth of cut

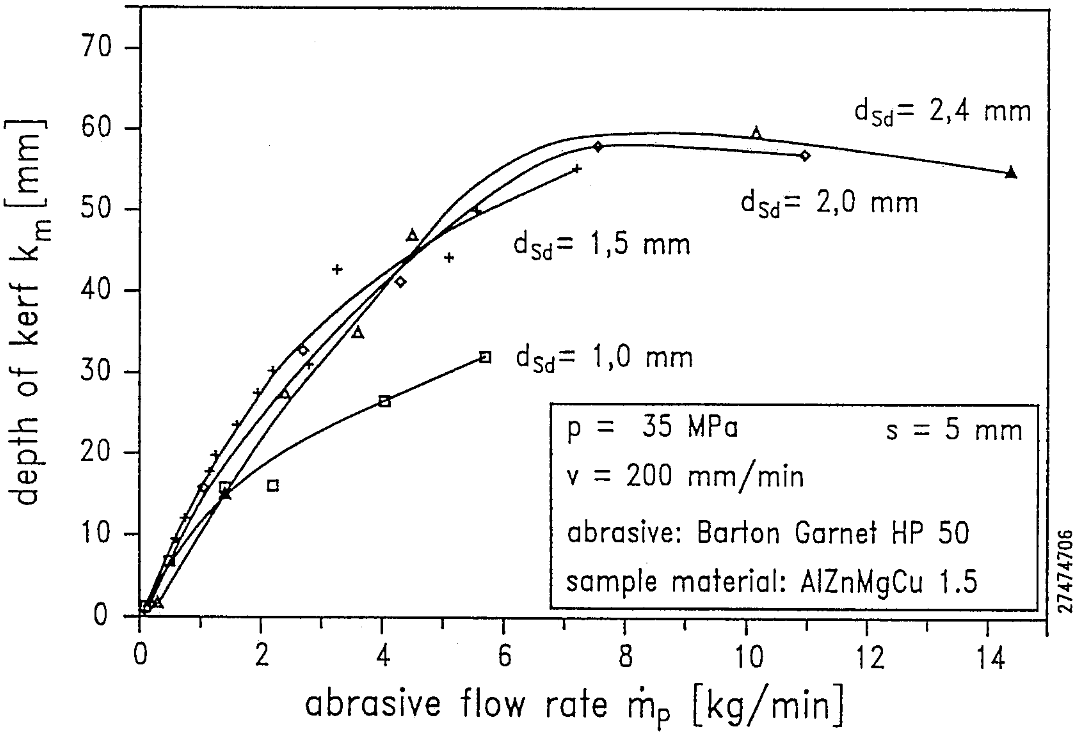

Figure 7: Effect of abrasive mass flow rate on depth of kerf for different nozzle diameters

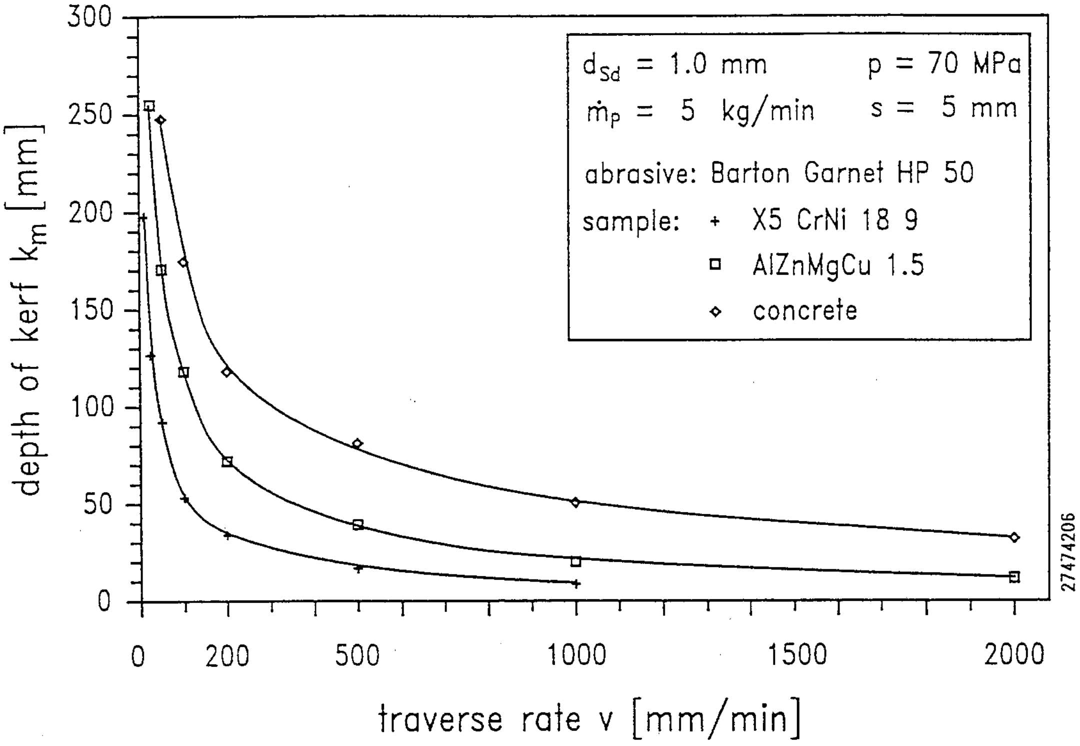

Figure 8: Effect of traverse rate on average depth of kerf for different sample materials

8th American Water Jet Conference
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Paper 16

ABRASIVE WATERJET CUTTING WITH A SHAPEJET™

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ABSTRACT

Research and development of abrasive waterjet cutting with conventional round jets has been well documented. The objective of this study is to compare an abrasive waterjet-Shapejet™ with a conventional round abrasive waterjet. Experiments verify that the abrasive water-Shapejets™ cutting performance is greater than that of a conventional round abrasive waterjet. This paper shows that high quality cutting and production rates can be achieved at lower pressure or power when using abrasive water-Shapejets™ .

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

First introduced in the early 1980s, abrasive waterjet cutting systems have several advantages as an alternative for conventional cutting tools or manufacturing processes. Abrasive waterjets provide industry with a high speed means by which to cut, virtually any material, without a heat or stress affected zone. Due to this and other advantages several studies have focused on defining optimum abrasive waterjet parameters, such as cutting speed, depth of cut, kerf waviness.

Over the years gradual improvement of the abrasive waterjet process has resulted from better understanding of cutting head design, abrasive feed mechanisms, and optimum utilization of waterjet power.

Prior to comparing an abrasive waterjet-Shapejet™ with a conventional round abrasive waterjet it was noted that:

- The optimum waterjet pressure for maximum cutting speed is in the order of 3 (three) times the material threshold cutting pressure (Hashish, 1988).

- It was reported that the maximum abrasive waterjet cutting depth obtainable using a conventional round focusing tube occurs when the focusing tube to waterjet orifice diameter ratio is in the order of 3 (three) to 1 (one) and found that with conventional round AWJ nozzles, the optimum mass of abrasive to water ratio is in the order of 0.10 to 0.17 and that variation from 0.10 to 0.17 was due to the length of focusing tube required to maximize jet cohesiveness (Chalmers, 1991).

- Models predicting cutting speeds, depth of cut (Zeng et al., 1992), and kerf waviness (striations) for a conventional round AWJ have been derived.

- The cut materials surface finish with respect to traverse speeds within a 0.1 mm allowable waviness had been investigated and reported the ratio for control to 0.1 mm to be in the order of 0.3 - 0.4 of the maximum cutting speed (Matsui et al., 1990).

- Studies on mixing head geometry for conventional round AWJ cutting with emphasis on the effects of distance from the waterjet to the focusing tube entry have been carried out (Galecki et al., 1987 and Abudaka, 1989).

- A spiral jet increases abrasive acceleration and jet energy transfer onto the target material and thereby improves conventional round AWJ cutting efficiency (Horii et al, 1991).

- Conventional round AWJ for turning, milling, drilling (Hashish, 1988 and Zeng et al., 1994), and threading composite materials and glass are also investigated (Hashish, 1992 and Sheridan et al., 1994). They predict a promising future for adaptation of AWJ systems as precision machining tools for cutting conventional or advanced composite materials.

- With the exception of substituting an abrasive water-Shapejet™ focusing tube and a conventional round focusing tube, when all other AWJ system parameters are held constant, the following benefits result:

  1. Improved cutting rates in all materials;
  2. Increased quality of the cut surface on all materials;
  3. Substantial reduction in waterjet pressure required to obtain benefits 1 and 2.

2. ABRASIVE WATER-SHAPEJETS™

Shapejets™ (Rankin) for AWJ cutting have been in successful use commercially since 1993. And this paper describes the results obtained from a singular controlled experiment to evaluate their relative effectiveness.

Shapejets™ (Rankin) for high pressure waterjetting (up to 30,000 psi) have been in successful use commercially since 1991 and have proven to be more effective than an ordinary round jet due to their inherent cohesiveness.

3. EXPERIMENTAL APPARATUS AND SETUP

An X-Y contour table with CNC control and graphics display monitor combined with a high precision micro-feeder abrasive delivery system receives high pressure water from a triplex positive displacement pump. The pump was equipped with a by-pass flow control valve in order to vary pressure from 10,000 psi (69 MPa) to a maximum of 20,000 psi (138 MPa). An on/off valve actuated by the CNC control timed the duration of cuts and controlled flow of the abrasive.

The mixing head design used permits substitution of an abrasive water-Shapejet™ and a conventional round focusing tube without changing other system elements. Still photographs and video records were made of the experiment.

Materials cut were: 304 stainless steel
6061-T6 aluminum
A36 carbon steel
Abrasive used were: 40 mesh copper slag
SJ-80sx Sharpjet

4. RESULTS

4.1 Nozzle/Focusing Tube Substitution No. 1

Target material: 304 stainless steel, 19 mm (3/4") thick.
Pump pressure: 89.6 MPa (13,000 psi).

Abrasive: Sharpjet SJ-80SX, flow rate 11.35 g/s (1.5 lb/min).
Focusing tubes: triangular abrasive water-Shapejet™ and conventional round tube.
Standoff distance: 2 mm & 14 mm.

Figure 1 plots the depth of cut (mm) versus traverse speed (mm/min) made by a triangular abrasive waterjet-Shapejet™ and a conventional round AWJ at a standoff distance of 2 mm.

Figure 2 plots the depth of cut (mm) versus traverse speed (mm/min) made by the same jets at a standoff distance of 14 mm.

Observations from these substitution tests are:

Abrasive water-Shapejet™ cuts deeper than the conventional round AWJ. At 2 mm and 14 mm. (Figures 1 & 2)

Abrasive water-Shapejet™ produces a cut with less kerf waviness (striations) than a conventional round AWJ. (Figure 3)

4.2 Nozzle/Focusing Tube Substitution No. 2

Target Material: 6061-T6 aluminum, 38 mm (1.5") thick
Pump pressure: 94 MPa (13.6 ksi)
Abrasive: 40 mesh (extra fine) copper slag, flow rate 19 g/s (2.5 lb/min)

Figure 4 plots the depth of cut versus traverse speed (mm/min) made by a triangular abrasive water-Shapejet™ and a conventional round AWJ at a standoff distance of 2 mm.

Observations from these substitution tests are that the triangular abrasive water-Shapejet™ continues to exhibit a trend toward deeper cutting of any material than a conventional round AWJ even when a soft and less sharp abrasive is used to cut the target material.

5. DISCUSSION AND THEORY

Because high pressure water-Shapejet™ are found to be more cohesive than ordinary round waterjets and are considered to be of a percussive form, it suggests that improved cohesivenesss and a potential to become percussive may also make an abrasive water-Shapejet™ more effective than an ordinary round AWJ. Early work by Nikuradse (White, 1986) (Figure 5) covering turbulent flow of fluids in a triangular duct show that it is reasonable to expect that mixing of fluid and abrasives at the sharp corners of an abrasive water-Shapejet™ will produce a different mechanism for the discrete removal of material compared to the removal mechanism present in an ordinary round AWJ.

Figure 6 is a photograph of a series of triangular abrasive water-Shapejet™ cuts. The pointed leading edge of the cuts indicate that a different cutting mechanism has occurred because the triangular abrasive water-Shapejet™ has a small sharp stream front followed by two larger rear stream fronts. An ordinary round AWJ stream front by contrast has less frontal contact perimeter and must therefore have less abrasive in contact with the target material. Based on the perimeter of a circle and that of an equilateral triangle jet for use with the same power, the difference in stream front contact with the target material is 74.7% greater for the triangular abrasive water-Shapejet™

6. APPLICATIONS FOR ABRASIVE WATER-SHAPEJETS™

A sharp edged abrasive water-Shapejet™ stream can be used to produce a desired kerf corner radius. This will enhance the acceptability of abrasive water-Shapejet™ as a tool to replace conventional machining of advanced materials.

6.1 Threading by Triangular Water-Shapejet™

Figure 6 shows that a triangular abrasive water-Shapejet™ will form the root of a thread avoiding an excessively large root radius.

6.2 Drilling/Milling by Rectangular Water-Shapejets™

A rectangular abrasive water-Shapejet™ (Figure 7) will facilitate fast and simple drill/mill machining operations. Prospects for ultra deep hole drilling of materials is especially promising.

6.3 Turning by Rectangular Water-Shapejets™

Zeng et al. (1994) found that a conventional round AWJ stream had an amount of abrasive particles in it which were not effective in removing material from the target. Jet stream deflection and particle rebound typically found in a conventional round AWJ during turning contribute to surface quality inconsistency and to lack of control of the precision of the cut. When a rectangular abrasive water-Shapejet™ is used in a turning operation the orientation of the rectangular abrasive water-Shapejet™ relative to the axial direction of travel makes it possible to control both the quality and precision of cut on the target material by reducing stream deflection and particle rebound. The result is an increase in target material removal by using less waterjet power while increasing production rate.

6.4 Part Polishing by Rectangular Water-Shapejet™

A rectangular water-Shapejet™ long axis spreads abrasive particles over a relative large stream front to provide a cost-effective time saving tool for material polishing.

7. CONCLUSIONS

Abrasive water-Shapejets™ are novel tools which now make it possible to more precisely control material removal during AWJ machining operations. Abrasive water-Shapejets™ can be used successfully with reduced pressure or power compared to conventional round AWJ.

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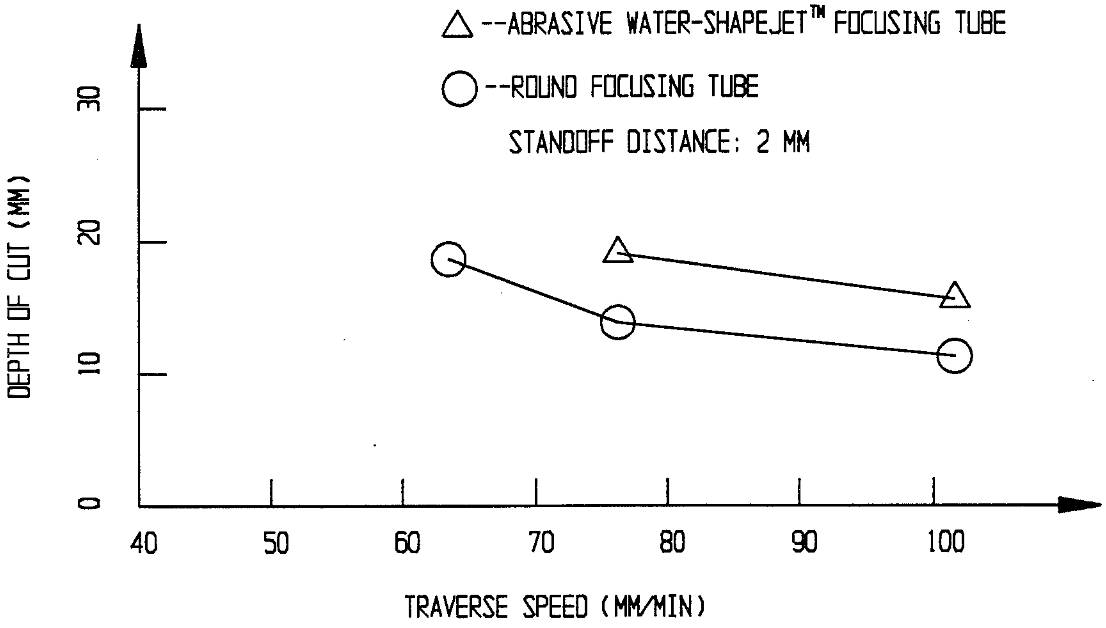


FIGURE 1

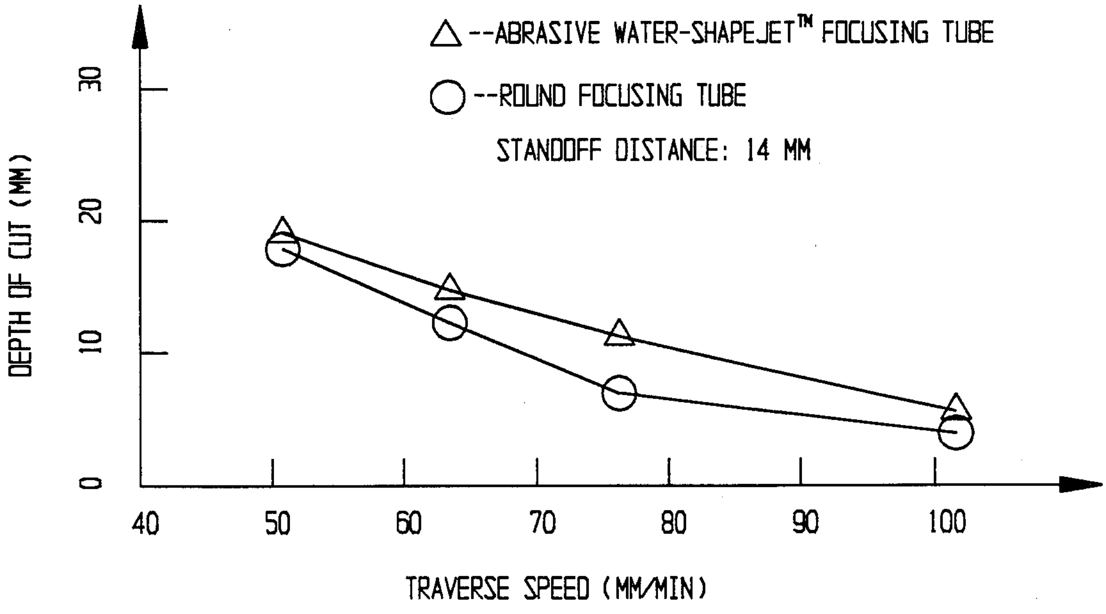
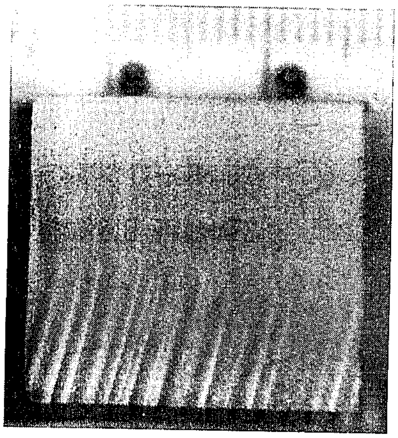
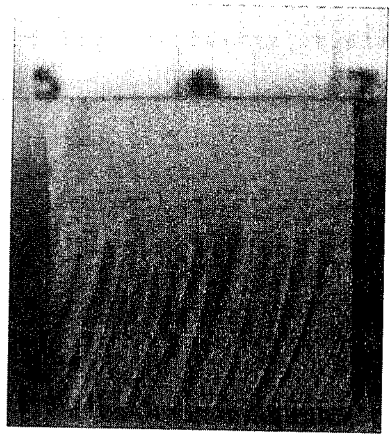


FIGURE 2



(A) ABRASIVE WATER-SHAPEJET ™



(B) CONVENTIONAL ROUND AWJ

FIGURE 3 COMPARISON OF KERF WAVINESS IN 304 STAINLESS STEEL

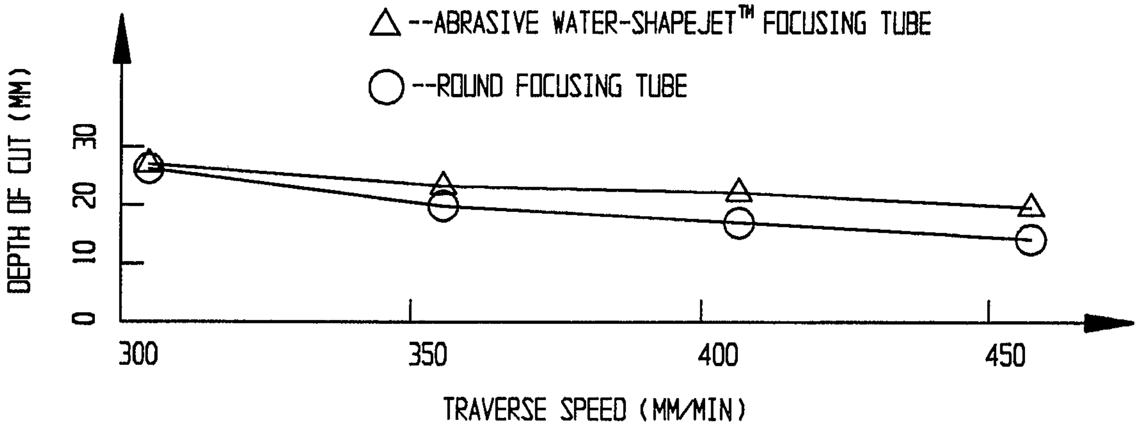
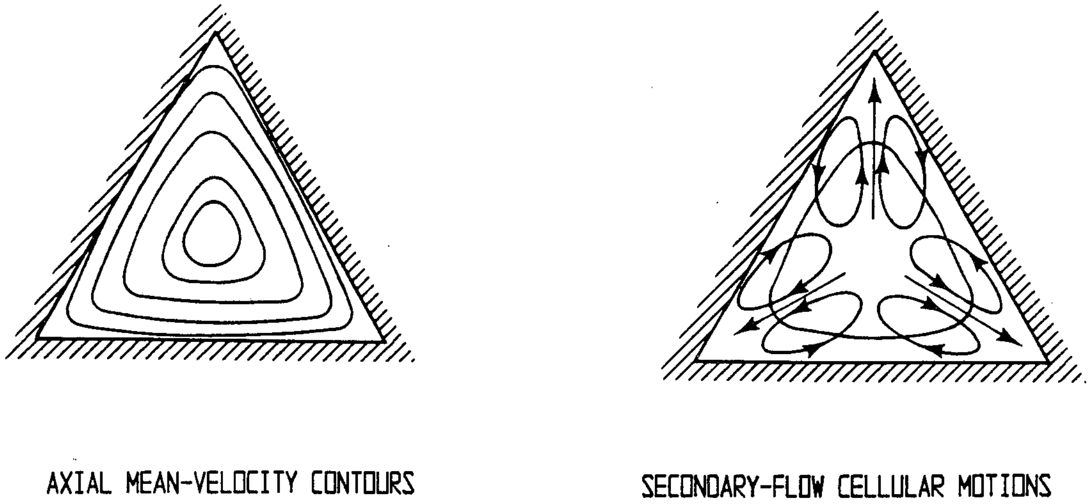
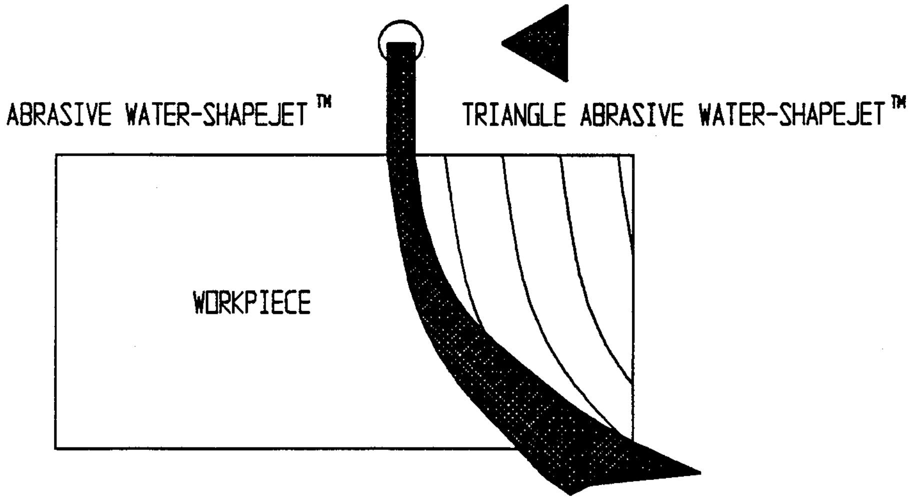


FIGURE 4



(A) FLOW PATTERNS IN TRIANGULAR CROSS SECTION



(B) SCHEMATIC OF ABRASIVE WATER-SHAPEJET™ MIXING PATTERN

FIGURE 5

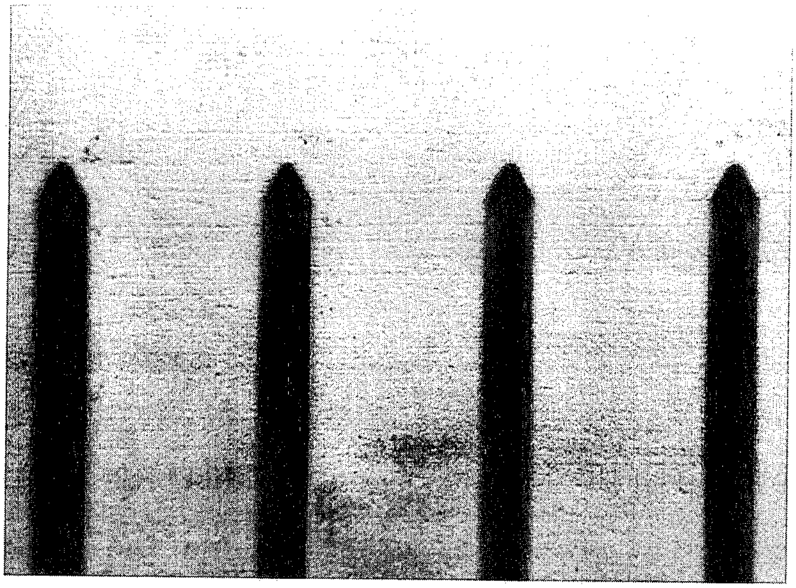


FIGURE 6 SHAPED KERFS PRODUCED BY ABRASIVE WATER-SHAPEJET™

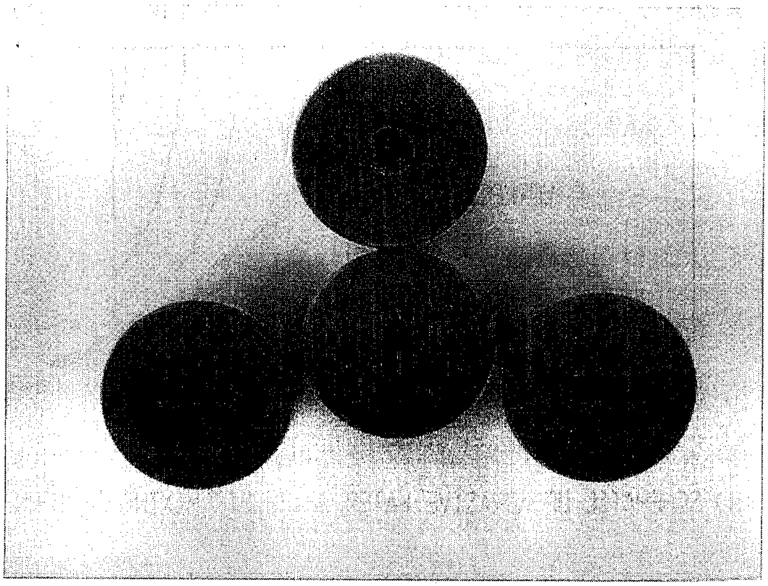


FIGURE 7 TYPICAL ABRASIVE WATER-SHAPEJET™ FOCUSING TUBES AND A CONVENTIONAL ROUND AWJ TUBE

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Paper 17

CUTTING REFRACTORY CERAMICS WITH ABRASIVE WATER JETS — A PRELIMINARY INVESTIGATION

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ABSTRACT

The paper discusses the material removal process of refractory ceramics cut by abrasive water jets. In particular, bauxite, sintered magnesia, and magnesia chromite, are cut in a wide range of pressures up to 350 MPa. The process parameters, such as pump pressure, traverse rate, abrasive flow rate, and abrasive type are changed during the experiments in order to find an optimum parameter combination. For all experiments, the depth of cut, the cut geometry, the surface structure of the generated cuts, and the material removal rates are measured and analyzed. Based on these measurements the specific energies are estimated. Using SEM microscopy it is found that the material removal mechanism changes with the depth of cut. In the upper region the main material removal mechanism is the simultaneously cutting of matrix and inclusion grains (transgranular). In the lower range of the cut the removal process is characterized by the removal of the binding matrix followed by a washing of the inclusion grains (intergranular).

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Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

The development of high quality refractory materials by the ceramic industry brought up latent problems with the machinability of the bricks being manufactured. To produce bricks of complex shape, advanced pressing methods, such as hot isostatic pressing, have been introduced. Unfortunately, this has led to high production costs and the produced refractory bricks have became very expensive. Abrasive water jet (AWJ) machining could be one of the possible solutions for manufacturing high quality refractory bricks of special shapes and formats. Despite these needs, the number of serious investigations on the machinability of ceramics by AWJs is comparatively low. An early attempt to use this tool for the machining of ceramic materials was made by Kim et al. (1985) who investigated ceramic stock removal using an AWJ. They conducted piercing and cutting experiments on alumina ceramics and discussed the influence of several process parameters on the piercing process. They could demonstrate that the AWJ can effectively be used to machine even high strength ceramics. Neusen et al. (1987) carried out cutting experiments on aluminum-silicon carbide and observed smearing of aluminum on the cut surface as well as embedding of fractured abrasive particles. They identified wear by individual abrasive particles as one of the micro mechanisms of material removal. Later, Freist et al. (1989) reported about the application of AWJs for the three-dimensional machining (milling) of alumina ceramics. This work included the development of a kerf geometry model as well as a limited parameter study. Hamatani and Ramulu (1990) used AWJ for piercing of ceramics. They found random damage generated by the AWJ on the top surface of the pierced holes as well as non-linear hole tapers. They also detected a notable increase in the target temperature and concluded that AWJ machining of ceramics may not be totally free of thermal effects. Zeng and Kim (1991) conducted SEM observations to evaluate the behavior of sintered aluminum oxide ceramics subjected to AWJs under different jet impingement angles. They observed intergranular cracking and plastic flow as the two major material removal mechanisms. The intergranular fracture dominates the material removal mode in the normal impingement, and has equal significance to the plastic flow for the small angle impact. In an advanced investigation, Zeng and Kim (1992) developed a material removal model as well as a kerf cutting model for brittle materials processed by AWJs. To verify their model they carried out cutting experiment under different process conditions, such as different pump pressures, traverse rates, abrasive flow rates, and AWJ nozzle diameter. Nevertheless, Momber and Kovacevic (1995a) found that intergranular fracture dominates the removal process only in materials that are characterized by a low strength matrix and fine inclusion grains. For materials with comparatively high matrix strength and coarse inclusions, cracking occurs through the matrix as well as through the inclusion grains and the failure is dominated by transgranular fracture. Ramulu et al. (1993) machined composite ceramics by AWJ at shallow impacting angles and observed erosion by microcutting in the matrix whereas the inclusions were removed by the shoveling action of the oncoming jet. In contrast to the kinetic process model, Kahlman et al. (1993), who observed the formation of high local temperatures (about 1280 °C) on the surfaces of ceramics during the AWJ cutting process introduced the failure of ceramic materials by thermal spalling. They assumed that the cooling by the water flow creates local stress fields. Based on SEM photographs and wear volume measurements these references defined the thermal shock resistance, R', as the main resistance parameter against AWJ machining action and defined a machining limit for ceramics at R' = 15 W/mm. Above this value the material removal rapidly decreases. Hochheng and Cheng (1994) reported about volume removal studies on aluminum oxide and silicon nitride ceramics. In their study, they investigated the influence of several process parameters, such as pump pressure and abrasive flow rate, on material removal rate and surface quality. Nevertheless, no attempt was made to discuss the presented experimental results in terms of basic material removal mechanisms.

2. INVESTIGATED MATERIALS AND EXPERIMENTAL SETUP

Three different types of commercial refractory ceramics were used in this study. The mechanical properties of the materials are listed in Table 1. Magnesia bricks are used as lining material for steel and cement furnaces. It consists mainly of periclase (95%). It has a high melting point and a high Young's modulus, but behaves very brittle under load. Magnesia chromite is used for the lining of steel and cement furnaces, and for non ferrous metal kilns where high spalling resistance and high temperature resistance are needed. The chromite phase reduces the Young's modulus but induces some plastification capability. Bauxite bricks are commonly used in the steel industry. The material mainly contains corundum (50%-70%) and mullite (25%-35%). It has an average Young's modulus and a relatively high compressive strength. Generally, the temperature resistance is low.

The abrasive water jet cutting unit used in this study consists of an intensifier pump, an abrasive cutting head, an abrasive storage and metering system, a catcher, and a x-y-z-positioning table. The cutting conditions are listed in Table 2. After cutting, the depth of cut, h, and the width of the cut, b, were estimated as the average of five measurements on every cut. The material removal rate, $\dot{V}_M$, was calculated by

$$\dot{V}_M = h \cdot b \cdot v, \tag{1}$$

where v is the traverse rate. The specific energy of the material removal process, E_{SP}, was calculated using

$$E_{SP} = \frac{E_A}{h \cdot b \cdot L}. \tag{2}$$

Here, E_A is the kinetic energy of the AWJ, and L is the length of the cut. For the surface measurements, a mechanical roughness measurement unit was used with different cut-offs.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Aspects of Parameter Optimization

In order to optimize the cutting process, the most important process parameters from the practical point of view, such as pump pressure (p), traverse rate (v), abrasive flow rate ($\dot{m}_P$), and abrasive type were varied.

Fig. 1a shows the influences of the applied pump pressure and of the abrasive type on the depth of cut. The generally linear trend as shown in this figure was observed under all cutting conditions and for all materials. The mathematical expression is

$$h(p) = C_1 \cdot (p - p_{thr}) . \tag{3}$$

The same qualitative trend is shown in Fig. 2a for the relation between the applied pump pressure and the volume removal rate confirming results from Hochheng and Chang (1994). In Eq. (3), the parameter p_{thr} is the threshold pressure which describes a critical abrasive velocity which must be overcome to introduce the damage process under the given conditions. It is interesting to note that the threshold pressure of the sintered bauxite does not depend on the abrasive type whereas the established cutting process is very strongly influenced by the abrasive type. Using corundum for cutting, the depth of cut can be doubled over the entire pressure range. Therefore, the constant C_1 in Eq. (3) may be very sensitive to the abrasive type. In Fig. 3a the specific energy is plotted versus the applied pump pressure. The high values for bauxite are due to the lower traverse rate used for this material. For this material the specific energy shows a strong relation to the pump pressure for low and medium pressures. In contrast, the specific energy values of the magnesia samples are not significantly influenced by the applied pump pressure. They show only a weak linear progress.

The influence of the traverse rate on the depth of cut is shown in Fig. 1b. These relations can reasonably be approximated by a parabolic equation as

$$h(v) = \frac{C_2}{v^{C_3}} . \tag{4}$$

The materials are sensitive against changes in the traverse rate especially in the range of low traverse rates (up to 4 mm/s). For traverse rates beyond this value, there is not a significant change in the depth of cut. A different trend is shown in Fig. 2b for the relation between traverse rate and volume removal rate. In this case the trend is almost linearly increasing. Every increase in the traverse rate leads to an increase in the volume removed per unit time. This observation is important for milling and turning of the ceramic materials with abrasive water jets. As Fig. 3b shows, the specific energy drop is approximately linear with increasing traverse rate. This tendency is very clear for the bauxite sample which also requires comparatively high specific material removal energies.

Fig. 1c shows the relation between the abrasive flow rate and the depth of cut. There is a linear trend with a constant progress for both materials for low abrasive flow rates. Later, at about $\dot{m}_P$ = 5 g/s, the progress starts to drop. A mathematical expression to describe these relations may be

$$h(\dot{m}_P) = h_0 \cdot \left(1 - e^{-C_4 \cdot \dot{m}_P}\right). \tag{5}$$

Here, h_0 is a maximum depth of cut which can be achieved under the given cutting conditions. It is very interesting that the ceramic materials show an identical behavior for low abrasive flow rates. Beyond an abrasive flow rate of about $\dot{m}_P = 8$ g/s the functions for the materials are very different. In this range, the magnesia chromite shows a significant increase in the depth of cut with rising abrasive flow rate, whereas the depth of cut in sintered magnesia remains approximately constant. A further increase in the abrasive flow rate does not lead to any improvement of the cutting process in magnesia chromite. A similar observation was made by Hochheng and Chang (1994) for ceramic processing at high pressures and coarse abrasive particles. Therefore, the parameter h_0 in Eq. (5) is much higher for the magnesia chromite. These observations show also that the equal depths of cut for both these materials presented in Fig. 1b are valid only for comparatively small abrasive flow rates. Fig. 2c exhibits the relation between the abrasive flow rate and the volume removal rate. For the sintered magnesia the trend is linear with a constant progress over the investigated abrasive flow rate range. In contrast, the curve for magnesia chromite shows a significant drop in the progress at abrasive flow rates larger than $\dot{m}_P = 8$ g/s. These observations are in agreement with the conditions shown in Fig. 1c. The specific energy drops with an increase of the abrasive flow rate as illustrated in Fig. 3c. The drop is linear with a very sharp progress for the magnesia chromite over the entire parameter range, as well as for the sintered magnesia in the range of small abrasive flow rates.

3.2 Aspects of Cut Quality

Fig. 4a shows the relation between the applied pump pressure and the width of the cut in magnesia chromite. The measured values are comparable to cut width measurement results from Hochheng and Chang (1994). There is no general tendency detectable in Fig. 4a but it can be seen that most of the cuts are tapered. Usually the top width is smaller than the width on the bottom of the cut. Exceptions are the cuts generated with pressures at 150 MPa and 250 MPa where the top width and the bottom width of the cuts are equal.

In Fig. 4b the cut widths are plotted against the traverse rate. There is a general trend visible that the cut widths on both locations, especially on the top, can be reduced by increasing traverse rate. The same trend was observed by Hochheng and Chang (1994) for alumina ceramics. Also, the taper can significantly be reduced with higher traverse rates. It is interesting to note a transition point at a traverse rate between $v = 3$ mm/s and $v = 4$ mm/s. At this point, the direction of the taper changes, or in other words, the width on the top of the cut exceeds that on the bottom of the cut. It was also observed that the average roughness of the cut surface decreases slightly with increasing traverse rate.

The influence of the abrasive flow rate on the cut geometry is shown in Fig. 4c. The width of the cut on the top as well as on the bottom increases almost linearly with increasing abrasive flow rate. Here, also a transition point can be noticed at a abrasive flow rate of $\dot{m}_P = 12$ g/s.

Fig. 5 shows the relation between the abrasive flow rate and the average roughness estimated on bauxite samples. The roughness values of about $R_a = 20$ μm are comparatively high compared to those measured by Hochheng and Chang (1994) on alumina ceramics

($R_a \cong 1.5$ μm). The reason may be the different locations of the roughness measurements in both studies. Hochheng and Chang (1994) used thin ceramic plates (thickness between 5 mm and 10 mm) and cut them through which usually yields low roughness values. Also, differences in the structure of the investigated materials may play a role. It can be seen from Fig. 5 that the average roughness decreases with increasing abrasive flow rate. Fig. 6 shows that the average roughness of the cut surface is significantly higher for AWJ cutting compared to diamond saw cutting.

4. MATERIAL REMOVAL PROCESS OBSERVATIONS

To understand the material removal processes involved in the machining of the ceramic materials, SEM studies have been carried out under different failure modes. Selected material samples are subjected to conventional tensile fracture, to diamond saw cutting, and to abrasive water jet cutting. For the discussion the results obtained on the sintered magnesia are used here. They are typical for the behavior of all investigated materials. Fig. 7 shows the surface of a fractured magnesia sample after the tensile test. The fracture is characterized by smooth surfaces and open pores with sharp pore edges. Obviously, these sphere shaped pores are originally isolated and closed, and are cut by penetrating cracks. The mechanism of the diamond saw cutting process is illustrated in Fig. 8. Here, a dark line goes through the figure indicating a sawing groove. Single diamond grains may remove small material particles and store them later in pores and cavities generating the dark cutting path. Therefore, open pores that may exist can not be observed in this figure. The fracture structure is very similar to that of the tensile fracture. In the top region the very smooth fracture surface of a periclase grain can be seen. It was also observed that some grains are pulled out. Fig. 9 shows a SEM photograph of the smooth cutting zone of a magnesia sample cut by AWJ. In the right top region a very smooth cut surface can be noticed, including open pores as observed during the brittle fracture of the material. The left side of the photograph shows periclase fragments. Obviously, the periclase grains are fractured due to the AWJ action. In this range, open pores with sharp edges can be seen, too. The material removal process can be characterized by transgranular fracture through matrix and inclusions. The situation is very different in Fig. 10 showing the exit zone of the same cut. Here, the periclase grains are completely intact but the matrix between them is removed. A further magnification has shown that penetrating cracks are stopped by the hard periclase inclusions. No open pores were found. This indicates a intergranular material removal mode. A systematic observation of the entire cutting front (from the entry to the exit) did not give any indication of an abrupt changing in the material removal mechanism. The changing from transgranular fracture on the top of the cut to the intergranular removal process is steady. This result supports the idea of a continuous energy loss of the abrasive water jet in the cut as recently supposed by Momber and Kovacevic (1994, 1995) and Raju and Ramulu (1994). In the beginning of the cutting process the single abrasive grains have sufficient kinetic energy to contribute to the cutting process. This assumption is supported by the existence of many single small fracture areas as shown in the left side of Fig. 9. The energy is high enough to cut the harder periclase grains (Vickers hardness of about 700 kg/mm^2). Due to friction, damping and generation of wear particles the AWJ will lose part of its kinetic energy during the cutting process. On the lower part of the cut the AWJ, which has a reduced kinetic energy can no longer destroy the inclusions, but can only remove the weaker matrix between single periclase grains.

5. SUMMARY

The results of the study can be summarized as follows:

- Abrasive water jets (AWJ) can generally be used to machine high quality refractory ceramics (bauxite, sintered magnesia, magnesia chromite) but from the point of view of economy as well as of surface quality AWJs will not be able to replace existing cutting methods, such as diamond sawing, for straight cutting operations.
- Material removal rates between 200 mm^3/s and 300 mm^3/s are achievable by using optimum process parameter combinations. Positive are high applied pump pressures, high traverse rates, and high abrasive flow rates. The usage of corundum can double the cutting efficiency compared to garnet for the materials investigated in this study.
- The specific material removal energy can be optimized. The lowest value obtained in this study was $E_{SP} = 100\ J/mm^3$. Positive are medium pump pressures, high traverse rate, and high abrasive flow rate.
- The cuts generated by AWJ are generally tapered.
- The roughness of the AWJ generated surfaces is high compared to surfaces created by diamond saw cutting. The roughness depends on the applied process parameters as well as on the processed material. The roughness is low for bauxite and high for magnesia chromite.
- The material removal process is a mixture between transgranular fracture and intergranular fracture. In the upper cutting zone transgranular fracture dominates whereas the bottom zone is characterized by intergranular fracture. These observations are explained by using the model for a continual loss in kinetic energy of the AWJ during the cutting process.

6. ACKNOWLEDGEMENTS

The authors are thankful to the Alexander-von-Humboldt Foundation, Bonn, Germany, and to the Center for Robotics and Manufacturing Systems, University of Kentucky, Lexington, KY, for financial support. Thanks is directed to Veitsch Radex AG, Austria, for delivering the ceramic specimens.

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Table 1. Mechanical Properties of the Investigated Refractory Ceramics.

Property → / Material ↓	Density [g/cm³]	Porosity [%]	Cold Compressive Strength [MPa]	Cold Bending Tensile Strength [MPa]	Young's Modulus [MPa]
Bauxite	2.89	15	126	19	59,00
Sintered Magnesia	3.00	15±2	40	14	85,00
Magnesia Cromite	3.26	15±2	30	3.5	13,00

Table 2. Cutting Conditions.

Parameter	Pump Pressure	Traverse Rate	Abrasive Flow rate	Abrasive Type	Focus Diameter	Focus Length	Orifice Diameter
Unit	MPa	mm/s	g/s	-	mm	mm	mm
Range	100 - 350	0.5 - 8.0	4.54-14.82	garnet # 36 corundum # 100	1.27	88.9	0.389

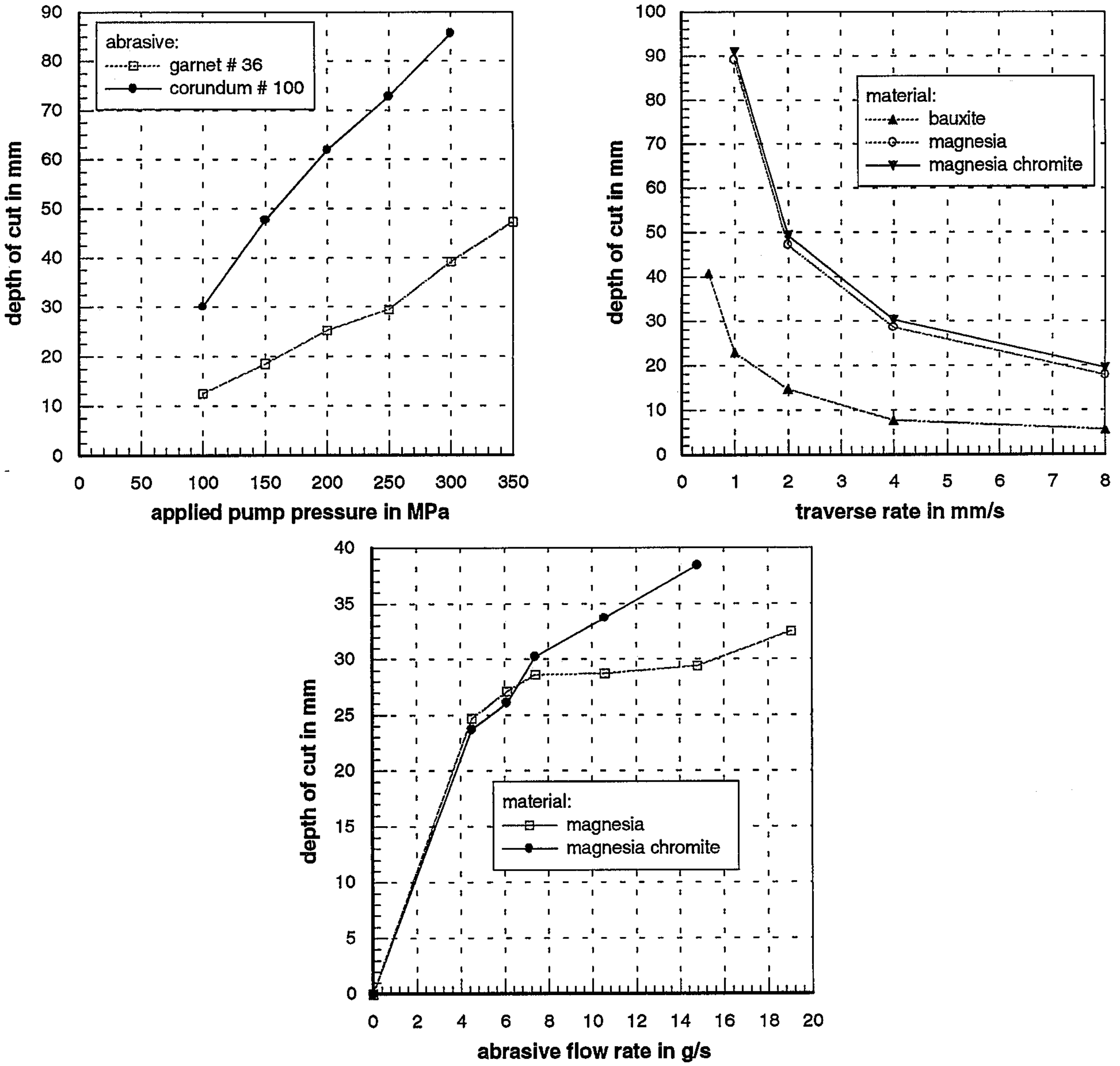

Figure 1. Parameter Influence on the Depth of Cut in Refractory Ceramic Samples.
a - Pump Pressure, b - Traverse Rate, c - Abrasive Flow Rate

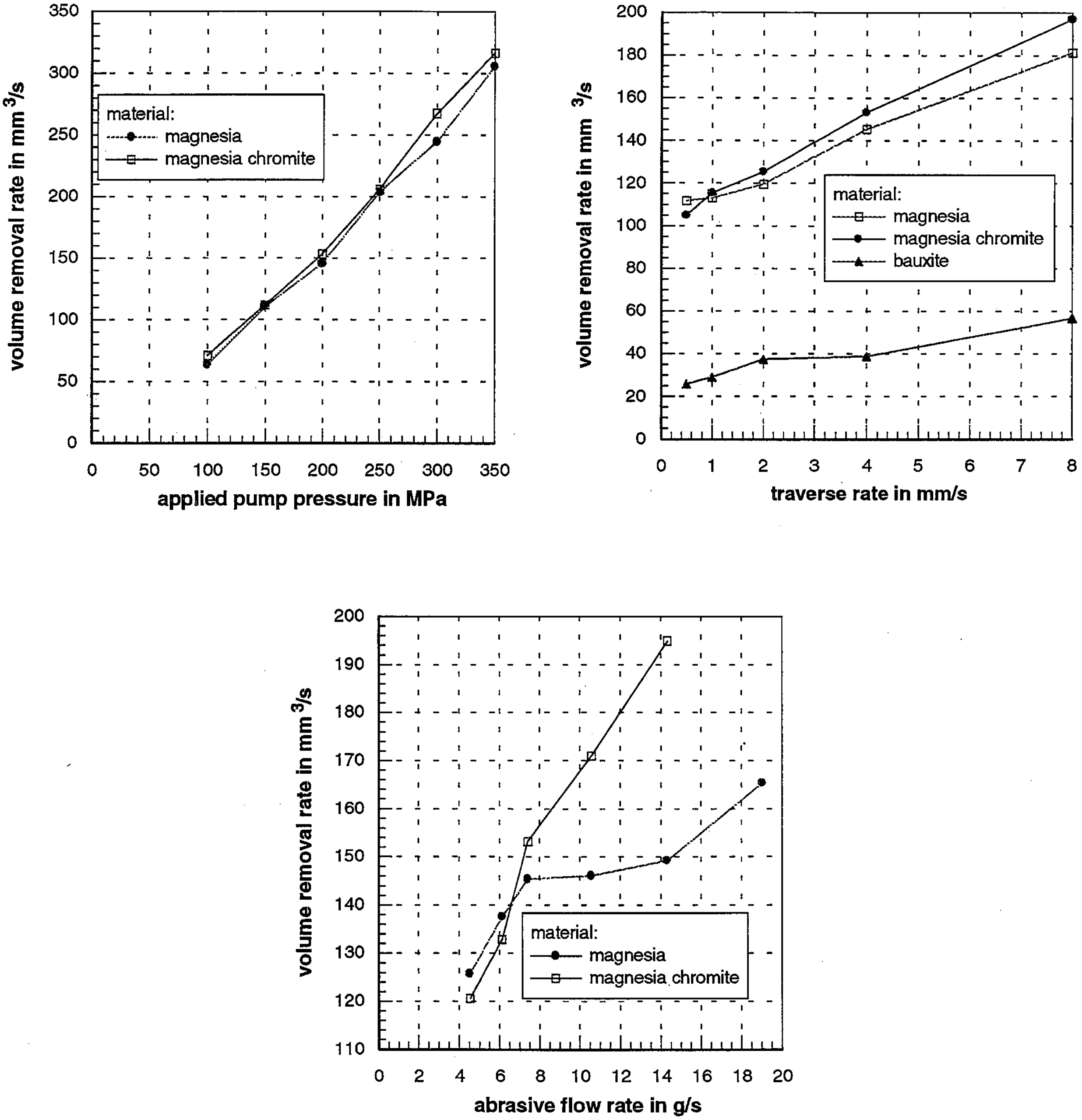

Figure 2. Parameter Influence on the Material Removal Rate in Refractory Ceramics.
a - Pump Pressure, b - Traverse Rate, c - Abrasive Flow rate

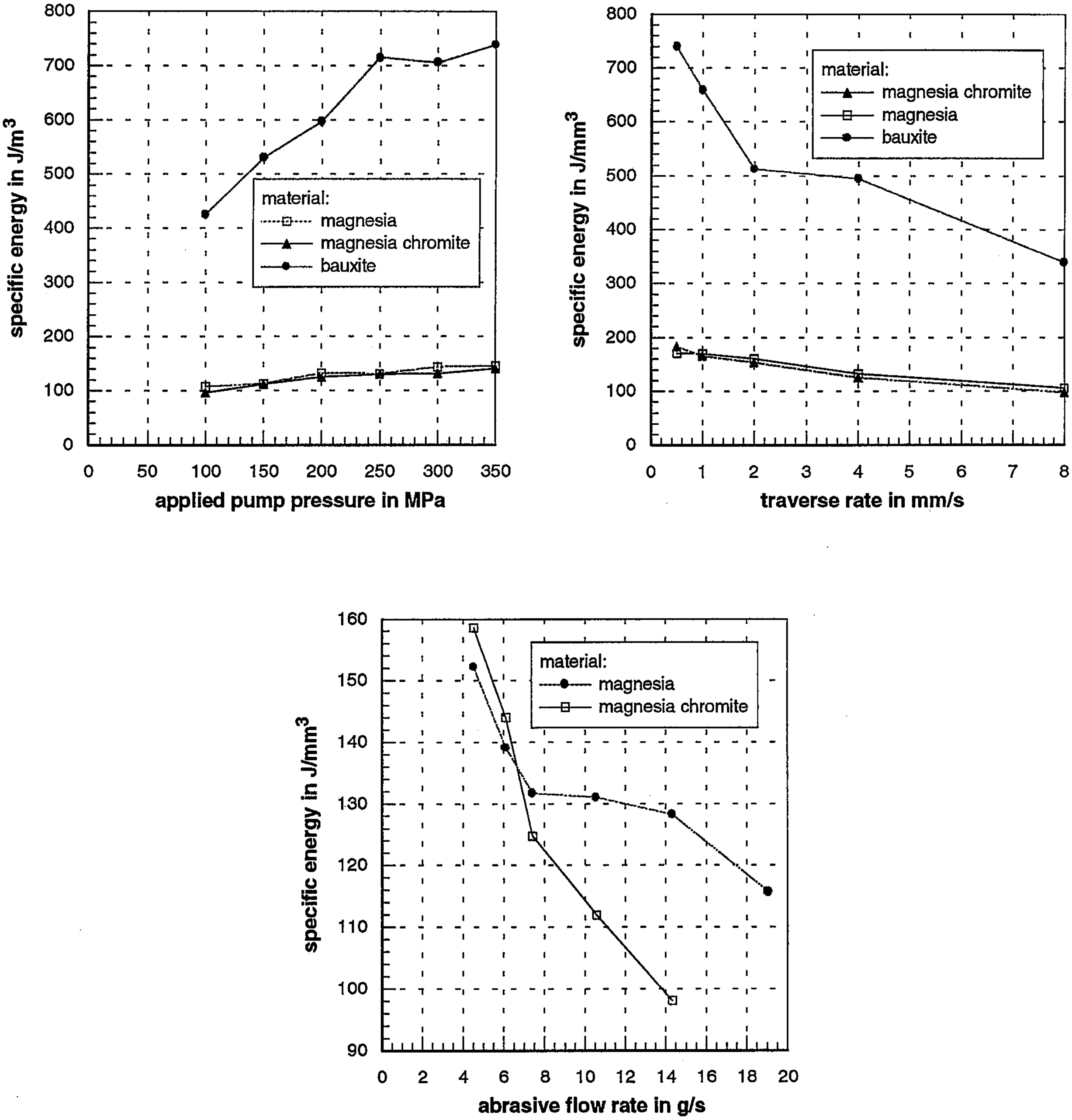

Figure 3. Parameter Influence on the Specific Removal Energy in Refractory Ceramics.
a - Pump Pressure, b - Traverse Rate, c - Abrasive Flow rate

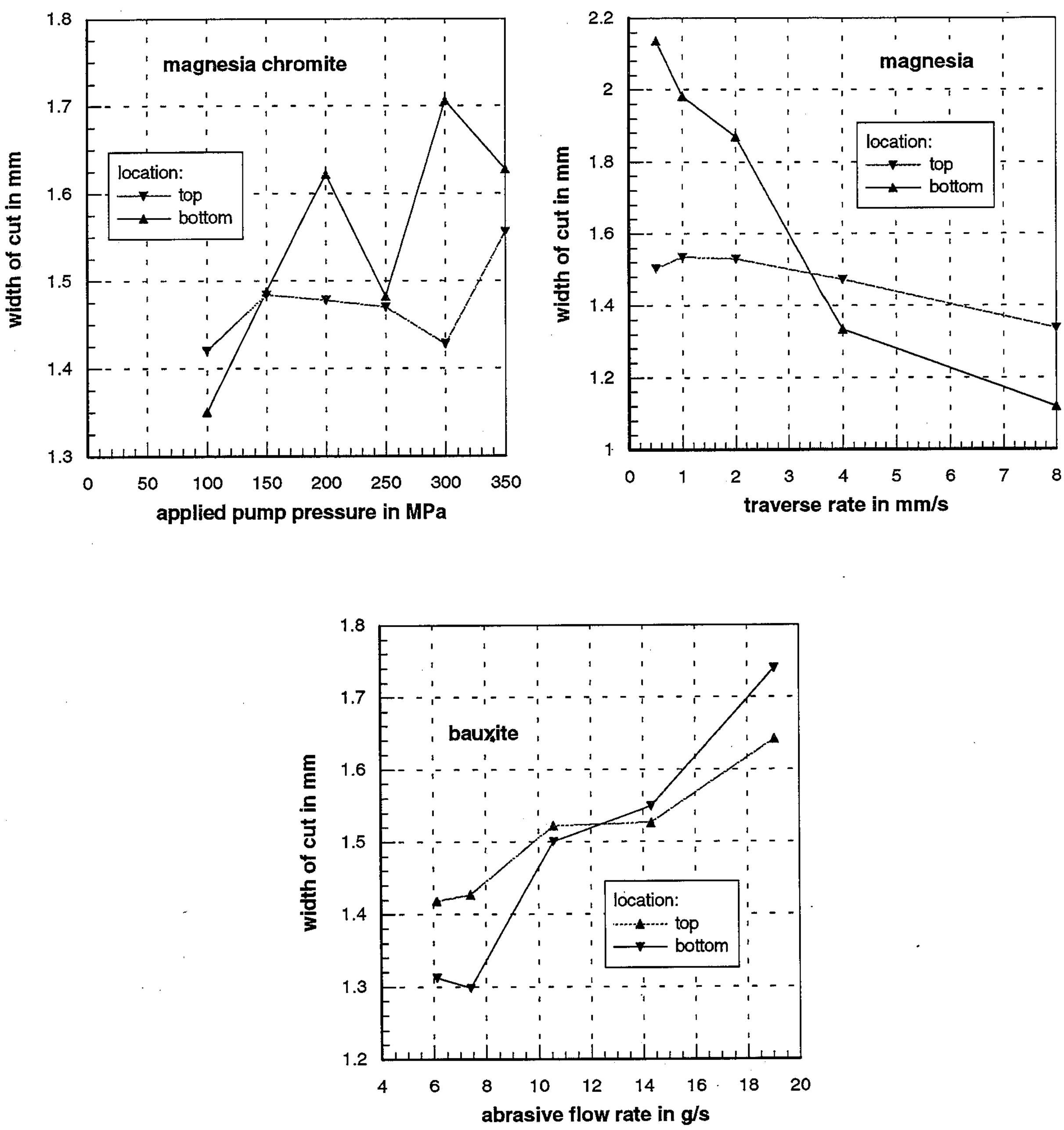

Figure 4. Parameter Influence on the Cut Geometry in Refractory Ceramics.
a - Pump Pressure, b - Traverse Rate, c - Abrasive Flow Rate

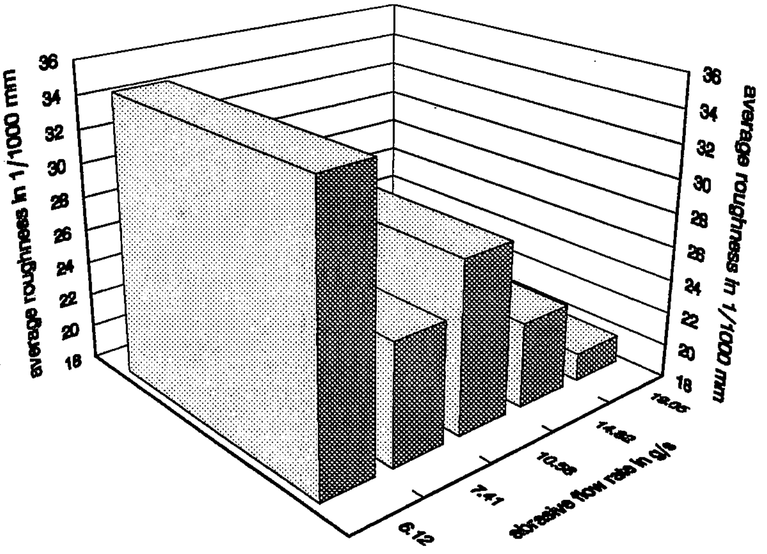

Figure 5. Relation Between Abrasive Flow Rate and Roughness (Bauxite).

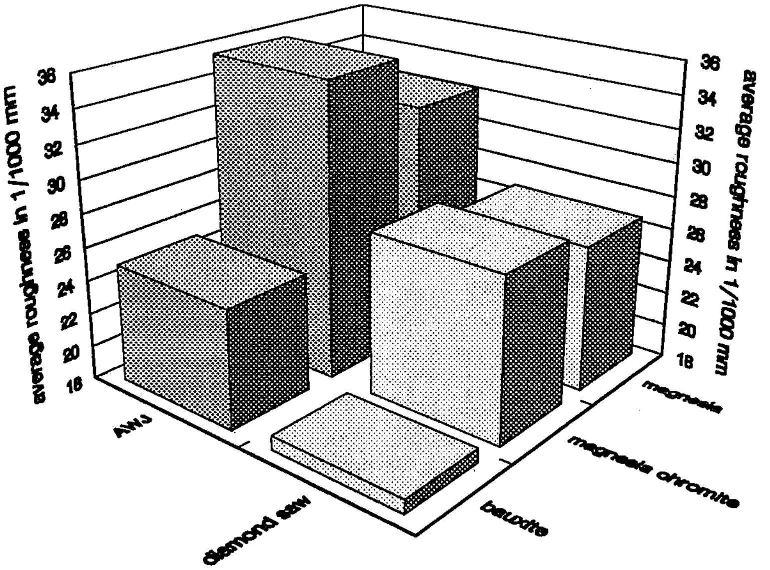

Figure 6. Surface Roughness of Refractory Ceramics Cut by Diamond Saw and by Abrasive Water Jet.

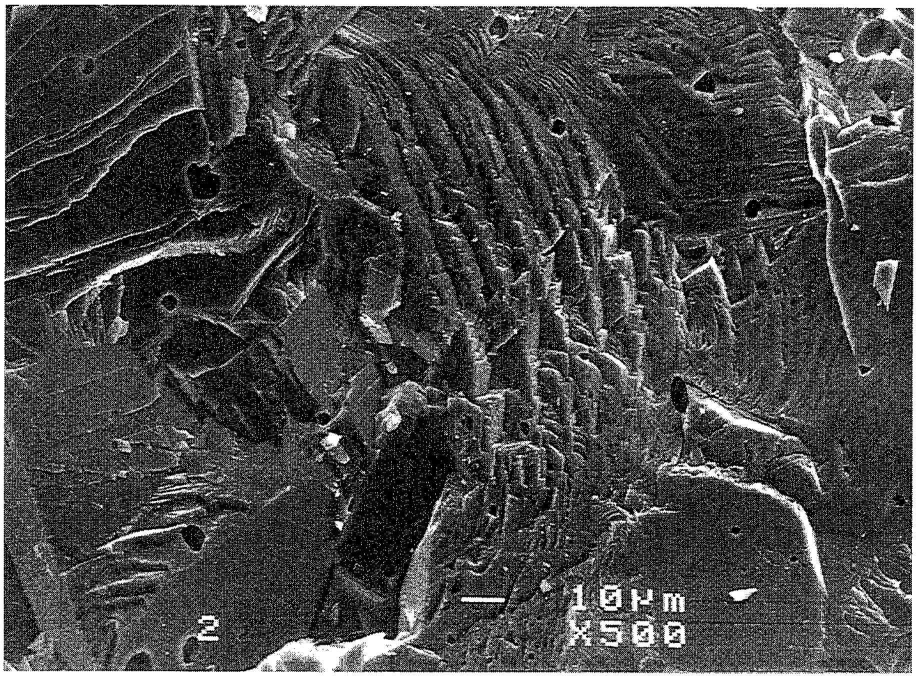

Figure 7. SEM Image of a Mechanically Fractured Magnesia Sample.

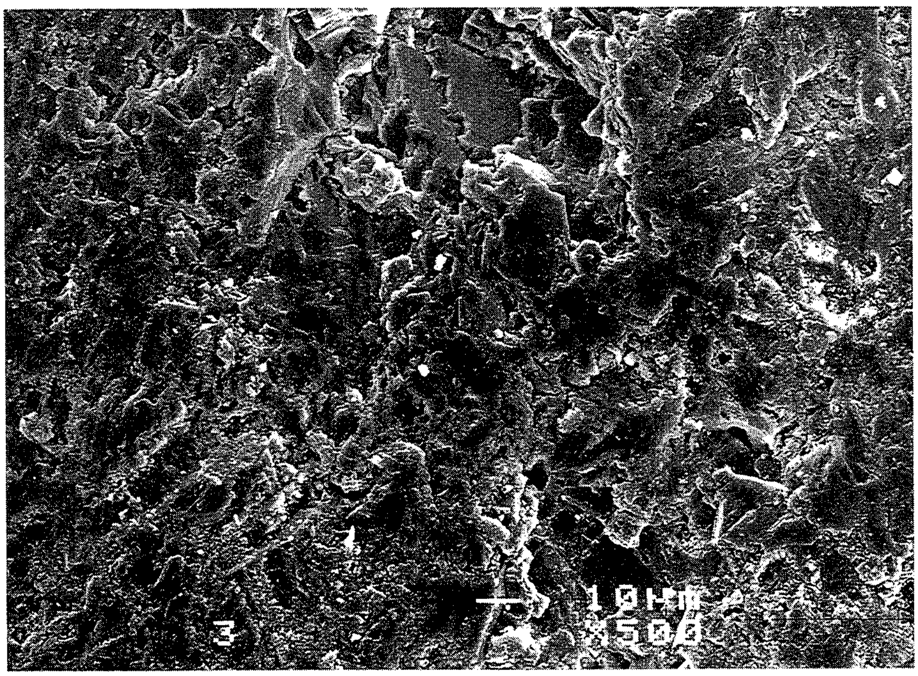

Figure 8. SEM Image of a Magnesia Sample Cut by Diamond Saw.

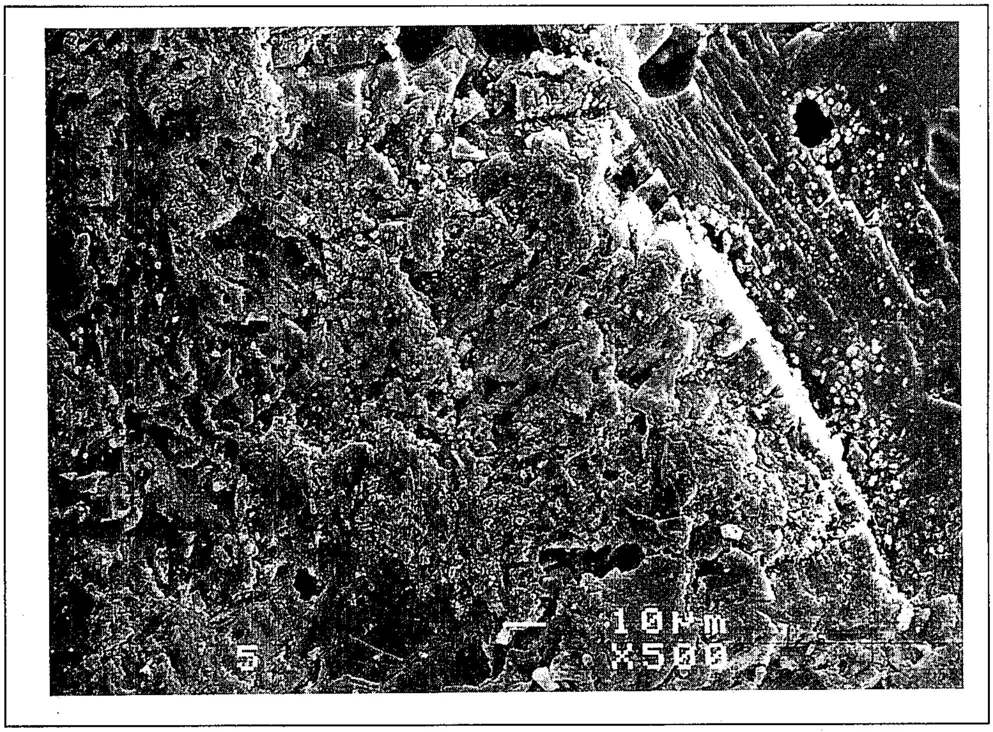

Figure 9. SEM Image of a Magnesia Sample Cut by Abrasive Water Jet.
(Smooth Cutting Zone)

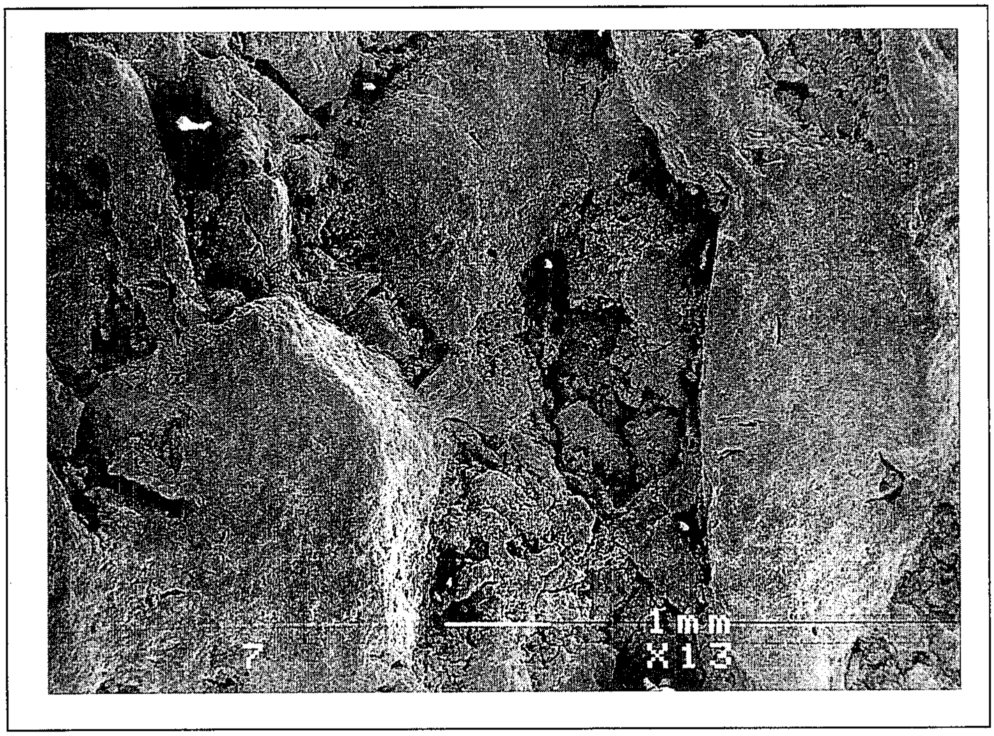

Figure 10. SEM Image of a Magnesia Sample Cut by Abrasive Water Jet.
(Rough Cutting Zone)

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Paper. 18

MICROSTRUCTURAL AND MECHANICAL CHARACTERIZATION OF THREADED COMPOSITE TUBES MACHINED USING AWJ CUTTING

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ABSTRACT

Joining of composite components is typically achieved by either adhesive bonding and/or bolted connections. These techniques are well developed and reliable design methodologies have been established. In this paper, the feasibility of using an alternate method, threaded joints, to join composite components is explored. Effective manufacture of threaded composites is made possible by the application of the abrasive waterjet machining process. Microstructural examination of machined threads reveal minimal microstructural damage. Mechanical characterization of threaded joint strength reveals a strong dependance of joint strength on composite fiber orientation. Numerical stress analysis of these joints provides estimates of potential joint strengths achievable with threaded composite joint connections. To demonstrate the potential for successful application of threaded composite joints, these estimates are compared with predicted strengths using a conventional composite joining technique. In addition, results of this experimental and numerical study provide the basis for guidelines for the design of threaded composite joints.

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1. INTRODUCTION

In the design of components constructed from fiber reinforced composite materials, the strength of the component is often limited by the strength of the joint to adjacent components. As a result, joining techniques such as adhesive bonding and bolted joints have received considerable attention. Recently, another joining technique, threaded joints, has also been considered for composite materials (Seidel, 1989, Dilintas, 1991 and 1992). The primary advantage of threaded joints is easy assembly and disassembly. Unfortunately, threaded joints are often impractical due to difficulties in machining high quality threads. As compared to monolithic material, machining of composites is complicated by the mismatch of material properties between the fiber and matrix phases. Also, in polymer matrix composites, even small amounts of machining induced heating can result in matrix damage. As a result, machining of composites with conventional techniques requires the use of coolants to prevent matrix damage.

It has been demonstrated the abrasive waterjet (AWJ) cutting is an excellent method for machining composite materials (Hashish, 1988, Arola and Ramulu, 1993, and Ramulu and Arola, 1993). In these studies, it has been shown that very high quality surface finish with minimal machining induced damage can be achieved. This result is attributed to the lack of localized heating due to the cooling provided by the water. Also, AWJ provides a flexible method for machining a variety of geometric shapes. In this study, the use of AWJ to machine threads in composite materials is explored. The strength of these joints is characterized and analyzed in an effort to assess the potential application of AWJ machined threaded composite joints.

2. MACHINING OF COMPOSITE THREADS

A study was performed in the Waterjet Laboratory of the University of Rhode Island to identify an effective procedure for machining external threads in composite rods and tubes. The URI Waterjet Laboratory is equipped with a Flow International 9XD-55 series dual intensifier pump, a model 414 Shape Cutter, a Dynapath Delta 10M CNC controller and a PASER II™ abrasive cutting head. To machine composite threads, a lathe was used to rotate the composite shaft while the waterjet traversed parallel to the rod axis. By controlling the angular speed of the rod, the axial traverse speed of the waterjet and the distance from the jet to the center of the rod (the crossfeed), a spiral groove (or screw thread) is machined in the shaft. A schematic of this experimental configuration is shown in Fig. 1. A photograph of the experiment is shown in Fig. 2. In the initial study to identify effective AWJ machining parameters, a 1.27 cm (0.5 in) OD unidirectional carbon fiber reinforced epoxy rod was examined.

It was found that the quality and dimensions of the thread can be controlled by adjusting the traverse speed, the crossfeed, the mixing tube nozzle bore and the orifice bore. A schematic of the PASER II mixing head is shown in Fig. 3. In the mixing head, a fine stream of high

™PASER II is a trademark of Flow International Corporation velocity water is accelerated in the orifice and is then mixed with abrasive in the mixing tube or nozzle. It was found that a nozzle bore of 0.0762 cm (0.03 in) and an orifice bore of 0.0254 cm (0.01 in) gives a good quality thread profile. Traverse speeds of 5.08 - 6.35 mm/sec (12-15 in/min) were found to give good result. Fig. 4 shows a typical thread profile obtained using these AWJ machining parameters. Details of this study are discussed by Sheridan et al., 1994.

The desired thread geometry was an ACME B1.5-1977 general purpose single start screw thread (see Fig. 5). Comparing Figs. 4 and 5, it can be seen that the actual thread profile obtained with AWJ closely matches the desired profile. As shown in Fig. 6, a standard ACME steel nut screws easily on the composite threads with minimal slack. One important difference between the AWJ machined profile and the desired profile are the rounded corners at the intersections of the side wall and the root and the side wall and the crest of the thread. Another important difference is the asymmetry of the thread angle. As discussed by Sheridan et al., 1994, this asymmetry is associated with the bidirectional deflection of the jet away from both the traverse direction and the axis of rotation of the shaft. As will be discussed below, the asymmetric thread angle is believed to degrade the strength of the threaded joint. The rounded corners, however, are believed to have little effect on the threaded joint strength.

A scanning electron microscopy study of the machined threads reveals an excellent surface finish. In particular, along the thread walls, root and crest regions, a very clean surface with little matrix or fiber damage is observed. This microstructure is similar to that reported previously (Ramulu and Arola, 1993). At the corners between the side wall and the root and the side wall and the crest, some frayed fibers are observed, indicating matrix damage and fiber pullout. As discussed below, this localized damage, especially at the thread root, is expected to degrade the threaded joint strength.

3. CHARACTERIZATION OF THREAD STRENGTH

To assess the load bearing capacity of threaded joints, a series of experiments was performed on 2.22 cm (0.875 in) OD, 0.953 cm (0.375 in) ID carbon fiber reinforced epoxy tubes. In these tubes, screw threads were machined using the AWJ machining parameters discussed above. A steel nut was the screwed on to the composite shaft. As shown in Fig. 7, the composite shaft / steel nut assembly was inserted into a tensile test fixture designed to pull the nut off of the shaft. To securely attach the other end of the composite shaft to the testing machine, an aluminum plug was machined and bonded to the ID of the shaft and a hole was drilled through the shaft and the aluminum plug. A steel pin was then used to attach the shaft to the base of an Instron model 1125 testing machine. This configuration provided adequate strength such that failure of the assembly occurred at the threaded joint.

To evaluate the effect of composite layup on threaded joint strength, two configurations were evaluated. In the first configuration, the fibers were aligned with the axis of the shaft. The other configuration consisted a woven fabric which was wrapped around a cylindrical mandrel. The primary difference between these configurations is the circumferential orientation of approx. 50% of the fibers in the woven fabric reinforced shaft as compared to 100% axial fibers in the unidirectional fiber reinforced shaft. Also, the crimp in the weave provides a small amount of fiber reinforcement in the radial direction. As discussed below, this radial reinforcement is believed to significantly enhance the strength of the composite threaded joint.

Typical load vs. time curves are shown in Fig. 8. As shown in Fig. 8a, the unidirectional fiber reinforced shaft fails at a relatively low load levels. Disassembly of the joint revealed that failure was due to shearing of the composite threads. Due to the unidirectional fiber orientation, the threads are sheared by cracking through the matrix with minimal fiber breakage. By comparison, the woven fabric shaft failures exhibit a series of load drops (see Fig. 8b). Again, failure is observed to be due to shearing of the threads. In this case, however, the crimp in the weave provides some fiber reinforcement across the thread. Therefore, shear failure of the thread requires some fiber failure. As a result, the strength of the woven fabric threads is significantly higher than that of the unidirectional fiber reinforced composite threads. The average maximum axial stress applied to the unidirectional and woven fabric reinforced shafts was 28.2 MPa (4,070 psi) and 47.4 MPa (6,850 psi), respectively.

4. ANALYSIS OF THREAD STRENGTH

To better understand the effect of thread profile and composite configuration on thread strength, a finite element analysis was performed. The analysis was performed using the software package I-DEAS™ to create the model geometry and the finite element analysis program ABAQUS™ to perform the analysis. The axisymmetric finite element model, designed to simulate the thread strength experiment discussed above, is shown in Fig. 9. Note that the actual AWJ machined composite thread profile was modeled. The steel nut profile was assumed to exactly match the ACME standard. As a result, contact between the steel nut and the composite thread is made at a single contact point for each thread. The boundary conditions imposed are zero axial displacement at the base of the steel nut and a uniform axial tensile stress applied at the lower boundary of the composite shaft. The steel nut elastic properties are taken to be a Young's modulus of 2.1 GPa (30 Msi) and a Poisson's ratio of 0.3. The cylindrically orthotropic elastic properties of the unidirectional and woven fabric reinforced composite are given in Table 1.

The results of the finite element analysis are shown in Figs. 10 and 11. In Fig. 10, the von Mises effective stress distribution is shown. The von Mises effective stress is defined as $(3/2\ s_{ij}s_{ij})^{1/2}$ where $s_{ij}=\sigma_{ij}-(\sigma_{kk}/3)\delta_{ij}$ is the stress deviator, σ_{ij} are the components of the stress tensor and δ_{ij} is the Kronecker delta. In these definitions, note that repeated subscripts imply summation from 1 to 3. Figs. 10a and 10b show the von Mises stress contours for the unidirectional and woven fabric reinforced composite threads, respectively. Note that in Fig. 10, the stresses are normalized by the applied axial stress. In both cases, it can be seen that

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™ ABAQUS is a trademark of Hibbitt, Karlsson and Sorensen, Inc.

the threads nearest the base of the nut carry the largest load. Note that the higher axial modulus of the unidirectional thread (see Table I) results in a slightly higher concentration of stress on the first (lowest) thread. This effect leads one to predict a slightly higher strength for the woven fabric threads.

Since failure of the threads is observed to be a shear failure at the base of the composite thread, the axial shear stress, σ_{rz}, contours for the unidirectional and woven fabric reinforced shafts are shown in Figs. 11a and 11b, respectively. In these plots, the applied axial stress is taken to be the experimentally observed failure stress. It can be seen that the shear stress at the contact point is very high and decays rapidly along the length of the thread. It is believed that this high shear stress near the contact point initiates the failure of the thread. Since the woven fabric has some radial fiber reinforcement, the woven fabric reinforced shafts can withstand higher thread shear stresses prior to failure. This effect is believed to be the predominant explanation for the higher strength observed for the woven fabric reinforced shafts.

It is of interest to consider the relation between the stress analysis predictions and the AWJ machining results. The asymmetry of the thread angle results in a single contact point between the steel nut and the composite thread. The stress analysis shows that this results in a stress concentration at the thread root where shear failure of the thread is initiated. Clearly, improved control of the thread angle will give a more uniform load transfer from the nut to the composite thread. This will reduce the stress concentration at the thread root and will therefore improve joint strength. Another observation is that failure initiates at the rounded corner between the thread root and the thread side wall. In this region, scanning electron microscopy revealed matrix damage and fiber pullout. This localized damage may act as a flaw and may contribute to premature failure of the thread. Therefore, future studies of AWJ machined composite threads will attempt to improve control of the thread angle, eliminate thread asymmetry and reduce localized damage at the corner between the thread root and the side wall.

Finally, to evaluate the potential application of composite threaded joints, it is of interest to compare the potential strength of composite threaded joints to a conventional composite joining technique. As discussed above, it is believed that the axial stress resulting in threaded joint failure (28.2 MPa - 47.4 MPa, 4,070 psi - 6,850 psi) measured in this study are lower bounds and improvements in thread profile will yield higher joint strengths. Consider now a conventional adhesive bonded single lap joint. While predicting adhesive bond lap joint strength is a complex calculation involving consideration of both composite and adhesive properties, simple estimates of joint strength are given by Dastin, 1969. For a 1.27 cm (0.5 in) single lap joint (similar in dimension to the threaded joint length considered in this study), Dastin's estimate of adhesive lap joint nominal shear strength is 10.4 MPa (1,500 psi). For a shaft with an OD of 2.22 cm (0.875 in), this nominal shear stress is reached whtn the applied axial stress in the shaft is 26.4 MPa (3,820 psi). Clearly, threaded joints have the potential to provide much higher strengths than this estimate of adhesive bond joint strength. In addition, threaded joints offer the additional advantage of ease of assembly and disassembly. In applications requiring disassembly, bonded joints are not suitable.

5. CONCLUSIONS

This study has demonstrated that composite screw threads machined using AWJ have a good potential as a new composite joining technology. AWJ machining provides a fast, reliable method of obtaining good quality thread profiles. The resulting threads have the potential to provide good strength as compared to adhesive bonded joints. Future work will focus on improving the thread profile which will lead to improvement in joint strength. Future studies will also investigate other composite configurations, such as 3D weaves and braided fiber reinforced composites, which are expected to provide good threaded joint strength due to a significant percentage of fibers oriented in the radial direction. It is anticipated that these studies which will correlate measured joint strength with predicted stress fields will form the basis for design methodologies for threaded composite joints.

6. ACKNOWLEDGMENTS

The authors would like to thank Lawrence A. Girouard and the Composite Development Corporation for their support of this project.

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Table 1. Elastic Properties of Carbon Fiber Reinforced Epoxy Composite Shafts
(based on properties given in Tsai, 1992)

Property	Unidirectional Fiber Reinforcement	Woven Fabric Reinforcement
Young' Modulus, E_z, GPa (Msi)	146 (21.1)	78 (11.3)
Young' Modulus, E_r, GPa (Msi)	9.6 (1.38)	9.6 (1.38)
Young' Modulus, E_θ, GPa (Msi)	9.6 (1.38)	78 (11.3)
Poisson's Ratio, ν_{rz}	0.02	0.037
Poisson's Ratio, $\nu_{\theta z}$	0.02	0.04
Poisson's Ratio, $\nu_{\theta r}$	0.3	0.3
Shear Modulus, G_{rz}, GPa (Msi)	4.5 (0.65)	1.4 (0.20)
Shear Modulus, $G_{r\theta}$, GPa (Msi)	1.4 (0.20)	1.4 (0.20)
Shear Modulus, $G_{\theta z}$, GPa (Msi)	4.5 (0.65)	4.5 (0.65)

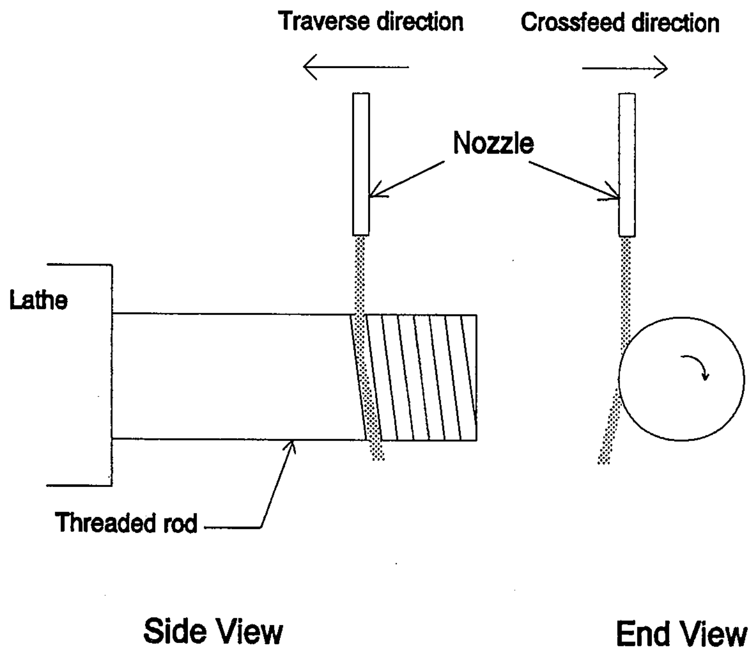

Figure 1. Schematic of Experimental Configuration

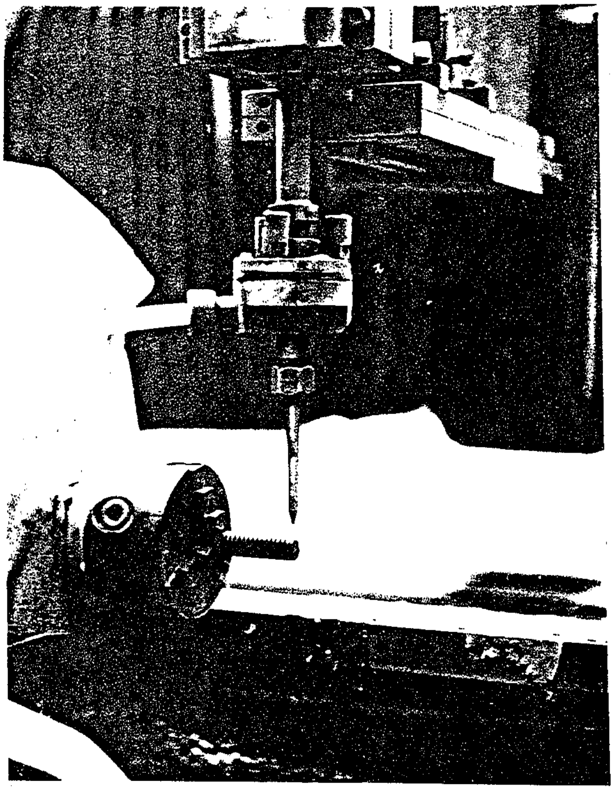

Figure 2. Photograph Of Experimental Configuration.

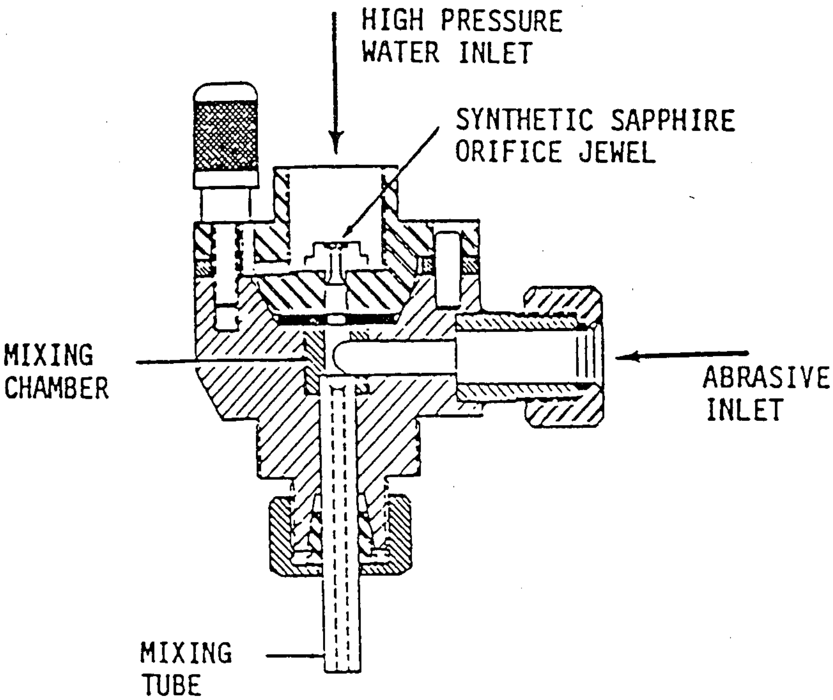

Figure 3. Schematic of Mixing Head (Mort, 1991)

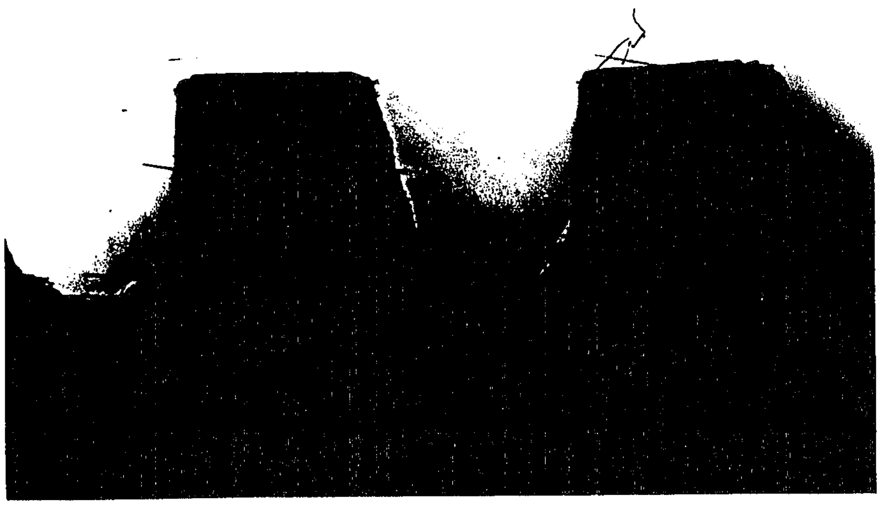

Figure 4. Photograph of AWJ Machined Composite Thread

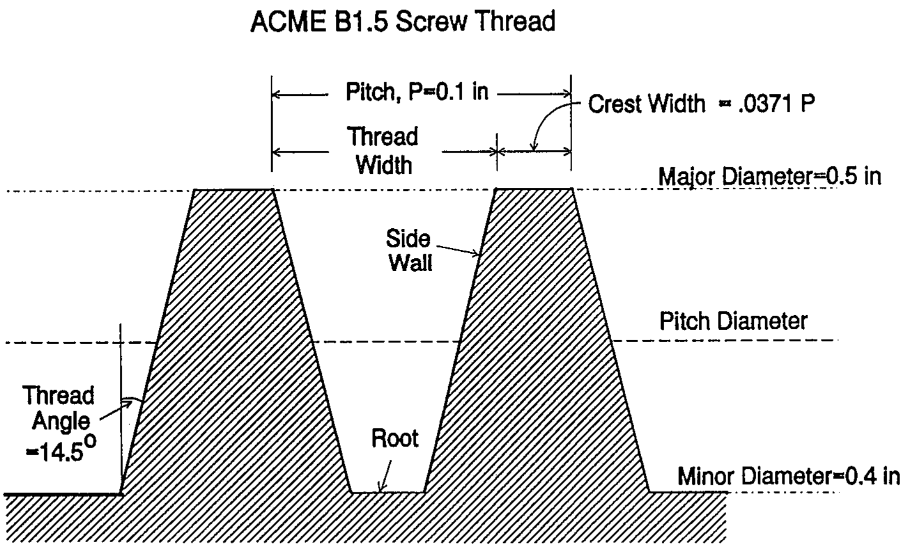

Figure 5. Acme Screw Thread.

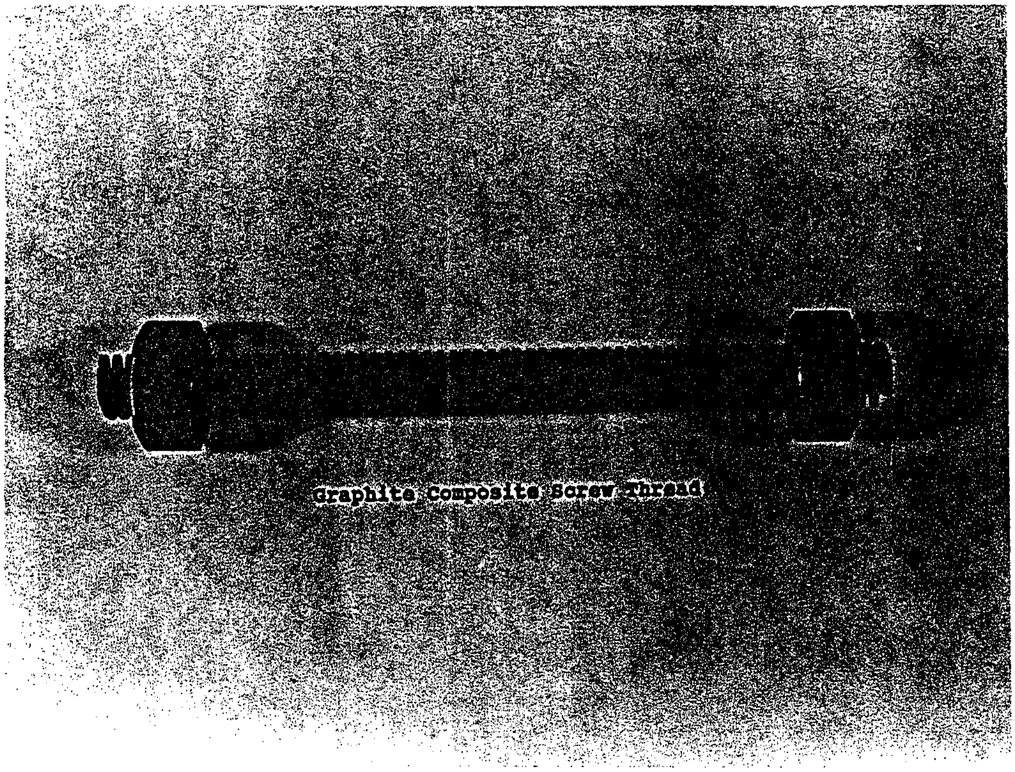

Figure 6. Threaded Composite Rod with Standard Acme Steel Nut.

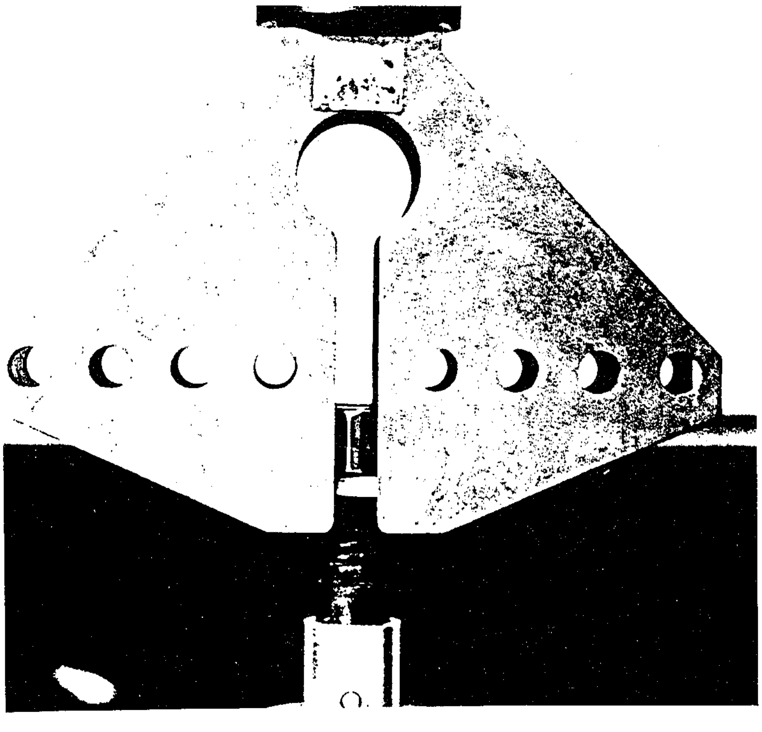

Figure 7. Photograph of Threaded Joint Strength Experiment

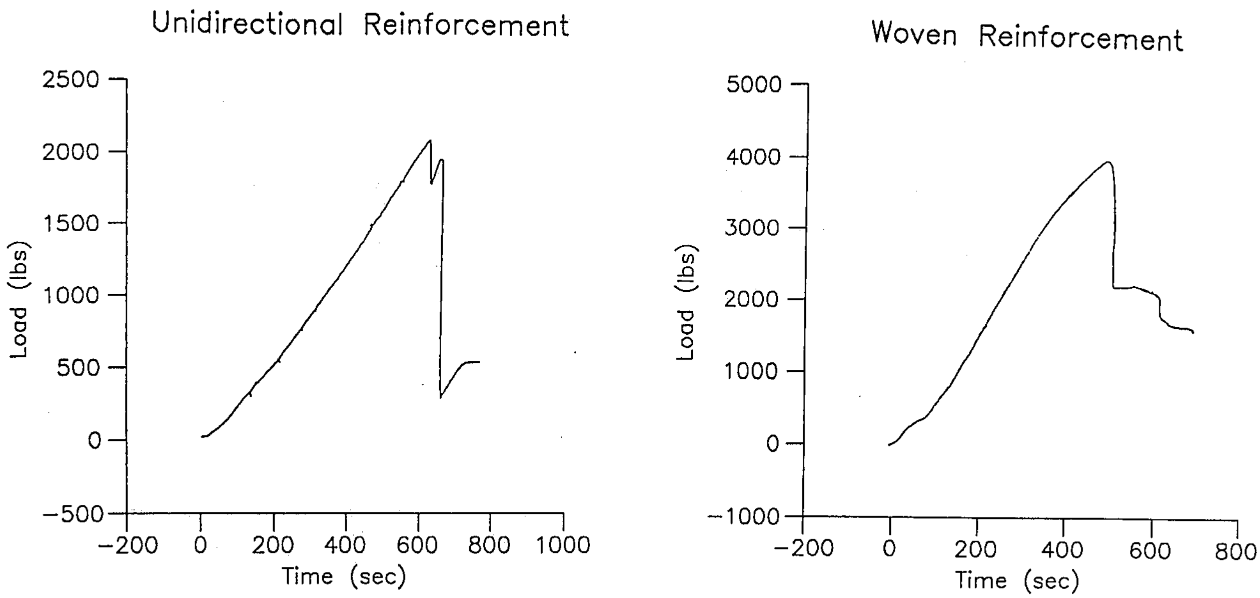

Figure 8. Typical Load vs. Time Curves

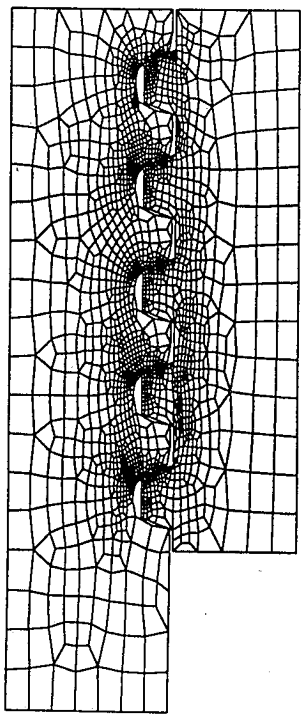

Figure 9. Finite Element Model of Composite Thread and Steel Nut

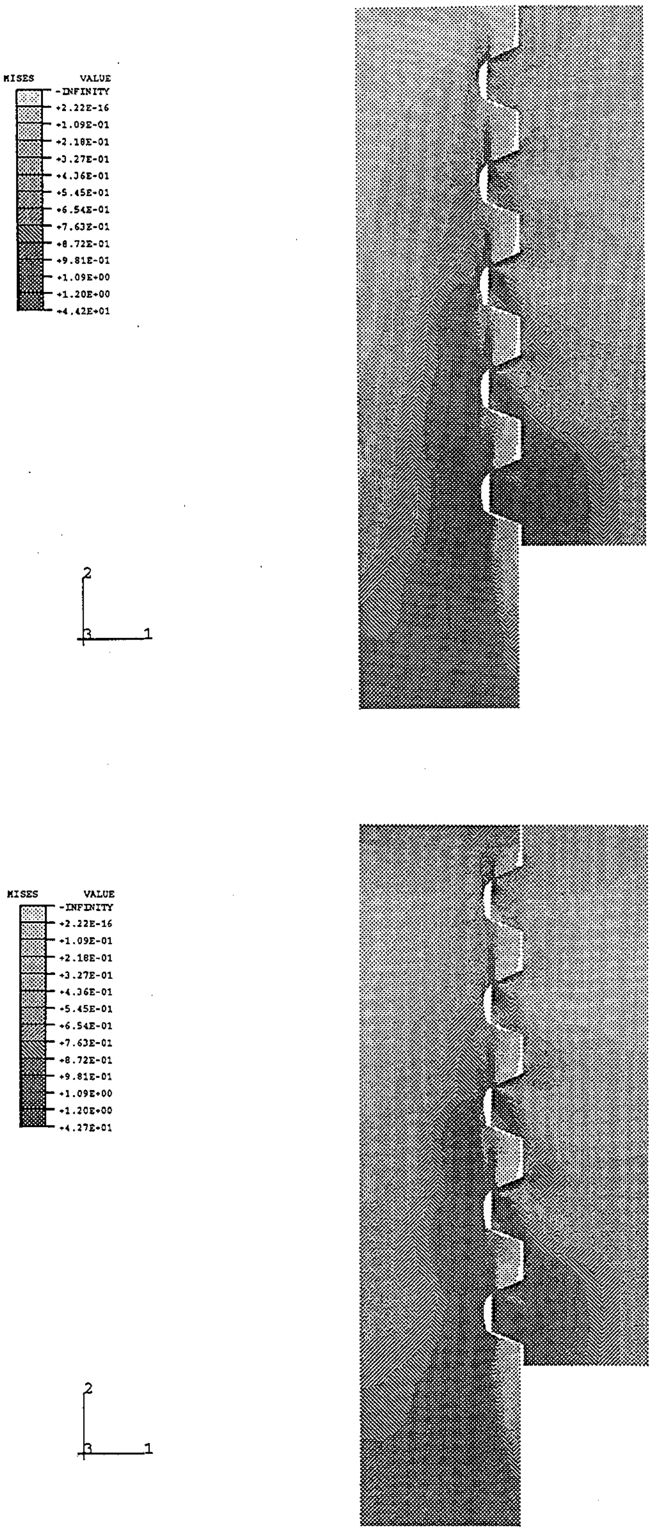

Figure 10. Von Mises Effective Stress Contours in a) Unidirectional Fiber Reinforced Shaft and b) Woven Fabric Reinforced Shaft.

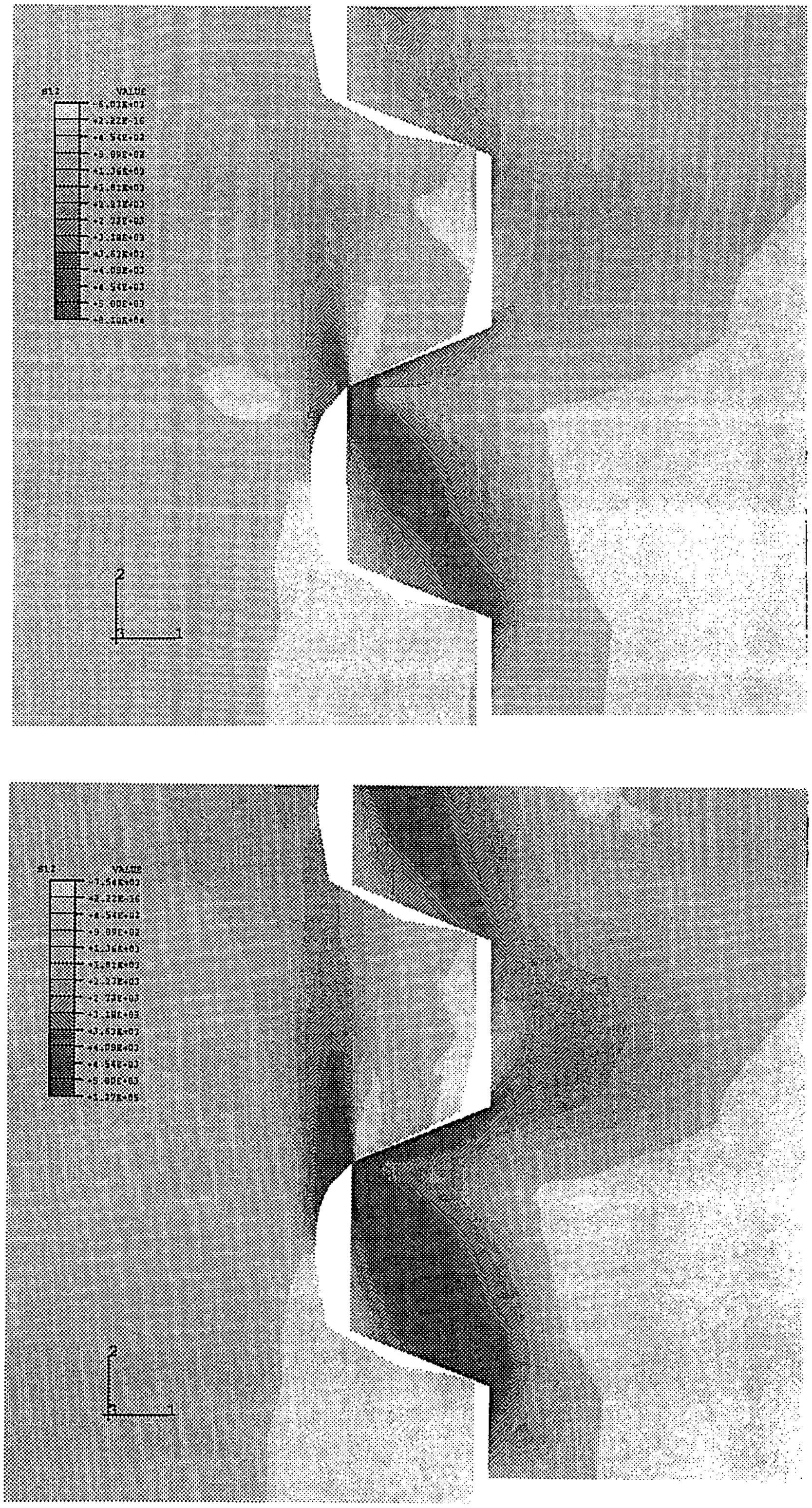

Figure 11. Shear Stress (σ_{rz}) Contours in a) Unidirectional Fiber Reinforced Shaft and b) Woven Fabric Reinforced Shaft.

8th American Water Jet Conference
August 26-29, 1995: Houston, Texas

Paper 19

RESULTS OF ABRASIVE WATER JET MARKET SURVEY

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ABSTRACT

The general objective of this survey is to understand the current and future uses of Abrasive Water Jet Cutting Systems and the needs as defined by users of the technology. The survey summarizes the use of Abrasive Water Jet Technology and categorizes the types of businesses using the technology. The survey outlines how and how much users use their equipment, the type of abrasives and nozzles used, what materials are being cut and what improvements or future needs are recommended for the technology.

Organized and Sponsored by the Water Jet Technology Association.

Boride Products/ROCTEC Abrasivejet Market Survey
October. 1994

1. Please describe your abrasivejet cutting activities:

A. Own and operate abrasivejet equipment	96	71%
B. Own equipment, not in operation	5	4%
C. Don't own, am interested	17	13%
D. Don't own, no interest	14	10%
E. No answer	3	2%
	135	

2. Please indicate which of the following activities best describes your abrasivejet activities:
(Multiple responses are included.)

A. I own and operate in-plant, stationary abrasivejet cutting equipment	58	52%
B. I own and operate mobile(contractor) abrasivejet equipment	25	20%
C. I am an original equipment manufacturer(OEM) of jet cutting systems and pumps	20	14%
D. I am a distributor, integrator, or supplier to the jet cutting industry	11	1%
E. I am involved in jet cutting related research or education	2	12%
F. Other(consultant)	2	1%

Data by prescribed categories crossed referenced by location

	North America	Europe	Asia	Totals	
in plant, stationary abrasivejet users	36%	5%	1%	48	42%
portable abrasivejet users	16%	3%	2%	24	21%
vendors to the abrasivejet industry	11%	8%	2%	24	21%
R & D, education, and consultants	9%	6%	1%	19	16%
				114	

Boride Products/ROCTEC Abrasivejet Market Survey

3. How do you categorize your business?

Manufacturing	10%
Job shop	37%
Industrial service contractor	21%
R & D	13%
supplier to the abrasivejet industry	17%
other	2%

Comment: Many respondents listed multiple answers. The single most logical and descriptive answer was used. Many of those listed as R & D and suppliers also use their equipment for demonstrations and job shop activities.

4. Describe your primary use of abrasivejet equipment. Secondary uses.

Comments:

A. This question was presented in an open ended fashion in an effort to gather organizational information involving end user terms. The responses are very diverse and difficult to organize and categorize.

A review of the data suggests the information could be organized in the following categories:

Ferrous	22%
high temp ferrous	14
malleable metals	2
glass	4
stone/rock	8
other	4
job shop	26
R & D	11
sales demonstrations and demos	9

39% listed using their equipment as being used for job shop activities as a secondary use.

20% of the systems appeared to be dedicated to a single application.

Boride Products/ROCTEC Abrasivejet Market Survey

5. Did you purchase your system from a pump manufacturer or a system sales group, such as a system integrator?

Pump Manufacturer	58%
Other-	42%

system integrator

re-sale

own system

6. What type of abrasive delivery system do you use? (air entrained, slurry, etc.)

air entrained	89%
slurry	11%

7. At what pressure do you typically operate your abrasivejet system?(PSI)

< 10 KPSI	13%
11 - 25 KPSI	4%
26 - 39 KPSI	19%
40 + KPSI	64%

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8. How many hours per week do you operate your system for abrasivejet cutting?

0 to 19	35%
20 to 39	14%
40 to 79	27%
80 +	20%
Varies	4%

Comment: Clearly, the primary users of abrasive nozzles are in the high use categories. When you analyze how many of the high hour users use the Boride nozzles, the results follow. Since some of the no responses are from users who buy from vendors who do not sell Boride nozzles, it can be concluded almost all high hour users who have access to Boride nozzles use them. Those who do not, based on their responses, are those who react to initial cost as opposed to real operational cost.

Users who operate 40+ hours per week, do they use Boride nozzles?

Yes	82%
No	18%

9. How many abrasivejet cutting heads are installed and used on your system?

1.	78%
2.	17%
3 +.	5%

10. How often do you use multiple heads in your abrasivejet cutting operation?(percent)

0% of the time	78%
0 - 33% of the time	11%
33 - 67% of the time	5%
67 - 100% of the time	6%

Observation: How often machines with multiple heads use multiple heads.

0 - 33% of the time	48%
33 - 67% of the time	19%
67 - 100% of the time	32%

Boride Products/ROCTEC Abrasivejet Market Survey

11. What abrasive do you use?(abrasives listed alphabetically)

A. Respondents who listed one type as at least 80% of total use.

aluminum oxide	1%
garnet	86%
olivine	1%
silica sand	1%
silicon carbide	1%
slag	3%
synthetic abrasives	3%
other	4%

B. Respondents who listed they use a certain abrasive.(i.e. 90% of the survey respondents use garnet at least some of the time)

aluminum oxide	11%
garnet	90%
olivine	15%
silica sand	11%
silicon carbide	2%
slag	15%
synthetic abrasives	9%
other	5%

Comments: All the high volume users use garnet, and most high volume users use garnet exclusively.

Boride Products/ROCTEC Abrasivejet Market Survey

12. What is your approximate use of abrasives per week in pounds? per year in pounds?

Average respondent to this question uses 109,000 pounds per year

Range of use between 300 pounds to 780, 000 pounds per year

13. What trends do you see in the use of specific abrasives?

no response	53%
none/same/no trends	6%
listed specific abrasive (garnet listed most frequently)	17%
more choices available	7%
needs to become more economical	8%
smaller sizes	2%
need to recycle/ environmental	5%
need to standardize	2%

Comment: This question was asked to gather information to determine a trend to where the market is going in terms of type of abrasives being used. For example, a trend toward more aggressive abrasives would suggest a need for longer life nozzles. No such trend is suggested.

Cost is an obvious concern, including environmentally related expenses.

Boride Products/ROCTEC Abrasivejet Market Survey

14. What size abrasive do you use?

A. Respondents who listed one size as at least 75% of total use.

16/30/36/40	21%
50/60/80/100	73%
120/150	5%
220/240	1%

B. In plant, stationary users who list one size as at least 75% of total use.

16/30/36/40	4%
50/60/80/100	86%
120/150	8%
220/240	2%

15. What trends do you see in the size of the abrasives that you use?

stay the same/ none	33%
larger sizes	2%
smaller sizes	11%
depends on hardware and material to be cut	4%
better size control, selection and cost	6%
NA/ don't know	44%

Same question, using only the answers that directly answer the question.

stays the same/ none	66%
larger sizes	4%
smaller sizes	23%
depends on hardware and material to be cut	7%

Comments: The responses apply to all types of abrasives.

There needs to be better particle size distribution of the abrasives, abrasives need to be cleaner, and costs need to trend down.

Regardless of size, experienced users want to standardize on one abrasive size and type to help control operational cost.

There is a trend toward standardizing on one abrasive size, users tend to use special sizes.

Boride Products/ROCTEC Abrasivejet Market Survey

16. What type of materials do you cut with abrasivejets?(i.e. steel, granite, glass, titanium, etc.) Answers should equal 100%.

Comment: The data suggests using the following material categories.

A. Respondents who listed one material as being at least 75% of what they cut.

ferrous	55%
high-temp ferrous	21%
malleable metals	0%
glass	14%
stone/rock	10%
other	0%

B. Respondents who listed one material as being at least 33% of what they cut.

ferrous	47%
high-temp ferrous	19%
malleable metals	11%
glass	6%
stone/rock	10%
other	7%

C. In plant, stationary respondents who listed one material as being at least 33% of what they cut.

ferrous	32%
high-temp ferrous	26%
malleable metals	20%
glass	11%
stone/rock	7%
other	2%

Boride Products/ROCTEC Abrasivejet Market Survey

17. Do you see any trends concerning the types of materials being cut with abrasivejets?

no answer	51%
no trends	17%
steel/alloys	8%
composites	6%
other	9%

Other includes: ceramics, harder materials, exotic materials, stone, glass, cutting in flammable environments, replaces conventional methods, and heat sensitive materials.

18. To what cut tolerance are you required to abrasivejet cut materials?

to . 010	44%
.010 to .025	21%
.025 +	17%
varies	9%
not a factor	9%

Comment: The intent of this question, in tandem with the next question, is to probe for data concerning whether nozzle wear is perceived to significantly impact holding tolerances in abrasivejet cutting systems. The data gathered from this question is probably insignificant for the purposes of this survey.

Boride Products/ROCTEC Abrasivejet Market Survey

19. A. What are the limiting factors with improving cut tolerances?(multiple answers included)

machine accuracy, table vibration, controller	38%
abrasives- size, cleanliness	8%
abrasive delivery system	5%
nozzle wear	22%
nozzle design, cutting head design, alignment	7%
kerf angle, surface finish, material	11%
cost of improving cut	3%
none	4%
cut speed	2%

B. Same question, in plant stationary users only.

machine accuracy, table vibration, controller	31%
abrasives- size, cleanliness	6%
abrasive delivery system	7%
nozzle wear	28%
nozzle design, cutting head design, alignment	9%
kerf angle, surface finish, material	9%
cost of improving cut	3%
none	3%
cut speed	4%
cut speed	4%

Comment: 89% of the respondents to this question use Boride nozzles. The 11% who do not use Boride nozzles is too small a sample to draw convincing comparative conclusions why they do not buy Boride nozzles.

The reason abrasivejet owners use, or do not use, Boride nozzles is better answered in the next question.

Boride Products/ROCTEC Abrasivejet Market Survey

20. Do you use Boride ROCTEC composite carbide, long life nozzles?

yes	42%
no- means yes	12%
don't know- means yes	8%
don't know	2%
no	36%

Same question, in plant stationary users.

yes	64%
no- means yes	20%
don't know- means yes	10%
don't know	2%
no	4%

Comments: 62% of all survey respondents use Boride nozzles. 94% of the in plant, stationary nozzle buyers use Boride nozzles. Almost 1/3rd of the in plant stationary group don't know they buy Boride nozzles,

Although 30% of the respondents of this survey own and operate portable abrasivejet equipment, their responses to this question, as a group, is insignificant because most do not have access to Boride nozzles from their primary vendors in the sizes they demand.

20. (Con't)

Why, or why not?(Do you use Boride...nozzles?)

Yes answers:

	all	in plant
buys what OEM offers	30%	32%
long life	54%	50%
cost	10%	12%
low downtime	3%	3%
cut quality	3%	3%

No answers:

	all	in plant
buys what OEM offers	10%	
no knowledge of Boride	33%	29%
cost	24%	57%
not available	23%	
breakage	7%	
too difficult to buy	3%	14%

Comments: The questions were asked in an open ended fashion, and the above categories seemed to be the best way to organize the data.

About 10% of the users commented the Boride nozzle price was too high. The no in plant group was only 7 abrasivejet users. This group is small enough to doubt the statistical accuracy of the responses.

Almost 1/3rd say they buy what their OEM offers.

Boride Products/ROCTEC Abrasivejet Market Survey

21. What size nozzles do you currently use?(list by diameter, length,and percent of use)

A. Respondents who listed one size at least 75% of the time.
All nozzle diameters standard sizes.

less than .030	6%
.030	36%
.035	4%
.040	24%
.043/.045/.047	11%
.050/.060	4%
.090/.095/.125	15%

Comments: Most users use longer nozzles.

22. How many nozzles to you use per year?

0 to 24	29%
25 to 50	27%
51 to 100	21%
101 to 200	8%
201+	12%
Don't know	3%

Same question, in plant stationary users.

	Boride	Lowlife
0 to 24	37%	0
25 to 50	18%	45%
51 to 100	32%	22%
101 to 200	5%	11%
201+	5%	22%
Don't know	3%	0

Comments: The low life group is very small; the numbers may not be statistically accurate.
The 37% of in plant users who use less than 25 nozzles per year is a very high number of users who probably under utilize their abrasivejet equipment.

Boride Products/ROCTEC Abrasivejet Market Survey

24. How do you rate the product support(warranty, technical assistance, etc.) you receive on your abrasivejet nozzles from your vendor? 1 is best, 5 is worst.

Overall results:

1	33%
2	42%
3	22%
4	1%
5	2%

Comment: The average rating is 1.99.

25. What can be done to improve product support on abrasivejet nozzles?

NA/don't know/nothing	64%
reduce price	11%
share empirical info/ share this survey/ react to this survey	10%
quality control	6%
vendor visits to view equipment	5%
longer life	3%
more selection of sizes	2%
warranty	1%

Comments: This open ended question data was organized in these categories. The overall responses seem to indicate users are happy with overall product support, but want to see more competition and continuing evolution of nozzle products.

26. What is the average life of the nozzles you use? List hours and reasons for failure.
Boride Products

0-30	10%
30-60	22%
60-90	15%
90-120	29%
120-150	10%
150-180	2%
180-210	6%
210+	6%

Average life approx. 96 hours

Failure mode:

worn	82%
fractured	14%
plugged	2%
kerf too wide	2%

Comments: Several of the very low hour nozzles were the result of start up fractures, which pulls down the average life.

Boride Products/ROCTEC Abrasivejet Market Survey

26.(con't)
Low life nozzles(Tungsten Carbide)

0-3	8%
3-6	41%
6-9	12%
9-12	15%
12-15	4%
15-18	12%
18+	8%

Average life approx. 8.8 hours

Failure mode:

worn	88%
fractured	12%

Comments: Based on this information, Boride nozzles life is 10.9 times that of other abrasivejet nozzles.. The response rate for the non- Boride nozzle sample is about one half the rate for Boride users. There were a few respondents who were obviously upset with start up fractures when using Boride nozzles.

27. Do you expect your purchases of abrasivejet nozzles to increase in the future? Why, or why not?

yes	74%
no	22%
maybe	4%

Comment: About 28% of the stated reasons for expecting to purchase more nozzles went toward a statement that the market for abrasivejet cutting was growing. 72% of the responses were because their business was growing.

About one half of the no responses were because the user was out of capacity with their existing abrasivejet cutting equipment, that the company was changing focus and concentrating on other business ventures, or existing contracts for jet cutting were about to expire.

28. Would you buy, and pay a premium for, nozzles manufactured to tighter tolerances?

yes	33%
no	51%
maybe	16%

Response reasons were few:

Yes-	if they last longer(2) for smaller nozzles
No-	wants nozzles not needing to be "burned in" no influence on cut tolerances(2) current nozzles OK no demand from the market place
Maybe-	if performance improves will require improved orifice life

29. Do you see a need to use more aggressive abrasives?(i.e. aluminum oxide, silicon carbide)

yes	35%
no	50%
maybe	10%

Number of responses to each position(yes responses offered more reasons than no responses):

yes-	cut speed improvement	12
	improved edge quality	3
	can cut new materials(ceramics)	6
	cut thicker materials	2
	reduces waste	1
no-	increases nozzle wear	5
	increases cost	2
	existing abrasives OK	4

30. What is important to you concerning the useful life of abrasivejet nozzles?

quality of cut	11%
nozzle wear rate/ life	34%
cost	28%
alignment/ jet quality/ diametric wear	15%
downtime	10%
breakage	2%

Comment: Quality of cut, nozzle wear rate, and jet quality refer to wear issues, and those issues account for 60% of the responses. Cost, downtime, and breakage are cost issues, which account for the other 40% of responses.

Many answers were given. Many respondents used multiple answers which are included. Most of the wear related responses are directly influenced by alignment and jet quality which relates more toward abrasive head design and use than to quality of Boride nozzles.

Breakage seems to be considered a minor problem.

31. Assume the nozzle cut cost per inch were the same for a nozzle lasting twice as long, but at twice the price. Would you buy such a nozzle? Why or why not?

yes	59%
maybe	14%
no	27%

Yes responses-	less downtime	72%
	more cost effective	11%
	more reliability	11%
	an option for customers	2%
	hold better tolerances	4%
No responses-	fracture problem	44%
	should be cheaper to use	38%
	downtime not a problem	18%

Same question, mobile users only:

yes	50%
maybe	18%
no	32%

Comment: The yes reasons went to downtime and cost, the no reasons were breakage and lost nozzles.

Same question, in plant stationary users only:

yes	60%
maybe	15%
no	25%

Comments: The cost of downtime outweighs the cost per inch cut of the nozzles. When I broke this data down by segment, the results were consistent with the results of the whole group. Most users of abrasivejets appear to be interested in longer life nozzle, and most will pay more for longer life.

32. Assume the nozzle cut cost per inch were the same for a nozzle lasting on half as long, but at one half the price. Would you buy such a nozzle? Why or why not?

yes	16%
maybe	11%
no	73%

No responses:

downtime too much	88%
reliability a problem	9%
current nozzles OK	3%

Yes responses(one response per reason):

Murphy's law applies to longer life nozzles
price should be less
need an alternative
fracturing a problem
downtime not a problem
less inventory costs

Comments: These answers reflect the industries acceptance of Boride nozzles. The previous question poses the opposite position to this question, but the answers are not exactly opposite.

33. Would you use longer lasting nozzles with more aggressive abrasives?

yes	54%
maybe	26%
no	20%

Comments: Most of the yes answers went toward cost issues, assuming more aggressive abrasives and subsequent faster cutting rates would lower overall costs. Most no answers were less explicit, saying they were satisfied with current abrasives.

Boride Products/ROCTEC Abrasivejet Market Survey

34. Would longer lasting nozzles allow you to cut materials currently not being abrasivejet cut?

yes	11%
maybe	8%
no	81%

35. Would you buy any additional nozzle sizes or configurations? List them by priority.

yes	25%	
yes(no size specified)	16%	
total yes		41%
maybe		13%
no		46%

Sizes listed(number of requests)

smaller diameters(8)
 010
 012
 015
 020
030x2(1)
030x3(1)
035x3(1)
050x3(2)
062(1)
095x6 and 125x6(1)
non circular(2)

Boride Products/ROCTEC Abrasivejet Market Survey

36. What improvements should occur with abrasivejet nozzles?

life of nozzle includes erratic wear at entrance	40%
cost most say nozzles need to be cost less	22%
design of cutting head includes being easier to align plugging problems	13%
brittle	9%
quality tighter tolerances hole accuracy better repeatability	8%
larger ID's, smaller ID's, shorter	4%
none	3%
more information to users	1%

Comment: Life and cost are clearly the most important aspects of nozzle use.

37. Would you like to see any other products manufactured from Boride ROCTEC long life materials?

yes	23%
yes(no suggestions given) 24% total yes	47%
no	8%
NA/don't know	56%

Specific suggestions(number of suggestions)

mixing chambers(8)

abrasive hose connector to abrasivejet cutting head(3)

orifices(3)

tank wear plates(1)

plungers/pump seals(2)
scatter shields for use when piercing(1)

Summary

The use of abrasive waterjet technology continues to grow but from a users point of view the industry seems to be lacking in fully understanding the broadness of the technologies use. Many users purchase abrasive waterjet equipment for a very specific application but may not fully understand the technologies capabilities for other uses for future business. To help promote the technology we thought it would be important for users to see how their colleagues are using AWJ technology today...and how they see its future.

Bases on the responses the industry has made it clear they value system improvements such as ROCTEC nozzles and other system components which deliver to maximize uptime and minimize downtime. This research also indicates a portion of the AWJ industry is hungry for a greater variety of nozzles sizes and configurations, and even tighter tolerances for some applications

It is clear the majority of AWJ users are in precision in-plant applications but their are indications that portable(mobile or contractor) applications for AWJ technology is growing. As these portable applications grow users will different needs and opportunities for their equipment.

Acknowledgment

The author would like to thank all the users, suppliers and integrators who were kind enough to respond to our survey and share their feelings and opinions of AWJ technology for others to learn from.

8th American Water Jet Conference
August 26-29, 1995: Houston, Texas

Paper 20

CONTROL OF SUBSTANCES HAZARDOUS TO HEALTH

Thomas H.W. Grieve I Eng Mieete

ABSTRACT

The paper will give an introduction to the Control of Substances Hazardous to Health Regulations (1988) as practiced in the UK, and illustrate the requirements of the Regulations and how the risk to health is assessed. It will also illustrate the methods of controlling the exposure and emphasize that the control measures are used by the operative in the correct manner.

Emphasis will be made in respect of preventing and controlling the exposure and the necessity of adequate information, instruction and training. Examples will be given of the benefits and weaknesses identified using compliance visits and a 10 point action plan for employers submitted.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

A century ago the death toll from industrial disease was of horrendous proportions. The industrial towns, both in Europe and Americas knew the effects of in the population, although this may not have been apparent as it would be "the way of life" at that time.

Slowly over the years many substances which were hazardous to health were identified and exposures controlled, e.g., silica, coal dust, heavy metals and coppers.

Nevertheless even in the 1980s and 1990s more people died from industrial disease caused by work than died as a result of accidents at work, and when this is further analyzed the figures have been estimated that 4% of all cancer deaths are related to occupation. This percentage takes into account only deaths from well recognized industrial disease for which exposure to substances hazardous to health was the main cause.

Employers and front-line mangers are in an excellent position to reduce or otherwise control occupational health hazards and exposures because of their:

* skills
* knowledge of the tasks
* good judgement
* natural concerns
* experience and personal contacts

It is undoubtedly difficult to identify the contribution that occupation makes to the causation of health hazards at work. This is due to the fact that there are frequently long latent periods of time, perhaps decades, between exposure to substances and subsequent disease, also the same disease or illness may be caused by non occupational as well as occupational factors.

The ACUTE condition is more readily known than the CHRONIC condition. An obvious example of the chronic condition is lung cancer, the acute conditions is amply illustrated in contact with a corrosive liquid.

We cannot be complacent about the risks presented by substances hazardous to health. Every year many thousands of employees have their health affected by being exposed to such substances. The results can be discomfort, pain, time off work, premature retirement, long term disability and even the ultimate—death.

Some common examples are:

* lung diseases following years of work in dusty conditions.
* skin disorders, dermatitis, skin cancer from frequent contact from oils, water wash.
* injuries to hands, face, and eyes from contact with corrosive liquids.
* asthmatic conditions resulting from contact with paints, isocyanates, and adhesives.
* death and injury from exposure to toxic fumes.

* poisoning by ingestion of contaminated foods caused by poor personal hygiene.
* cancer causing deaths many years after the exposure to carcinogenic work.

On reflection many of these ill health syndromes can be prevalent in the water jetting operations.

Apart from the pain and suffering of the employee there are high economic factors involved also:

* lost work time
* loss of earnings
* loss of productivity
* loss of experienced employee
* law suites
* prosecutions

Clearly there is requirement in view of the industrial illness caused by exposure to substances to do something meaningful in controlling exposures. Much work is being done in the UK and in the USA in this regard and many delegates here today will be more informed about the current legislation in this regard.

What is most certain is that the control of substances hazardous to health is

<u>"THE AGENDA FOR THE DECADE"</u>

2. CONTROL — HAZARD AND RISK

Control of any substance is based first on the recognition of "the hazard" and second on the assessment of "the risk."

The distinction between HAZARD and RISK is fundamental to any assessment and is frequently misunderstood. It is of critical importance to distinguish between them; failure to do so often results in incorrect assessment of risk.

2.1 Hazard

The "hazard" presented by a substance is <u>its potential</u> to cause harm!

Should you be exposed to the substance it can make you cough, damage your liver, cause leukemia, even kill you, and harm you in different ways. Some substances cause harm in several ways if:

* you breathe it in (INHALATION)
* contaminate your skin (ABSORPTION)
* swallow (INGESTION)

Some examples of the "hazard"

Benzene	—	can cause leukemia
Dusts	—	lung disorders
Hydrocarbon Oils	—	dermatitis, cancers
Acids	—	severe corrosion

2.2 Risk

The "risk" from a substance is its likelihood to cause harm in the actual circumstance of use."

This will depend on several factors:

* what is the hazard?
* how is it used?
* how much is present?
* is there an exposure?
* how often is it used?
* control measures available?

There can be a substantial risk even from a substance that is in minute quantity. Typical examples:

* Hydrogen sulphide
* Cyanide

On the other hand the risk from the most lethal of substances can be rendered INSIGNIFICANT when the proper controls are in use.

* Hydrogen Sulphide	—	when totally enclosed
* Cyanide	—	encapsulated

2.3 Control

It can be seen now that CONTROL is paramount to the risk to health from the exposure to any substance and the control can be brought to bear by a variety of methods.

There is a hierarchy of control methods which can be introduced but the following are a general guide:

* Eliminate the hazard
* Substantiate the hazard
* Isolate the hazard
* Introduce procedures
* Provide adequate ventilation

It should be observed that the introduction of Personal Protective Equipment should only be considered as a "last resort" and not, as is so common in industry at present, as a "first resort."

We cannot be too complacent about the health effects in our industry. As well as controlling the exposure of the hazards there is a need to have in place procedures and systems that will alert everyone to previously unsuspected hazards.

3. ROUTES OF ENTRY

IT IS NOT NECESSARY TO BE FAMILIAR WITH THE WHOLE MEDICAL PROFESSION OR THE MINUTE DETAIL OF TOXICOLOGY OR OCCUPATIONAL HYGIENE TO EFFECTIVELY CONTROL HAZARDS.

It is important however to be aware of the following:

* Routes of entry into the body
* Key health effect of the substance
* Levels of exposures
* Composition of substance, i.e., powder, solid, liquid, mist, vapor, and dust fibre

By controlling exposures and the level of exposure of substances, a whole range of chemically induced diseases can be prevented.

3.1 Skin Contact

Absorption of toxic substances through the skin is well recognized and some substances can be readily absorbed particularly in the solvent range and the skin is in itself a target organ for:

* Hydrocarbon oils
* Corrosives
* Degreasers
* Kerosene
* Gasolines

It is not uncommon for some substances to be absorbed through gloves, and leather boots. Chemicals readily absorbed include:

* Benzene
* Toluene
* Mercury
* Lead

3.2 Ingestion

Ingestion of substances through the digestive system is rarely of significance and adults do not knowingly eat or drink toxic chemicals (other than medicinal purposes) although eating and drinking in areas where toxics are present may cause problems. Good wash up facilities and personal hygiene are essential to prevent ingestion.

3.3 Inhalation

Inhaled substances can be rapidly taken into the body system and this is by far the most common route of entry. Many airborne contaminants remain in the lung and give rise to severe irritation, and in many cases the toxic gas and vapor inhaled penetrates the whole respiratory system causing widespread illness both acute and chronic.

In the water jet industry, I would suggest that skin contact and inhalation routes of entry are predominant and you will have experiences of your own to substantiate my thoughts.

4. TYPES OF HAZARDS

Health hazards in industry can generally be grouped into four categories:

Chemical	—	Any natural or artificial substances whether in solid, liquid, gas, vapor, fume, dust form, which can be hazardous, i.e., have the potential to cause harm.
Physical	—	Noise, vibration, heat, cold, light and radiation.
Microbiological	—	Any microscopic biological entity capable of replication, i.e., legionella, viruses, mites, yeasts, etc.
Ergonomic	—	Hazards that arise from the position of the body in relation to the task being executed, i.e., machine work, handling hoses, lines, etc.

All of these hazards are present in the petroleum industry and indeed may be present in your own industry. It is however impossible to enumerate all the categories and we will confine our paper to the CHEMICAL grouping, although the process of suitably and sufficiently assessing the risk to health is identical.

5. ASSESSING THE RISK TO HEALTH

Assessing the risks to health arising from substances hazardous to health is a systematic and logical process and can be carried out by front-line managers and engineers who are competent to do so.

The cornerstone of any system which assesses risk to health from any substance satisfies the three POINT RULE:

1. **Recognition**	—	Recognize that substances exist, they are hazardous to health — there is a potential to cause harm.
2. **Evaluation**	—	Evaluate the potential, can it be inhaled, absorbed, etc.
3. **Control**	—	What controls are in situ or can be introduced to reduce the risk to health.

In general terms the essential steps in any assessment are:

* Identify the hazards
* Evaluate/assess the risks from exposure
* Control the exposure
* Ensure controls are effective

Only by a systematic approach to the assessment stage can the risk to health be assessed, and once assessed, then controlled.

The assessment of the risk to health is the keystone or cornerstone of the system in that without it the risk cannot be concluded. It is an information gathering exercise intended to lead to correct decisions about health risks and the precautions required to control them. The precautions should be appropriate to the risk. In many cases "over precaution" can occur.

The assessment can be divided into five stages:

* Gather information
* Evaluate the risk to health
* Decide an action
* Record transaction
* Review procedure and programme

Gather information:

* WHAT substances are present and in what form?
* HOW are they used and in what form?
* WHO could be affected — frequency, duration?
* WHAT is the potential for exposure?
* HOW will that exposure happen?
* WHAT action is required?

How can the hazardous substance be recognized?

* Knowledge and experience
* Manufacturers information
* Authority guidance

* Very toxic, toxic, harmful, corrosive/irritant
* Technical literature
* Professional advisors

How are they hazardous?

* Inhalation
* Ingestion
* Absorption through skin, eyes
* Injection by high pressure equipment (water jet)

What are the effects? (see target organ chart and table)

* Short term (acute) Long term (chronic)
* Narcotic
* Carcinogenic
* Specific organ attack
* Mutagenic
* Other effects

Who could be affected?

* Water jet workmen
* Maintenance
* Visitors
* Contractors

What are the working practices?

* Written procedures
* Any previous mishaps
* Control measures in place
* Permit system
* Restricted area

6. EVALUATE THE RISK TO HEALTH

In order to reach a conclusion about the risk, the gathering information must be "evaluated" to determine the risk.

* What is the chance of exposure occurring?
* What are the exposure limits?
* Are they within the limits?
* What is the time scale?

* All existing controls effective and reliable'?
* Is sufficient information available to evaluate the health risks.

After systematically and logically considering the information and controls, the following conclusion is reached.

The risk to health of my employee when carrying out his prescribed task, with exposure to a specific substance is:

I. RISK TO HEALTH INSIGNIFICANT
II. RISK TO HEALTH SIGNIFICANT
III. RISK TO HEALTH NOT SIGNIFICANT DUE TO EFFECTIVE CONTROL MEASURES

6.1 Risk Indicators

The following examples are obvious indicators where exposure is likely to constitute a risk to health:

* Particular deposits on personnel or surfaces
* Particles visible in the atmosphere
* Broken, ineffective or badly maintained control measures
* Bad working practices
* Complaints of discomfort
* Detection of ill health linked to exposure
* Excessive use of PPE

6.2 Decide on Action

* Risk Insignificant

If the risk is insignificant the conclusion must be attributed to the fact that the "substance" is user friendly and does not present a potential hazard to health. The assessment is complete and no further action is necessary (until reviewed).

* Risk Significant

Look critically at existing control measures (if any) and decide what additional controls are necessary to reduce the risk.

* Identify deficiencies
* Establish priorities for improvements
* Decide what control measures are required

The exposure, when the risk to health is high or significant must either be <u>prevented</u> or, where this is not reasonably practicable, be <u>adequately controlled</u>.

6.3 Prevention of Exposure

* Eliminate the use of the substance or hazardous process

* Substitute the substance by using a less hazardous one, e.g., toluene for benzene — so that in the circumstances of work presents no risk, or less risk, to health. If possible change the form of the substance, e.g., pellet form instead of powder — wet wash replacing dry operation (water jetting?)

6.4 Control of Exposure

There are a wide range of approaches available to control exposure to hazardous substances. Environmental legislative requirements obviously must be taken into account and completed within the main, however, "control measures" must be appropriate to the work situation in order to deal efficiently with the situation and can be controlled using any combination of the following:

* totally enclose the operation
* good plant or operation design or work systems which minimize the generation of hazardous contaminants
* partial enclosure with local exhaust ventilation (LEV)
* local exhaust ventilation
* reduction of the number of employees exposed
* reduction in period of contaminant
* provision of means of safe storage and dismissal of substances hazardous to health
* prohibition of eating, drinking, smoking, etc. in contaminated areas
* provision of adequate messing and washing facilities
* suitable personal protective equipment (IF and only IF the exposure cannot be adequately controlled by any of the other methods)

The control measures above fall into three broad categories:

* Engineering
* Procedural
* Personal Protective Equipment (PPE)

It must be emphasized that PPE should only be used when other control measures are not practicable and feasible. Control is usually considered adequate if most people would suffer no adverse health effects if exposed to substance at that level day after day. Exposure limits are widely documented in the US and are found in Health and Safety Product Data Sheets.

6.5 Risk to Health Not Significant Due to Effective Control Measures

The majority of assessment findings fall into this category and it is essential to ensure that the control measures in situ are adequate, in good efficient working order, and good state of repair.

It is of paramount importance that the control measures perform as originally intended and continue, effectively, to prevent or adequately control exposure to the employee of substances which are hazardous to health.

The following activities are required to ensure that control measures are effective and continue to remain so:

* maintenance examination and testing
* routine inspections of pipes, hoses etc.
* defect reporting procedures
* routine monitoring of exposure
* health surveillance
* operating procedures
* correct use of control measures
* visual checks at routine intervals
* adequate knowledge and supervision
* emergency procedures

7. INFORMATION, INSTRUCTION & TRAINING

It is of the utmost importance that employees receive information, instruction and training for them to know and be aware of:

* the nature of the substance they are working with and the risks created (if any) by exposure to such substances
* the precautions that should be taken
* control measures, their purpose and how to use them
* how to effectively use personal protective equipment
* results of exposure monitoring
* emergency procedures
* the risk to health

These important duties are often overlooked, with serious consequences to the employee, should they be unaware of the health effects.

7.1 Recording and Reviewing the Assessment

Unless the assessment is so simple that it can easily be recalled it should be recorded. Preferably on a proforma and standardize the method. Obviously the recording system should contain sufficient information to show how decisions about risks and control, etc., have been established.

The assessment of the risk to health should be reviewed whenever there is reason to believe:

* it is no longer valid

* there has been a significant change in the work to which the assessment relates
* changes in plant or process
* new evidence about the hazards of the substance
* loss of control
* new control techniques
* ill health reported relating to the task

Winston Churchill is quoted:

"To look is one thing. To see what you look at is another. To understand what you see is another.

To learn from what you understand is something else. BUT TO ACT ON WHAT YOU LEARN is all that really matters."

8. MAIN DUTIES — GUIDANCE — ACTION PLANS

The following points will give guidance on the requirements necessary to initiate the enthusiasm and efforts necessary to overcome the apparent difficulties in setting up your own hazard communication programer in line with the statutory requirements which prevail in the US at this time.

The bottom line whatever the country is a "safer and healthier place of work."

1. Main duties imposed on employer
2. Steps in making an assessment
3. Guidance on assessments
4. Check list
5. Measures for preventing or controlling exposure
6. Compliance visit defect list
7. Benefits due to compliance visits
8. Ten point action plan

9. CONCLUSION

The Control of Substances Hazardous to Health Regulations introduced 1989/90 require employers to look at their employees in a new light. Many employees were exposed to many, many substances, both in the UK and other parts of Europe and these "substances" as such, are harmful to the health of the individual.

These regulations have placed duties and constraints on the employer to protect his employee from exposure to substances with which he has to work. They also have presented a new and comprehensive legalistic approach to the prevention and cure of the exposure to hazardous substances by applying the same principles and objectives to all workplaces and virtually all substances.

Many employers still have a long way to go before they fully understand the principles underlying the objectives and whole-heartedly accept the particular need to comply.

There is no doubt that these far reaching principles and objectives, of controlling substances which are hazardous to health, will create and generate long term improvements in the health of the workplace within the UK and other European countries.

So long as the present momentum is maintained, by the end of this decade there will be a significant reduction in occupational ill health caused by exposure to substances which are hazardous to health. This awareness must continue in order to reap the long term benefits of improved occupational health.

Surely the Control of Substances Hazardous to Health must be:

"THE AGENDA FOR THE DECADE"

10. ACKNOWLEDGEMENTS

Morgan, Lynne, Senior Occupational Hygienist, BP International Ltd.

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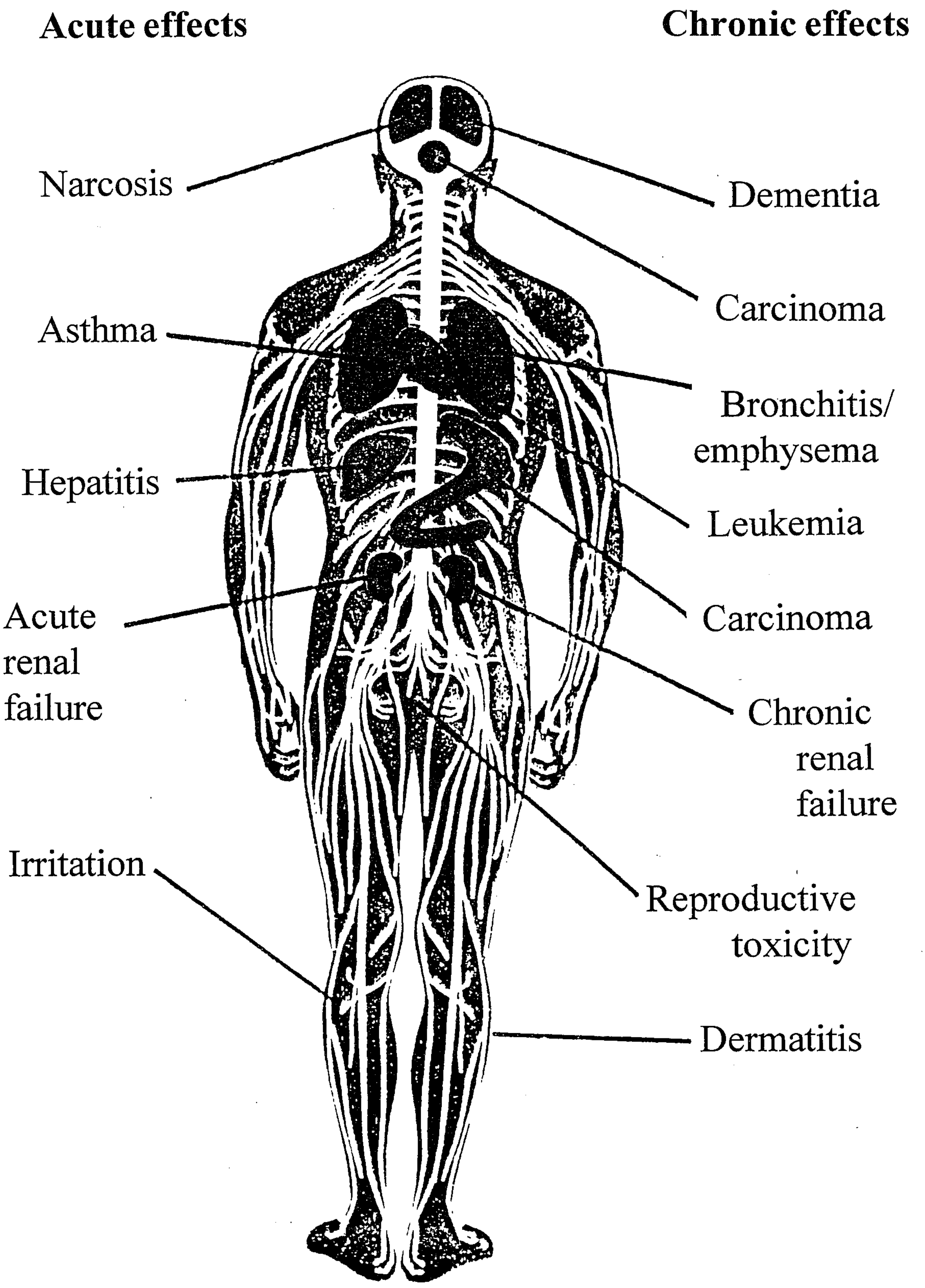
TARGET ORGANS & TOXIC EFFECTS

TARGET ORGAN	SUBSTANCE	TOXIC EFFECT
BLOOD	BENZENE LEAD	LEUKEMIA APLASTIC, ANEMIA ANEMIA
BRAIN	MERCURY (METAL) MERCURY (ORG.) CARBON DISULPHIDE	NEUROPSYCHIATRIC NEUROLOGICAL NEUROPSYCHIATRIC
NERVE	N-HEXANE ORGANOPHOSPHATES	NEUROPATHY ACUTE & CHRONIC NEUROPATHY
KIDNEY	CADMIUM	PROTEIN LEAK
BLADDER	AROMATIC AMINES	BLADDER CANCER
REPRODUCTIVE	GLYCOL ETHERS	TESTICULAR DAMAGE
SKIN	SURFACTANT EPOXY RESIN	IRRITANT DERMATITIS ALLERGIC DERMATITIS
LIVER	CHLORINATED HYDROCARBONS VINYL CHLORIDE	NECROSIS LIVER CANCER
LUNG	OXIDES OF NITROGEN ISOCYANATES SILICA ORGANIC DUSTS CHLOROMETHYL ETHERS	ACUTE INFLAMMATION ASTHMA PNEUMOCONIOSIS ALVEOLITIS CANCER

SUBSTANCES HAZARDOUS TO HEALTH



MAIN DUTIES IMPOSED ON EMPLOYER

ASSESS THE RISK
TO HEALTH

ASSESS THE STEPS
NEEDED TO MEET
THE REQUIREMENTS

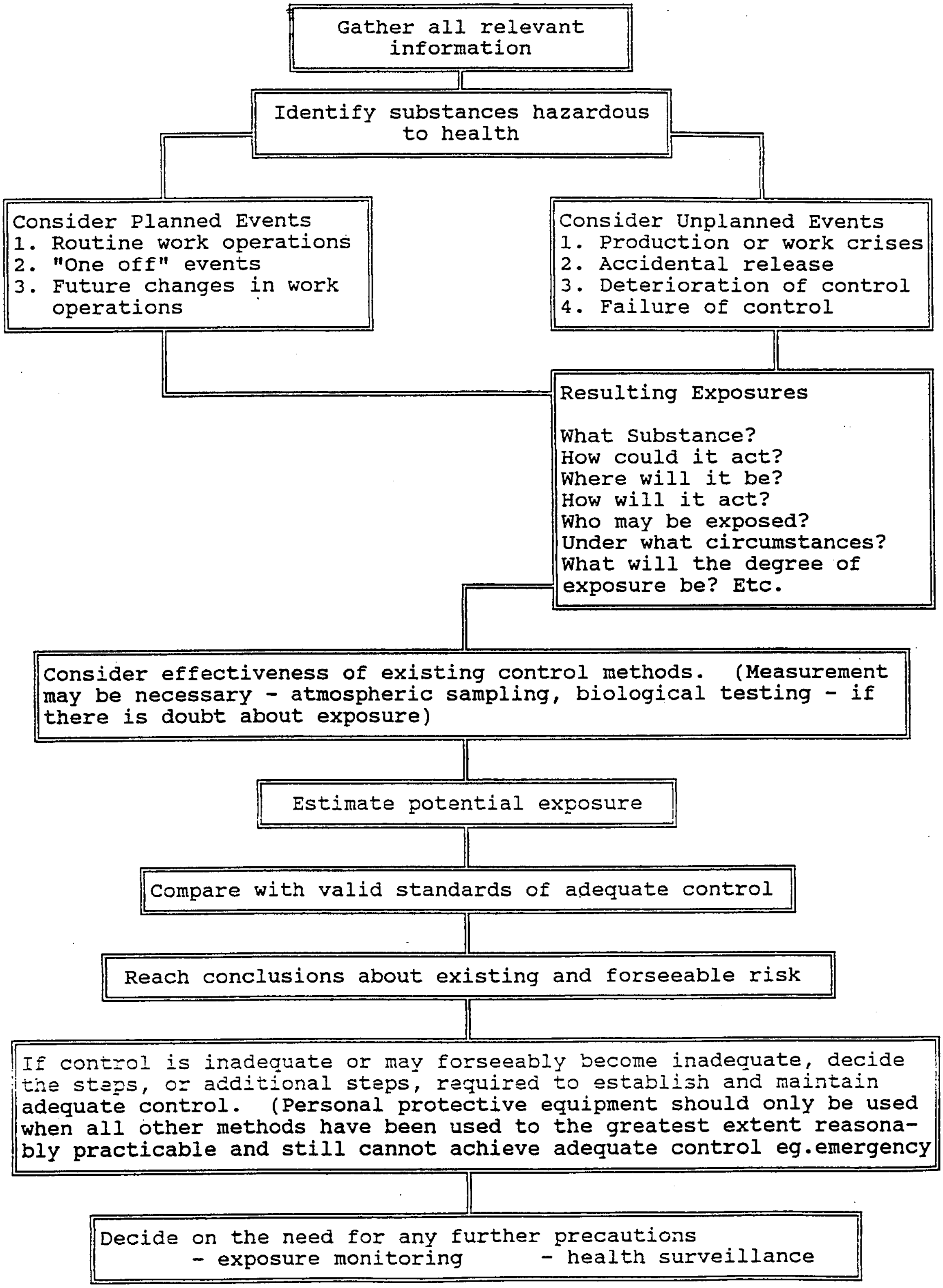
PREVENT OR AT LEAST
CONTROL EXPOSURE

ENSURE THAT THE CONTROLS
ARE PROPERLY USED AND
MAINTAINED

EXAMINE AND TEST THE
CONTROL MEASURES
IF THIS IS REQUIRED

INFORM, INSTRUCT AND
TRAIN THE EMPLOYEE
AND NON-EMPLOYEE WHO
IS ON HIS PREMISES

THE STEPS IN MAKING AN ASSESSMENT



GUIDANCE ON ASSESSMENTS

1. RESPONSIBILITY

1.1 The employer

2. ASSESSMENT

2.1 Define the work

2.2 List of the substances

2.3 Obtain data on the substances

2.4 Consider routes of entry
  (i) inhale
  (ii) skin absorb
  (iii) ingestion

2.5 Evaluate the exposure

2.6 Consider generic substances

2.7 Non routine or "one off" works

2.8 Conclusion of risk
  (i) not significant
  (ii) significant
  (iii) not significant due to adequate control

2.9 Action plans
  (i) information
  (ii) monitor
  (iii) modify
  (iv) control

3. COMPETENT PERSON

3.1 Necessary training, information and instruction

3.2 Systematic and logical approach

3.3 Recognition of own limits

3.4 Seek specialist support if necessary

4. ASSESSMENT IMPLICATIONS

4.1 Steps taken to protect employee

4.2 Risks defined at that time

4.3 Implement action plans

4.4 Further assessments - new info

4.5 Review the assessments

CHECKLIST

1. HAS AN ASSESSMENT OF HAZARD(S) BEEN MADE OF THE SUBSTANCE?
2. CAN IT BE SUBSTITUTED?
3. ARE DATE SHEETS AVAILABLE?
4. HAVE EXPOSURE VALUES BEEN IDENTIFIED?
5. ARE CONTROL MEASURES USED OTHER THAN PERSONAL PROTECTIVE EQUIPMENT (PPE)?
6. CAN OTHER CONTROL TECHNIQUES BE USED?
7. ARE MECHANICAL CONTROL MEASURES EXAMINED AND TESTED?
8. IS THE CORRECT P.P.E. PROVIDED FOR THE HAZARD IDENTIFIED?
9. IS THE P.P.E. KEPT CLEAN?
10. DO YOU TAKE CARE OF THE P.P.E. ?
11. ARE WASHING/MESS FACILITIES AVAILABLE?
12. IS HEALTH SURVEILLANCE NECESSARY?
13. IS FIRST AID EQUIPMENT AVAILABLE?
14. HAS THE RISK BEEN CONCLUDED?
15. ARE THERE ANY ACTIONS NECESSARY?
16. WILL THE ASSESSMENT NEED REVIEWING?
17. HAVE I RECHECKED THE ASSESSMENT?
18. IS IT SUITABLE AND SUFFICIENT?
19. AM I SATISFIED WITH THE ASSESSMENT?

MEASURES FOR PREVENTING OR CONTROLLING EXPOSURE

PREVENTION

ELIMINATE	hazardous substance
SUBSTITUTE	less hazardous form or less hazardous substance

CONTROL

CLEAN	to remove solid/liquid contaminants
CONTAIN	hazardous substance during process
DISPOSE	of hazardous substances safely
ENCLOSE	the hazardous substance
EXCLUDE	non-essential personnel from the contaminated area
MINIMIZE	generation of hazardous substances
PROVIDE}	suitable personal protective equipment
	adequate facilities for washing, changing & storing clothes, eating, drinking & resting
PROHIBIT	eating, drinking, smoking etc. in contaminated areas
REDUCE}	the number of employees exposed
	the period of exposure
STORE	hazardous substances safely
SUPPRESS	airborne contaminants during processing
VENTILATE	to remove airborne contaminants

COMPLIANCE VISITS

IN SHORT COMPLIANCE VISITS ARE NECESSARY IN ALL WALKS OF LIFE AND GENERALLY SHOULD INDICATE:

* THE DEFICIENCIES ESTABLISHED
* THE CORRECTIVE ACTION REQUIRED
* THE AGREED CORRECTIVE PERIOD
* THE PERSON RESPONSIBLE FOR CORRECTIVE ACTION

THE MOST COMMON DEFICIENCIES ESTABLISHED,

* NO INVENTORY OF SUBSTANCES
* LACK OF INFORMATION AND DIRECTION
* MISUNDERSTANDING BETWEEN "HAZARD" AND "RISK"
* ASSESSMENTS NOT COMPLETE
* OPERATIVE EXPOSED TO CONCENTRATION ABOVE LIMITS
* LITTLE ACTION TO SUBSTITUTE SUBSTANCES
* INFORMATION AND TRAINING INADEQUATE
* LITTLE OR NO PROCEDURES IN PLACE
* RECORDS POOR TO NON-EXISTENT
* EMPLOYEES NOT AWARE OF ASSESSMENTS
* EMPLOYEES NOT AWARE OF RISKS
* DATA SHEETS OUT OF DATE
* INSPECTION TESTING AND MAINTENANCE OF CONTROLS, POOR
* LACK OF MONITORING TO ESTABLISH EXPOSURE LEVELS

BENEFITS DUE TO COMPLIANCE VISITS

* DATA BANK OF ALL IDENTIFIED SUBSTANCES

* EMPLOYEE(S) HAS GREATER AWARENESS OF SUBSTANCES

* SUBSTANCES ELIMINATED/SUBSTITUTED

* MORE DATA AVAILABLE AT WORK STATION

* MAINTENANCE PROGRAMS INTRODUCED

* AREAS OF INVOLVEMENT

  - PERSONAL PROTECTIVE EQUIPMENT
  - PERSONNEL MONITORING
  - TRAINING

* MANY ACTIONS IDENTIFIED

* CONTRACTOR AWARENESS ACTION

* IMPROVEMENT OF HEALTH AT WORKPLACE

10 POINT MANAGEMENT ACTION PLAN

THESE 10 SIMPLE AND PRACTICAL STEPS HAVE BEEN IDENTIFIED AS THE RESULT OF SEVERAL YEARS OF COMPLIANCE VISITS AND INVOLVEMENT IN ASSESSING RISK TO HEALTH.

1. PREPARE AN INVENTORY OF **ALL** SUBSTANCES USED IN PRODUCTION, MAINTENANCE ETC.

2. IDENTIFY POINT OF USE FOR EACH SUBSTANCE, I.E., WORK TASK.

3. PREPARE LIST OF WORK EMPLOYEE TASKS.

4. OBTAIN HEALTH & SAFETY DATA SHEETS FOR ALL SUBSTANCES AND IDENTIFY HAZARD.

5. ELIMINATE SUBSTANCES IF NOT ASSOCIATED WITH POINT OF USE.

6. SUBSTITUTE SUBSTANCES WITH THOSE OF A LESS POTENTIAL HAZARD.

7. COMMENCE A PROGRAM OF RISK ASSESSMENT
   EMPLOYEE - TASK - SUBSTANCE - RISK

8. INTRODUCE POLICY STATEMENT ON CONTROL OF SUBSTANCES HAZARDOUS TO HEALTH.

9. INTRODUCE A PROCEDURE FOR THE PURCHASE OF SUBSTANCES.

10. INFORM, I NSTRUCT AND TRAIN IN AND ON CONTROL OF SUBSTANCES HAZARDOUS TO HEALTH.

ON COMPLETION OF THIS 10 POINT PLAN

"STAND BACK AND WATCH THE SUCCESS"

8th American Water Jet Conference
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Paper **21**

WORKERS' COMPENSATION—FRIEND OR FOE?

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!IMPORTANT! READ THIS! DISCLAIMER!

The information contained in this paper refers to **TEXAS LAW ONLY**. The Author is an attorney licensed to practice only in the State of Texas, who is not board certified by any board of legal specialization. All individuals, business entities, and aliens are **STRONGLY** urged to **SEEK QUALIFIED LEGAL COUNSEL** before undertaking any action whatsoever regarding workers' compensation issues within their control.

THIS PAPER IS PUBLISHED FOR DISCUSSION PURPOSES ONLY AND IS NOT INTENDED OR TENDERED AS LEGAL ADVICE IN ANY CAPACITY.

Organized and Sponsored by the Water Jet Technology Association.

I. INTRODUCTION

KNOCK!
KNOCK!
KNOCK!

"Who goes there, friend or foe?"

As a private solo practitioner in the State of Texas, business clients often ask whether or not they should consider workers' compensation coverage under the Texas Workers' Compensation Act ("the Act") as a friend or a foe.

Many Texas attorneys who before 1990 focused their law practices on workers' compensation injury recovery would, in many cases, consider the Act a foe. The Act was overtly intended by the Texas Legislature to limit contingent fee agreements between attorneys and injured workers. The Act's enactment closed a chapter in the legal profession's fiscal involvement in workers' compensation claims for the most part.

A subscribing employer whose employee experienced grave injury or death while acting in the course of scope of his employment would, most probably, consider the Act its great friend. This employer would probably embrace the Act gladly because an operating business remains and was not closed by litigation.

But to you, gentle reader, employer or employee in the Texas private sector, what do the words "Workers' Compensation," mean? Is the Act your friend or your foe? This question can only be answered by examining your individual circumstances and a complete evaluation of your business and its operation by a competent, credible professional. But for purposes of this discussion, read on to be further enlightened regarding workers' compensation nuances and how they may apply to you.

2. WHAT IS WORKERS' COMPENSATION OTHER THAN EXPENSIVE?

Workers' Compensation is:

- A limitation of the extent of an employer's liability for injuries sustained by its employee.
- A manner of paying claims to injured employee workers for damages and injuries sustained in the workplace while in the course and scope of employment.
- Insurance coverage purchased by employers for these purposes.
- In light of the alternatives, usually a good deal.

REMEMBER! This paper refers to Texas only!

2.1 Texas Employer Classifications:

A) SUBSCRIBERS: Employers who provide workers' compensation coverage on their Employees. There are three types of subscribing Employers; they are:

1) Mandatory Coverage Subscribers:
Some groups are required by the Act to provide workers' compensation coverage for their employees. Governmental agencies, State agencies, and other groups especially tagged (such as motor carriers in Texas) must provide workers' compensation coverage.
2) Elective Coverage Subscribers:
Private sector businesses may elect to subscribe to the Act by purchasing Texas Workers' Compensation Commission approved workers' compensation coverage from approved insurance carriers.
3) Self-Insured Subscriber Employers:
Private sector businesses may provision for, apply for, and acquire a certificate of self-insurance from the Texas Workers' Compensation Commission. Although they do not purchase coverage via premium payments to an insurance carrier, by virtue of their Texas Workers' Compensation Commission Certification of Self-Insurance and compliance with the underlying rules and regulations, all workers' compensation legal protections apply.

B) NON-SUBSCRIBERS: Employers who provide NO workers' compensation coverage on their employees.

2.2 Workers' Compensation History

Workers' compensation provisions are drafted by the Texas Legislature. From 1913 to 1990, day to day operations of workers' compensation matters were governed by the Industrial Accident Board. But from 1984 to 1989, workers' compensation premium rates increased in Texas by 148%. These increases focused legislative attention on the workers' compensation industry. As a result, the Act was enacted by the Texas legislature in 1989. The Act was effective January 1, 1991, so dissolving the Industrial Accident Board and creating the Texas Workers' Compensation Commission.

It should be noted that the Texas legislature clearly intended to limit attorney's fees in workers' compensation cases, whereby limiting involvement of the legal profession in the workers' compensation industry.

The Texas Workers' Compensation Commission was created effective April 1, 1990, and is a six member part-time commission comprised of three wage earners and three employers.

Each commissioner serves one six-year term. Those terms are staggered between the commissioners and at no time are all six seats vacant. The commission meets once per quarter to address issues brought before it.

Although the history of the Industrial Accident Board and the Texas Workers' Compensation Commission is long and involved, most business operators ask these two questions:

Why does my business purchase coverage, and, what does my business get for its dollar?

3. SUBSCRIBERS TO THE ACT

The most reasonable response to this question is that, as a subscriber employer, workers' compensation coverage buys a degree of peace of mind because, inevitably, **ACCIDENTS HAPPEN.**

Any individual or business entity who hires people to work or provide services in exchange for wages, as defined by the Act, is classified as an employer. The employer to employee relationship is carried out at the workplace while the employee is engaged in the course and scope of his employment. Employees are covered by workers' compensation when they are engaged in the employer's general business enterprise. There is excluded conduct which is not compensable by workers' compensation; but still ACCIDENTS HAPPEN. Any injury to an employee may result compensable damages. Workers' compensation insurance converts the recovery of compensable damages from a negligence based theory of recovery to a contractual base where the employer's negligence is immaterial. Compensable damages are paid on behalf of a subscriber employer by the insurance carrier to the injured employee.

A subscriber employer is absolutely liable to pay workers' compensation benefits to an employee when that employee is injured in the course and scope of his employment. But a subscriber employer does not pay benefits to the employee; rather, the insurance carrier pays the benefits on behalf of the employer to the employee.

THE GOOD NEWS:

Employees working for subscriber employers lose their right to sue the employer under negligence based common law or statutory theories. What this means in plain English is that employees cannot sue their employer for negligence related damages if they are injured on the job. (What a relief!) So employers, "Get in the Act." Subscribe! A company that subscribes to workers' compensation coverage is protected from employee lawsuits to a degree found nowhere else in the law.

So, for example:

If a subscriber employer's employee is injured on the job and the employee was acting within the course and scope of employment:

1. who pays the employee's medical expenses, lost wages, and other compensable damages?
   THE INSURANCE CARRIER.
2. whose lawyer defends the employer?
   THE INSURANCE CARRIER'S.
3. who evaluates and manages the claim?
   THE INSURANCE CARRIER.

All subscriber employers should still be fully aware of the terms of their policy and its rules and regulations. They should communicate with their workers' compensation insurance carrier and comply with all requirements. Proper notice and complete forms for the insurance carrier must be correctly submitted for coverage to be extended and employers must be properly trained and ready in case of any emergency or injury. Subscriber employers FAMILIARIZE YOURSELF and your key employees with all workers' compensation insurance carrier rules and regulations.

EMPLOYERS BE AWARE:

That even if an employer's carrier accepts liability, the employer may contest compensability.

4. NON-SUBSCRIBERS TO THE ACT

Open season on non-subscriber employers by plaintiff's attorneys.

Lawyers are (typically . . .) not pursuing claims for workers' compensation against subscriber employers because of the economic and legal limitations imposed by the Act. But non-subscribing employers are free game for recoverable liability and open season has been declared on compensable damages sustained by employees working for non-subscriber employers.

Employers carry the primary, continuous, and non-delegable duty to provide a safe place and safe conditions for employees to work in. But, as stated before, . . .ACCIDENTS HAPPEN.

Non-subscriber employers, by not subscribing and not purchasing workers' compensation insurance coverage, waive their common law and statutory defenses. Non-subscriber employers cannot proffer the defenses of contributory negligence, assignment of the risk and negligence of a fellow employee. Considering the duty imposed on the employer to provide a "safe" workplace for the employee, and the inevitable "accidents happen," a non-subscriber employer has exposure for a negligence claim brought by an injured employee. So long as there is a showing that employer breached a duty which caused the employee's injury, a claim for negligence can attach.

An attorney representing an injured employee of a non-subscriber employer is not required to report litigation transactions to the Texas Workers' Compensation Commission. Nor is that attorney bound by law to take twenty-five percent (25%) or less of the recovery as his fee.

Attorneys focusing their practices on these types of injuries have been forced to be efficient, imaginative, and innovative in pleading and proving the negligence of non-subscriber employers.

An employer is required to exercise ordinary care, caution, and diligence in the operation, maintenance, and management of the workplace. That workplace must be kept in a reasonably safe condition. Further, the employer must exercise reasonable care to prevent a dangerous condition on the worksite <u>or</u> to exercise ordinary care to correct any such condition after the employer knew of the dangerous condition. Even when an employer **should** have known of the existence of a dangerous condition through the exercise of ordinary care, a non-subscriber employer can be liable for an employee's injuries and damages.

The exposure of non-subscriber employers is obvious. The non-subscriber employer is prohibited from asserting common law defenses to the negligence based liability claims of injured employees. What better way to protect from employee workers' compensation claims of negligence than for an employer to purchase workers' compensation coverage for all employees? The investment in workers' compensation coverage can purchase a great deal of intangible value when compared to an employer's uncovered exposure by non-subscription.

5. WORKERS' COMPENSATION SUBSCRIPTION IN TEXAS

So an employer seeks workers' compensation coverage on its employees. Where is it found? How is it purchased? How can costs and premiums be reduced?

The answers to these questions depend on each individual employer and the time, effort, and capital that an employer chooses to invest in acquiring coverage. An investment in prevention, education, and policy development can (in many cases) yield a substantial return. First, evaluate the needs and resources of the individual employer. Second, develop a plan to reduce the exposure, experience modifier, and expense of coverage. Third, select a manner of coverage. Workers' compensation policies of coverage are available in Texas through the following vehicles:

1. <u>**Assigned Risk Pool**</u>

   Subscribers that do not meet the criteria of the Texas Workers' Compensation Fund, self-insurance, or a private policy will, most probably, be able to acquire coverage in the assigned risk pool. This coverage is pooled to spread the risk over many subscriber employers. Various businesses are covered in the pool. The employer's risk is evaluated by several criteria, two being prior experience and prior claims. All insurance rates are set by the State of Texas and a business' experience rate is calculated by the state charts for fees. Rates are so determined, and with any allowable costs, they are calculated by the carrier into premiums.

Employers with prior injury experiences and rate modifiers will suffer higher premium rates than employers with "cleaner" records. An employer who wishes to reduce its premium rate must diligently work to enact and enforce programs to reduce injuries. In time, an employer's record can clear if no further injuries are sustained. Then, the employer may be eligible to apply for coverage in the Texas Workers' Compensation Fund.

2. <u>Texas Workers' Compensation Fund</u>

Employers who seek coverage under the Texas Workers Compensation Fund ("The Fund") must have above average experience with few accidents and injuries sustained by workers. This experience is calculated over a time period preceding application as determined by the rules and regulations of the Fund. To acquire this coverage, employers should have a written Employment Handbook, a written Safety Policy, a written Drug Abuse Policy, an accessible first aid kit, and maintain a schedule of frequent safety meetings. The workplace should be clean and well-kept and employees should use necessary safety equipment while on the worksite (e.g., safety shoes, glasses, hats, and clothing).

An employer who seeks Fund coverage should first contact their carrier and request an application for coverage under the Fund. The employer should simultaneously prepare the necessary documentation, install the required equipment, and initiate regular safety meetings.

In many cases, this additional effort can yield great savings on premiums. The employer's efforts can directly benefit employee morale by providing more support and education for those employees on the worksite.

3. <u>Self-Insurance and Other Coverage</u>

Employers who make application for and acquire Texas Workers' Compensation Commission Certification can be self-insured subscribers to the Act. In many cases, those employers seeking self-insurance through the Texas Workers' Compensation Commission should employ a consultant to assist in the application for certification. Self-insured subscribing employers enjoy the full protection of the Act and do not waive their common law and statutory defenses.

Also available are individually written workers' compensation coverage policies. These policies are not underwritten out of the Assigned Risk Pool, nor the Texas Workers' Compensation Fund. Although not as common as the Assigned Risk Pool and the Texas Workers' Compensation Fund coverage, such policies are available to an employer in need of that coverage.

6. CONCLUSION

Employers and employees of Texas, protect yourselves. Actively work together to reduce accidents. Maintain a clean and safe workplace. Educate yourselves. Draft and implement a written Safety Policy, a Drug Abuse Policy, and an Employee Handbook.

Be accountable for your actions towards each other and predictable in your reactions. Develop and diligently maintain the business enterprise in the equipment and the workplace; because, without these no business can operate. Work together to enact these policies and procedures and enjoy success in reducing the overall costs of workers' compensation insurance premiums.

7. TABLE OF AUTHORITIES

Texas Workers' Compensation Act, Revised Civil Statutes, §8308-1.01 et. seq., Vernon's Texas Statutes Annotated, Civil Statutes §8308-1.01 et. seq.

8th American Water Jet Conference
August 26-29, 1995: Houston, Texas
Paper 22

HIGH PRESSURE WATER BLAST TRAINING

A PRIMER FOR TRAINING YOUR TRAINER

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ABSTRACT

Training employees to safely and effectively operate high pressure water jetting equipment is no longer a nebulous event that may or may not take place in the field under the guise of "on-the-job training". Effective training is not only mandated by the federal government, it is a primary step in a contractor's competitive edge, a necessary self-defense against rising medical costs, and a true sign of professionalism and leadership in an industry that is still in its infancy.

All too often, this crucial responsibility is left in the hands of an employee who is technically competent - one who can get maximum effectiveness from the water jetting equipment. Unfortunately, being able to use water jetting equipment, and being able to teach its use to others, are two entirely different skills.

This paper will detail the "how-to's" of effective training - specifically how to prepare the training course and the potential trainer to present it, beginning with important aspects of course design, determination of instructional objectives, adult instructional techniques, preparation of the training environment & trainee, and concluding with presentation tips and appropriate documentation techniques and forms. The object is to ensure that course and presentation can stand up to federal scrutiny if need be; the aim is to protect the employee and employer through competent, thorough, well-documented training.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

"Each Employer ... shall furnish to each of his employees employment and a place of employment which are free from recognized hazards that are causing or are likely to cause death or serious physical harm to his employees; ..."

With those words the Occupational Safety and Health Administration (O.S.H.A.) officially put employers on notice that they are to be held responsible for ensuring that employees who are, or can reasonably be expected to be, exposed to "recognized hazards" are properly prepared to handle those tasks safely. As anyone who has had to deal with O.S.H.A. can attest, this "general duty clause" has far reaching implications. In the absence of specific legislation, the general duty clause is O.S.H.A.'s first line mechanism to encourage workplace safety. The mandate, vague at best, leaves interpretation to the investigating officer, which in turn leads to subjective enforcement standards that can vary with the individual inspector and the particular circumstance. What is found to be entirely satisfactory with inspector "A" today, can result in fines when inspector "B" comes to call tomorrow.

The idea of having a technically competent employee handle on-the-job training is one that seems to make sense. "Have the new guy work with Bob for a day or two," is one common way to approach skill acquisition. And there's nothing wrong with it ... **until the day that the new laborer gets seriously injured**. Once an injury occurs, all of the efforts to prepare that laborer for the hazards he/she was to face come under the microscope. "What was he taught?" "Who taught her?" "What qualified the trainer to train in the first place?" "Can you prove that this training ever occurred?" How can an employer protect himself? How much is enough? Where can the line be safely drawn?

2. OVERVIEW OF A WATER BLAST TRAINING COURSE

Any effective training course meets many criteria:

1. It provides information that a trainee must know.
2. It provides opportunity for skill acquisition.
3. It is properly documented to allow for consistency as it is presented over and overagain.
4. It provides a "paper trail" that indicates:
   a. Who took the course
   b. Who taught the course
   c. When the course was presented
   d. Documentation of skill/knowledge acquisition

There are as many ways to accomplish these objectives as there are training consultants! The following is one effective approach.

3. WHERE DO YOU BEGIN?

A wise man (perhaps from the AAA) once said that the very first step in any journey is to determine where you want to end up. It is only after completion of this critical step that a specific route can be planned. The same is true in training. The first step must be to determine where you want to end up. That point can be determined by asking several questions:

1. What do they need to know?
2. What do they have to be able to do?
3. How well do they have to do it?
4. If I were to watch somebody really good at this, what would I see?
5. How will I determine when the training is successfully completed?

The answers to these questions become "Instructional Objectives". They define the intent of the course, and the standards to evaluate both course and trainees before any other development work is ever begun. Instructional objectives are the equivalent of your training road map.

At MPW, the instructional objectives for water blast training are stated as follows:

"Upon completion of this course, the trainees should be able to:

1. Demonstrate ability to recognize delivery hose.
2. Demonstrate ability to distinguish between male and female hose couplings.
3. Demonstrate ability to properly connect hose sections together.
4. Demonstrate ability to recognize and size lances.
5. Demonstrate ability to properly set up a water blast area
6. Demonstrate ability to properly execute emergency shut-down procedures
7. Demonstrate ability to safely operate water blast guns
8. Demonstrate ability to safely operate water blast lances."

You'll notice that each of the objectives deals directly with competencies that are demonstrated by the trainees. That's an important point. All too often, if you ask a trainer "What is the objective of this course?", you'll get an answer like "To inform the class that...." and other statements that describe *what the trainer is planning to do*. That is not an instructional objective. Instructional objectives should take the form **"Upon completion of this course, the trainees should be able to...**" Stating objectives in that form will keep you on track.

Notice that each objective is dependent upon the trainee being able to "demonstrate ability" to accomplish a goal. The goals are simply stated. In the documented content of the course, each goal is clearly spelled out with applicable standards of performance. *The intent of the course is to prepare each trainee to successfully pass the tests implied by these objectives.* At the end of the course, evaluation is simple. Can the trainee perform to stated standards? If the answer is "yes", the trainee is considered to have passed the course and gets credit for acquired skills. If a trainee cannot perform to the stated standards, the trainee is not considered properly trained. If none of the trainees can properly perform, then there's a problem either with the course design, its presentation, or both.

If instructional objectives are the first step in the preparation of a course the next step is to prepare course documentation. Course outlines range from simple to extremely complex, depending on the content of the course, and the experience level of the trainer. An outline for a course that I am to personally deliver may be as simple as a single sheet of paper listing course content, with notations as to when to use any instructional aids. On the other hand, if the course is to be presented by one of my designated trainers, the format changes radically.

Page 1 consists of the **Course Description**. Information on this page includes the course title, audience (who will attend the course), prerequisite courses when appropriate, a general description of the course, a listing of instructional objectives, methods to use to evaluate trainee competency, materials and equipment necessary to present the course, a specific listing of necessary visual aids, and a listing of each of the overheads that were generated for the presentation. A typical MPW course description sheet is included in the appendix to this paper.

The remainder of the document is the **Course Outline**. Each page of the course outlines for MPW's designated trainers are divided into 3 sections: Content, Instructional Tactics, and Aids.

The **Content section** specifies information that is to be covered in the course. Organized in outline form, it details the information that is to be shared with trainees. It is mandatory that all information listed in the content section is included in the course in the order listed.

The **Instructional Tactics** section lists effective ways to communicate the information listed in the content section to the trainees. These are "notes" to the trainer. They give ideas and suggestions as to presentation techniques and appropriate procedures. They are not mandatory. If the trainer wishes to present the material in some other fashion than the one listed, that's fine *if it is effective*. What is important is the delivery of content, not the particular style of the instructor.

The **Aid section** lists handouts to deliver, overheads to display, and any other "prop" to use during course presentation. When potential trainers attend our Train-The-Trainer courses, they leave with complete packets of course descriptions, outlines, and support materials. A typical MPW Course Outline sheet is included in the appendix to this paper.

One of the questions that I am frequently asked is "How did you ever learn all this stuff?" (referring to course content). The simple answer is that no trainer ever comes to a course with all of the knowledge necessary for its completion. Trainers interact with operations people, safety people, administrators and any others *who already have the knowledge that needs to be learned by others*. The trainer collects information as to how things should be, defines (with appropriate input) and documents instructional objectives, determines the level of skills already in existence, and finally develops the course. To be truthful, the less knowledge of the subject the trainer initially has at the beginning of the development process, the better an introductory course will probably be.

The reason for this, is that an introductory course is designed to be presented to trainees who have no knowledge of the subject. When the trainer finds himself in that position, he is forced to ask the same kind of questions that the trainees will ask, and in the process of finding those answers the course is developed. The greatest sin that a trainer can commit is to assume that trainees know more than they do. The second greatest is to assume that trainees know less than they do. Walking that fine line in between is what adult instructional techniques are all about.

4. ADULT INSTRUCTIONAL TECHNIQUES

There is a tremendous difference between "teaching" and "training". Some differences involve the type and character of information covered. Teaching is generally thought to be more cognitive in nature. This involves the transfer of information, resulting in questions along the line of "Does he know?". Training, on the other hand, is generally assumed to be more skill-based, resulting in questions along the line of "Can he do?".

Remembering back to my school days, it seems that instructors were typically placed in the front of the class and spouted wisdom, which we, as students, dutifully wrote down and then parroted back during exams. We (the students) knew nothing (or very little). They (the teachers) had the knowledge and were willing to share it. **This is certainly not training!** For a training class to be effective, it must be dynamic and interactive.

Much has been written about the differences between working with adults and working with children. Children are trusting - adults are not. Children are content to be led - adults are not along for the ride, they participate in the trip and the instructor is more of a coach/referee/pilot than a driver.

To set the stage for adult learning to take place, the instructor follows a very definite plan. The steps to that plan include:

1. Introduction of the immediate objectives
2. Covering of the material in detail
3. Testing or recapping as appropriate

4.1 Introduction of the Immediate Objectives

As stated earlier, adults are not trusting. They want to know where this bus is headed, when it's going to get there, and the route it's going to take. Their need to know these details before serious instruction ever begins, is critical. Skill acquisition or knowledge retention is improved dramatically when courses, modules, and even individual ideas are properly introduced.

The format for each introduction is very similar. You inform the class as to the course (or module, or idea) that is to be covered, why it is important, and what they (the trainees) should be able to do when the training is complete.

Needless to say, some introductions are more detailed than others. If you are introducing a course to a group of newly hired trainees, you might include descriptions of the length of the course, whether there are both classroom and field modules, where restrooms are located at the training facility, whether or not smoking is allowed, course evaluation procedures and specific ground rules as to what you expect from them ("Sleeping in the back of the room will **not** get you certified!"). Introduction of a module within the course, on the other hand, may be no more than a statement of the instructional objective.

Example - "Now that you have a grasp of the safety procedures we expect you to follow and the personal protective equipment we expect you to wear, it's time to take a look at the actual equipment that you will be working with. When this section of training is completed, you should be able to recognize each of the pieces of equipment that is used for water blasting. You will also be able to properly connect each of those pieces of equipment together, and perform proper start up procedures to begin a water blast job."

4.2 Cover the Material in Detail

Okay - You're off and running. The course is introduced, the trainees know where you're coming from (and where you're headed) and now comes the serious part. How do you most effectively cover the material to ensure retention? There are a plethora of support materials available to today's trainer -- Books, Audio Cassettes, Videos, Lecture, Overhead Transparencies, Handouts, Live Demonstrations, Focus Groups, Interactive Computer Programs, the list goes on and on. How do you choose?

There are many reasons for why one chooses any specific training approach. Any of them can be justified at any given time. Studies have proven that, while any method can be used to introduce information to the trainee, information is *retained by* the trainee at rates that vary from 10% to 90% depending on the choice of presentation method. The following are my biases:

The most effective training method is to have the trainees actually do something. They will retain up to 90% of the procedures they learn and perform. When *doing* is not feasible, **get trainees to discuss issues** (as opposed to lecturing to them). Trainees retain 70% of the material they have the opportunity to discuss.

Example - In our water blast course one of the instructional objectives is for the trainee to demonstrate ability to perform an emergency shut-down of the equipment. We address this issue in the classroom discussing reasons why it is an important procedure to know. We demonstrate the procedure when we are at the field training site, but most importantly *each trainee shuts down the pump and disengages the PTO as part of the training*. When the training water blast job is underway, we will simulate emergency conditions necessitating the immediate shut-down of the equipment. The trainee must respond appropriately or does not get course certification.

Watching videos is not synonymous with learning! In most cases, trainees watch videos the same way they watch television, with about the same retention rate (30%). At MPW we use videos only to simulate a training environment that we cannot actually create ourselves.

Example - we utilize videos in driver training program that show, from the cab of an 18 wheeler, how to react when another driver unexpectedly swerves into your lane. The information is presented in a dynamic way that we would not be able to duplicate in a classroom setting. On the other hand, we don't watch video programs that detail the different parts of a material safety data sheet. We'd rather put an M.S.D.S. into the trainees hand and discuss the different parts with them.

Reading course materials has been shown to achieve a retention rate of only 10%. For that reason alone I steer clear of reading as a primary method of instruction.

Vary techniques when possible and appropriate. This helps to keep courses didactic. Even hands-on training courses have classroom modules. I utilize overheads, small group interactions and limited lecture in the classroom, and workgroups with "elected" leaders for field modules (building on or performing procedures that were first introduced in the classroom).

Example - in the classroom we will discuss the site preparation that is necessary before beginning a water blast job. This includes use of barricade tape and appropriate signage, placing of stanchions, policing the area for unneeded objects, selecting locations for spray deflectors etc. When we adjourn to the water blast training area, the task of "properly securing the area and preparing it for water blasting" is turned over to a "crew" of trainees who (under supervision) perform the tasks while policing themselves. Their efforts are critiqued and we give them praise or redirection as appropriate.

Ask trainees for the answers to questions instead of lecturing. This gives trainees the opportunity to show what they know, and automatically builds class participation. The technique is a simple one to adopt, and is extremely beneficial.

Example - Asking "Who can tell me what O.S.H.A. stands for?" is always preferable to simply stating "O.S.H.A. stands for the Occupational Safety and Health Administration." If it turns out that no one knows what it does stand for, you still have the opportunity to explain the term.

Recognize that people need breaks. There is a definite correlation between the amount of information that anyone can absorb and the amount of time they sit in the classroom. I try to give breaks every 1-2 hours, depending upon the familiarity of the class with training and the difficulty of the material.

Example - If I have a room of new trainees I will give more frequent breaks than if I have a room of field supervisors in their 3rd day of a 4-day class. I will give more frequent breaks during a Hazard Communication training program than I will for a class on the rebuilding of air support equipment. Remember, breaks are for the release of stress and emotion, not merely to "stretch the legs".

Instill confidence on the part of the trainee. The most difficult of tasks can be broken into manageable parts. Trainees, especially those new to the organization, can quickly become overwhelmed and intimidated by what will, in time, become routine procedures. One job of any trainer is to promote the attitude that "You can do this."

5. PREPARATION OF THE TRAINING ENVIRONMENT

There are many considerations in the preparation of a suitable training environment for your water blast course.

5.1 The Class Room

I vividly remember the last course presentation that one of my designated trainers conducted. Unfortunately, what I remember was that he presented it in a garage where mechanics were trying to repair a water blast truck. Between the noise made by the mechanics, by dropped tools, by the truck engine turning over (and finally starting), the overpowering smell of partially burned diesel fuel and the fact that I was *cold* I paid very little attention to the course material. Neither did anyone else.

Classrooms are more than just a place to deliver information. The layout and ambiance of a classroom impacts the success of course presentation. To achieve maximum effectiveness, the classroom should be large enough to comfortably seat all of the expected trainees. Temperature should be controlled with thermostats in the room itself, as putting many people in a room will heat it quickly.

Support materials such as marker boards, easels, overhead projectors, screens, video playback decks and monitors should be at least available and definitely on-hand if their use is mandated by the dictates of the course outline.

Chairs should be comfortable to sit in for long periods of time. Accommodations for taking notes (whether the chairs are accompanied by tables or have writing surfaces built in) should be routine. I like the flexibility of tables and chairs, as it is easy to rearrange classroom seating to facilitate small group interaction. The moving of tables and chairs is also a good way to re-energize trainees who tend to get sluggish after the lunch break.

5.2 Training Sites

Sites for field training in water blast skills must be selected with care, but need not be prepared before the arrival of the trainees. *The preparation of a site for water blasting is an* *integral part of a water blaster's skill base. Therefore, it is important that he/she has the opportunity to properly prepare the site.* Requisites of a site are discussed in the classroom, and actual site preparation is a procedure to be completed prior to commencement of jetting activities. Appropriate procedures involve removing unneeded materials from the site, placement of blast deflectors, stringing of barricade tape, posting appropriate signage, etc. Depending upon the specifics of our job scenario, we also incorporate ground plastic and booms to ensure collection of all waste materials generated through the cleaning process.

The site itself needs to be located away from high traffic areas. It must have a water supply adequate to supply a water blast pump. Site needs include a drainage system for used water, and, most importantly, something to be cleaned. In our training we use a variety of items: fabricated plates that we cover with paint, tube bundles plugged with concrete, or materials such as grates from paint booths covered with overspray.

5.3 The Trainee

Prepare the trainee? You bet! The ultimate success or failure of your program depends upon how well the trainee performs. If he/she does something incorrect because he doesn't know any better, you deserve the criticism. If, on the other hand, he/she does something incorrect because of the tremendous amount of information he's received in the last four hours and is a bit overwhelmed - that's another story. To ensure that each trainee performs up to his/her abilities it is appropriate for the trainer to have a "hard hat" meeting with the "crew", just as a field supervisor would before any job undertaken in the field.

This meeting gives the trainer the opportunity to refresh in the trainees minds what the standards of performance are to be for the field module. He can reinforce specifics that he will be looking for - both positive and negative.

It gives the trainees a final opportunity to ask questions about information or procedures that they may be unclear about. Most importantly, it gives the closure to the course. You've done your best to prepare the trainee for the upcoming test. Now it's up to him/her.

6. APPROPRIATE TESTING

What kind of testing is appropriate for a water blast course? Well, what are your instructional objectives? If they include items such as "Given specifics of flow rates and pressure settings, demonstrate ability to select appropriate nozzles", then you probably will need to have pencil and paper tests to determine competency.

On the other hand, if your objectives include "Demonstrate ability to properly replace washers in water blast hose couplings", then the only way to allow trainees to properly demonstrate proficiency is to give them a handful of washers, "o" rings and hose couplings, and watch the results. Generally, I steer clear of pencil and paper tests whenever possible. Skill-based training demands skill-based tests. They are more practical and much easier to administer. Our procedures include having the trainees select and deliver to the site specific materials that are requested by the trainer in the set-up of the job site. If the trainer requests a 20,000 psi blast gun and the trainee delivers a 10,000 psi unit, we obviously have a problem.

7. DOCUMENTATION TECHNIQUES AND FORMS

How do you develop a form to document skills and/or knowledge tests? Again, look to your instructional objectives. The test should be a reflection of the competencies listed there. Appropriate documentation should include the following:

Opening statement that clearly defines the purpose of the form. This statement should take the form "I certify that the trainee named below has demonstrated proficiency in each of the following areas:"

Clearly understandable statements of expectations. These statements are a reworking of the instructional objectives.

Example - "Ability to recognize the difference between 1½" and 2½" fill hose" or "Ability to operate a lance safely".

A method of signifying that the skill was properly demonstrated. This is probably best addressed with boxes that can be checked off as each skill is executed.

Signatures and dates of completion for both trainee and trainer. This is a must! Documentation without a signature from all parties involved will not stand up in case of government inspection. Having a trainee sign a form that states as of today he/she is able to perform properly also helps to reinforce the idea that these are the standards that he/she will be held accountable to in the future.

A typical skills documentation checklist is included in the appendix to this paper.

8. SKILL TRANSFERENCE

You would think that with each of the aforementioned ideas properly executed that you should have nothing to fear in the event that O.S.H.A. comes calling. Unfortunately, that might not be the case. The final step of any good training program must be its insistence that *what was learned in the classroom is practiced in the field.* Many court cases have been lost due to "inadequate training" when indeed they were really lost for lack of management control.

The finest training program will fail to protect the company if the points it makes and procedures it expounds never leave the office. If there are additional points that need to be considered when viewing your water blast training program they are these:

1. Management must become involved with the training of their employees.
2. Supervisors must make themselves aware of what the employees are learning.
3. Supervisors must facilitate the transfer of new skills and knowledge to the workplace.
4. Jobs must get set up in such a way as to allow trainees to use those skills they have been taught.

Training

MPW INDUSTRIAL SERVICES TRAINING COURSE

DATE: 7/1/91
REVISION DATE: 6/23/94

COURSE TITLE: Water Blast Hands-On-Skills-Training (H.O.S.T.)

AUDIENCE: All MPW Industrial Cleaning new hires

PREREQUISITE COURSES: Personal Protective Equipment

DESCRIPTION: Water Blast Hands-On-Skills Training is a program to present to the MPW new hire the equipment they will work with, and the procedures that they will be expected to follow in the delivery of our water blast services. Combining both safety and skills procedures, the course length is determined largely on the number of trainees. The course contains both classroom and field modules.

OBJECTIVES: **Upon completion of this course, the trainees should be able to:**

1. Demonstrate ability to recognize delivery v/s fill hose.
2. Demonstrate ability to distinguish between male and female hose couplings.
3. Demonstrate ability to properly connect hose sections together.
4. Demonstrate ability to recognize and size lances.
5. Demonstrate ability to properly set up a water blast area.
6. Demonstrate ability to properly execute emergency shut-down procedures.
7. Demonstrate ability to safely operate water blast guns.
8. Demonstrate ability to safely operate water blast lances.

EVALUATION: Trainees will be evaluated through instructor/trainee interaction and proficiency in hands-on operations.

MATERIALS/EQUIPMENT: MPW Training Log, Water Blast Training Checklist, Water Blast Truck/Trailer, Water Blast Fill Hose (assorted sizes), Water Blast Delivery Hose (assorted sizes), Male and Female Couplings, Coupling "O" Rings, Blast Guns and Lances, Water Blast Training Site Preparation Checklist

VISUAL AIDS: Overhead OH-01 - "Typical Water Blast Set Up", Overhead OH-02 - "Water Blast Safety Concerns", Overhead OH-03 - "Mandatory Personal Protective Equipment", Overhead OH-04 - "Safety Procedures -- General", OH-05 - "Safety Procedures -- Water Blast", Overhead OH-06 - "Safety Procedures -- Lancing"

Content	Instructional Tactic	AID
5. Never pull the nozzle out of a tube until the pressure has been dumped.	***Test / Recap*** You have covered a lot of material in this section. It is appropriate to ask your trainees several questions before going any further. Ask questions like -- "Bob - Name one piece of mandatory PPE for water blasting. Bill -- What's another? Jim -- What is the last thing you do before putting nozzles onto blast guns or lances?" etc. Do not continue with the course until you have satisfied yourself that the trainees know the information that has been covered up to this point. ***New Module Introduction*** When you do feel comfortable with the trainee's knowledge, introduce the next section by saying something like "O.K., now that you have a good grasp of the safety procedures we expect you to follow and the PPE we expect you to wear, it's time to take a look at the actual equipment you will be working with. When this next section of training is completed, you should be able to recognize each of the pieces of equipment that is used for water blasting. You will also be able to properly connect each of those pieces of equipment together, and perform proper start up procedures to begin a water blast job.	
IV. WATER BLAST EQUIPMENT A. Delivery Hose 1. ½" Blast Hose 2. 1" Blast Hose B. Fill Hose 1. 3/4" Chicago Hose 2. 1½" Fire Hose 3. 2½" Fire Hose	Show the equipment to the trainees in a logical, planned approach. First show all of the fill hoses, then move on to the delivery hoses or working equipment. ***The order is not important, but the idea of completely covering one area of equipment before moving on to the next is***. For example, don't show 3/4" fill hose, then 1½" fill hose, and then start showing couplings (neglecting 2½" fill hose). Once you begin showing fill hose, show all of it before moving on to other equipment. After showing (and naming) each piece of equipment, point to pieces of gear and ask trainees "What is this?" or "If I asked you to get a 2½" fire hose, what would you bring me?"	

WATER BLAST TRAINING CHECKLIST

I certify that the trainee named below has demonstrated proficiency in each of the following areas:

- ☐ Ability to recognize the difference between blast hose and fill hose
- ☐ Ability to recognize the difference between ½ inch blast hose and 1 inch blast hose
- ☐ Ability to recognize the difference between 3/4 inch Chicago fill hose, 1½ inch fill hose, and 2½ inch fill hose
- ☐ Ability to recognize the difference between a male hose coupling and a female hose coupling
- ☐ Ability to properly inspect and replace faulty "o" rings and back up rings in hose couplings
- ☐ Ability to connect hose sections together properly
- ☐ Ability to recognize the differences between a 10,000 psi blast gun and a 20,000 psi blast gun
- ☐ Ability to recognize the differences between a 1/8 inch lance, a ¼ inch lance, and a ½ inch lance
- ☐ Ability to properly execute emergency shut-down procedures
- ☐ Ability to operate a blast gun safely
- ☐ Ability to operate a lance safely

______________________________ ______________________________

Trainee/Date **Trainer/Date**

8th American Water Jet Conference
August 26-29, 1995: Houston, Texas

Paper 23

DEVELOPMENT OF AN EXTREMELY DURABLE HIGH PRESSURE PUMP FOR CEMENT SUSPENSION

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ABSTRACT

Jet grouting is one of the soil improvement methods in which very soft soil is made hard enough to support building structures. Thirty percent of the land in Japan consists of soft soil, and more than eighty percent of the population is located in such areas.

Soil improvement methods are thus essential to maintain the Japanese infrastructure.
In the jet grouting method, a cement suspension is jetted out at high pressure.
A major problem with this method has been the durability of the high pressure pump for cement suspension. We therefore modified the valve and plunger packing system of the existing high pressure pump and succeeded in greatly extending its durability compared to existing pumps.

This paper describes this high pressure pump complete with a newly developed valve and packing system and discusses the results of a durability test conducted on the new pump.

Organized and Sponsored by the Water Jet Technology Association.

1. PREFACE

To develop waterfront areas in Japan, poor ground is increasingly being used. Under the circumstances, soil is also frequently improved to construct safe structures on the poor ground.

Among the various methods of soil improvement that are implemented, the jet-grout method, which creates a column under the ground by injecting cement slurry at high pressure, has been used extensively. This is regarded as one of the best soil improvement technologies, and different versions of it are now being developed to obtain higher quality and performance.

One of the newly developed jet-grout technologies applies a pressure of over 30 MPa. However, this technology has the drawback that the high pressure pump and the packing for the plunger is not very durable.

To seal the plunger of a high pressure pump V packing, U packing, and gland packing sheets are used. This report describes the tests conducted to study the durability of the pressure pump and its plunger when cement slurry is used. The U packing sheet has excellent sealing performance in that it is compact, and a single sheet can withstand a pressure of 70 MPa. When the rib fails and starts to leak cement slurry, however, leakage cannot be stopped unless the U packing sheet itself is replaced.

If cement slurry starts to leak during the injection process, therefore, it is difficult to find a first-aid measure to stop the leakage. In the worst case, this would make it necessary to interrupt the construction work to replace the packing sheet.

On the other hand, more than one V packing sheet can be used depending on the working pressure. However, in such a case, the packing chamber would have to be large. Another disadvantage of this particular packing sheet is that its friction resistance is larger than that of the U packing sheet. If leakage occurs in the injection process, however, it can be stopped by simply adding another packing sheet and retightening them, which means that the construction work would not have to be interrupted.

In view of the features of the V and U packing sheets, we conducted combination tests to develop a compact and durable packing sheet that would embody the advantages of both of these types of packing.

To lubricate the plunger seal, grease and oil, which have a substantial effect on the durability of the seal, are normally used. Moreover, grease and oil sometimes pose a problem by leaking into the cement slurry.

Therefore, we used a water-soluble lubricant in place of grease or oil, and conducted tests to compare its effect on the durability of a seal.

2. TESTS

2.1 Factors that Affect the Durability of the Packing

There are four important factors that affect the durability of a plunger in a high pressure pump.

1) Material, shape and combination of different types and/or quantities
2) Type of lubricant and method of lubrication
3) Sliding speed between the packing and plunger
4) Concentration of cement slurry

We tested a three-plunger high pressure pump to study the effects of 1) and 2) on its durability when cement slurry is used, while keeping factors 3) and 4) constant.

2.2 Test Conditions

1) Packing for the plunger

We adopted the following test pieces and test conditions.

(1) Five V packing sheets (proof pressure 30 MPa) (Fig. 1)

We sealed cement slurry at 30 MPa using five V packing sheets. When the cement slurry leaked, we retightened the packing sheets to stop the leakage.

(2) Five V packing sheets (proof pressure 30 MPa) plus a U packing sheet (proof pressure 70 MPa) (Fig. 2)

We sealed the cement slurry at 30 MPa with a U packing sheet. When the cement slurry leaked, we added more V packing sheets and retightened them to stop the leakage.

(3) Three V packing sheets (proof pressure 4 MPa) plus two U packing sheets (proof pressure 70 MPa) (Fig. 3)

We sealed the cement slurry at 30 MPa using two U packing sheets. When the cement slurry leaked, we added more V packing sheets and retightened them to stop the leakage.
(We should have used five V packing sheets, but the packing case could not accommodate more than three sheets due to dimensional restrictions.)

2) Lubricant

The lubricant used to seal the cement slurry plays an important role in cooling the sealing part and reducing the frictional resistance between the plunger and packing, thereby extending the life of the packing. We used three types of lubricant in the tests.

(1) Water-proof and heat-proof grease

(a) Lubrication of about 40 cc once every 20 minutes
(b) Lubrication of about 40 cc once every 10 minutes
Fig. 4 shows the grease-supplying device (grease gun).

(2) Oil (lubricant for rock drill)

We adopted the oil bath method (Fig. 5), and replaced the oil in the oil cap when cement slurry was found in it.

(3) Water-soluble lubricant

(Properties)
Solubility .... ∞g (infinite) for water
Inflammability ... None
PH 8.4

We adopted the oil bath method (Fig. 5), and replaced the lubricant in the oil cap when cement slurry was found in it.

3) Valves

Valves were not relevant to the durability test conducted on the plunger seal. However, we will explain the valves used for the three-plunger pump. (Three valves were used on the suction side, and another three were used on the delivery side.)

Plunger pumps normally use a ball-type valve (Fig. 6) or a cone-type valve (Fig. 7). In this test, however, we used a flat-type valve (Fig. 8), a patent of YBM, which features the following.

(a) The elastic sealing material fixed at the valve seat makes a compact and lightweight configuration and improves the follow-up movement of the valve against the flow in the pump cylinder.
(b) The symmetric construction of the valve allows it to be reused in reverse if one side has worn out. This is also true of the valve seat.

4) Plunger pump

We used an SG-75 pump, which has three plungers and the following dimensions

Type	SG-75 -7
* Plunger stroke	46 mm
* Plunger diameter	ϕ 50 mm
* Crank-rotating speed	280 rpm

* Plunger speed 0.43 m/sec
* Maximum discharge pressure 40 MPa
* Discharge quantity 70 l/min
* Driving-motor output 55 kw

3. TEST PROCEDURE

1) Fig. 9 shows the general view of test equipment.

We prepared 20 m^3 of cement slurry (by mixing 760 kg of cement, 100 kg of hardening inhibitor, and 660 kg of water per cubic meter to a specific gravity of 1.5) and stored it in a tank.

We used a hardening inhibitor to prevent the cement slurry from hardening.

We installed packing sheets in the high-pressure plunger pump SG-75 (Fig. 10), and applied a lubricant before injecting the cement slurry prepared in the tank continuously at 30 MPa and 70 l/min. The cement slurry was circulated between the plunger pump and the water tank. We recorded the injection pressure, flow rate, motor current, temperature of the packing gland, and seal leakage every hour.

2) Test modes

The following Table lists the combinations of packing sheets and lubricant used for the test.

Table 1. Combination of packing sheets and lubricant used for the test.

Test No.	Packing	Lubricant
1	5 V packing sheets + 1 U packing sheet	Grease (once per 20 min.)
2	5 V packing sheets + 1 U packing sheet	Grease (once per 10 min.)
3	3 V packing sheets + 2 U packing sheets	Grease (once per 10 min.)
4	5 V packing sheets + 1 U packing sheet	Water-soluble lubricant
5	3 V packing sheets + 2 U packing sheets	Water-soluble lubricant
6	5 V packing sheets + 1 U packing sheet	Oil
7	5 V packing sheets	Oil

We conducted tests No. 1 through No. 7 by injecting cement slurry for eight hours continuously from 9:00 AM to 5:00 PM, and repeated this procedure for a total of 100 hours or until leakage occurred and made it impossible to continue the test.

When cement slurry started to leak from the seal, we retightened it to stop the leakage. If this did not stop the leakage, we terminated the test.

After injecting cement slurry for 100 hours, we disassembled the packing and determined the degree of wear.

We used new plungers for each test.

4. TEST RESULTS

Fig. 9 shows the set-up of the testing equipment. We circulated 20 m^3 of cement during the tests. Prior to injecting the cement slurry, we cooled it in the water-jet injection pipe. Nevertheless, its temperature rose to about 80°C due to the insufficient cooling capacity of the system. Therefore, the tests were conducted under unusual conditions.

Figs. 11 to 15 show the V packing and U packing sheets before and after the test. In test No. 1, a lump of cement clogged the suction strainer, thereby creating negative pressure in the cylinder chamber and deforming the U packing sheet. Thus, the cement slurry started to leak after 20 minutes.

We were also able to determine that shorter greasing intervals substantially increased the life of the packing. The life of the packing also increased when the V packing was used together with the U packing. When only the U packing was used, it was more effective when two sheets were used together. The different types of lubricant (grease, oil, and water-soluble lubricant) had no significantly different effects on the life of the packing, when the packing sheets were greased at regular intervals. See Table 2 for the test results.

5. DISCUSSION AND CONCLUSIONS

1) The V packing extended the life of seal when it was used with the U packing. Therefore, we can conclude that the U packing should be used for primary sealing of the plunger pump in the case of cement injection, and the V packing sheet should be added and retightened if cement leaks during the construction work.
2) More frequent greasing will extend the life of the packing.
3) To lubricate plunger pumps, a water-soluble lubricant can be used in place of other lubricants.
4) If the suction side becomes clogged, insufficient suction may create a negative pressure in the cylinder and deform the packing sheet.
5) Flat valves can be used for 600 hours continuously.

In the above tests, the temperature of the cement slurry rose to about 80°C, which is 50°C higher than under normal conditions, because it was circulated for repeated use.

It is said that resins used for sealing deteriorate twice as fast as usual when the temperature rises by 10°C. This suggests that the packing would have been more durable, if the tests were conducted under normal conditions, that is, if the cement slurry had not been reused.

There are various packing types other than the U and V types. Even among the U and V types, there are a number of different materials and hardnesses.

In the future we will continue to conduct tests to develop sealing methods with a longer durability.

6. ACKNOWLEDGEMENT

We would like to express my gratitude to Mr. Hiroshi Yoshida of Chemical Grouting Company for his contributions and encouragement in the implementation of the tests.

7. REFERENCE

F. Oishi and I. Narisawa, "Durability of Plastic Materials," The Nikkan Kogyo Shimbun Ltd.
S. Omori, "Q & A, Essence of Sealing Technology," The Nikkan Kogyo Shimbun Ltd.

Table 2. Test results.

Test No.	Operation hours	Packing sheet	Lubricant	Max. temperature of the packing gland surface	Max. temperature of the cement slurry	Incidence (Remarks)	V packing sheet inner diameter (mm)	U packing sheet inner diameter (mm)
1	20 minutes	Five V packing sheets plus a U packing sheet	Greasing every 20 minutes	14 °C	16.5 °C	Cement slurry leaked from the packing gland. A lump of concrete clogged the suction strainer, creating a negative pressure in the cylinder and deforming the U packing sheet.	48.5-48.8	48.4-48.6
1-2	34 hours	Five V packing sheets plus a U packing sheet	Greasing every 20 minutes	96 °C	50 °C	Cement slurry leaked from the packing gland.	49.8-50.2	50.1-50.4
2	60 hours	Five V packing sheets plus a U packing sheet	Greasing every 10 minutes	66 °C	52 °C	Cement slurry leaked from the packing gland.	49.9-50.2	50.2-50.5
3	100 hours	Three V packing sheets plus two U packing sheets	Greasing every 10 minutes	88 °C	52 °C		49.7-49.9	i)50.4-50.6 ii)49.9-50.2
4	100 hours	Five V packing sheets plus a U packing sheet	Water-soluble lubricant	70.5 °C	66.5 °C		49.8-50.0	50.0-50.4
5	100 hours	Three V packing sheets plus two U packing sheets	Water-soluble lubricant	85.7 °C	78.3 °C		49.5-49.9	i)50.2-50.3 ii)49.8-50.1
6	100 hours	Five V packing sheets plus a U packing sheet	Oil	86.0 °C	77.5 °C		49.9-50.1	50.0-50.3
7	63 hours	Three V packing sheets	Oil	86.3 °C	79.0 °C	A large quantity of cement slurry leaked into the grease cap.	49.9-50.3	-
							A new packing sheet 48.5-48.7	A new packing sheet 48.4-48.5

* i) : Cylinder case side
ii) : Crank case side

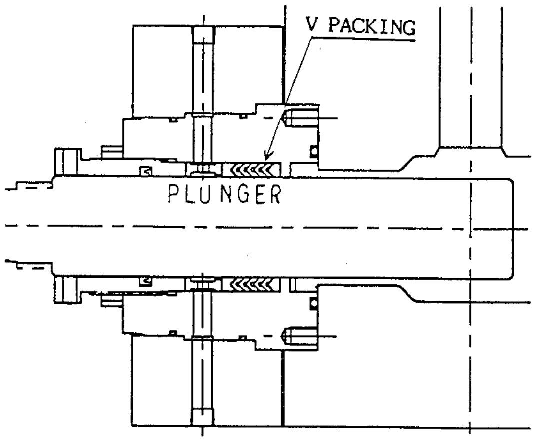

Fig. 1

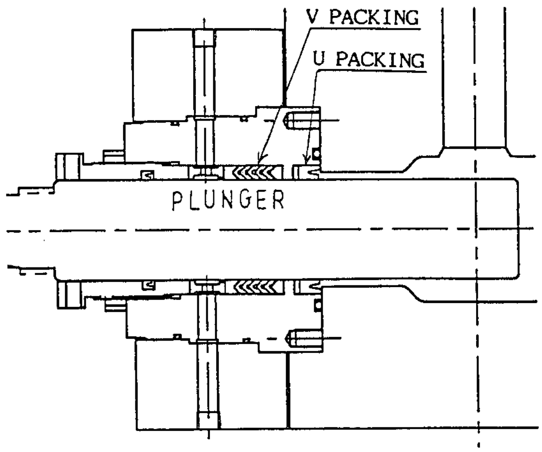

Fig. 2

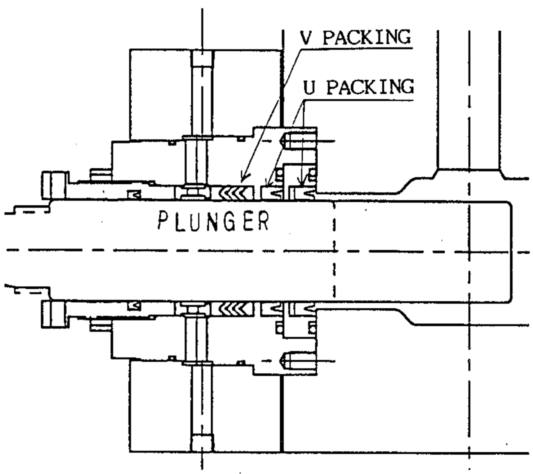

Fig. 3

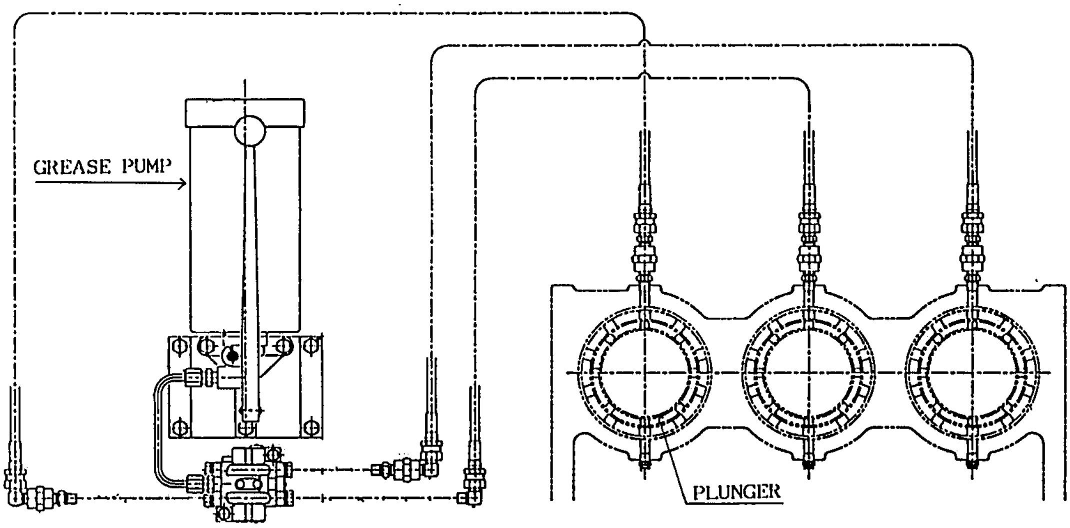

Fig. 4

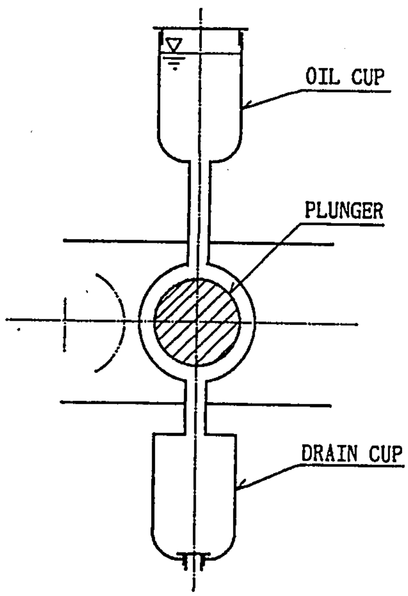

Fig. 5

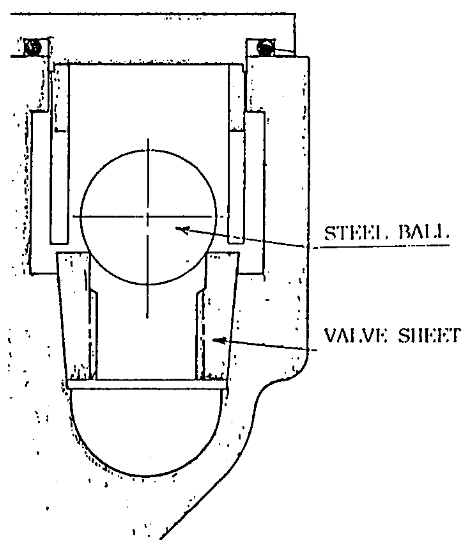

Fig. 6

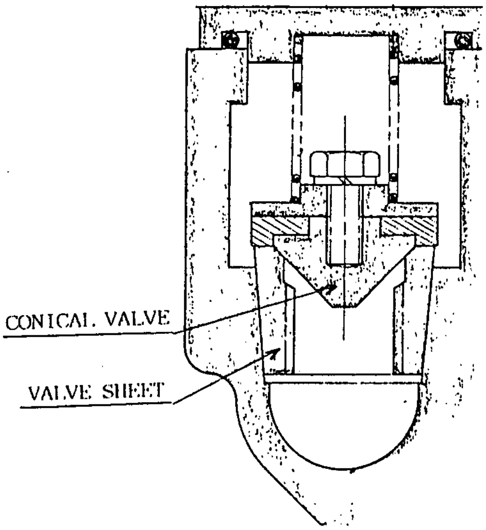

Fig. 7

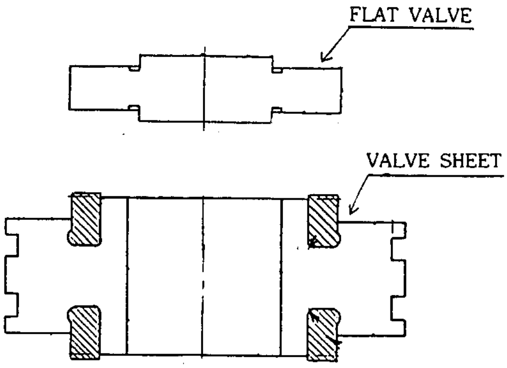

Fig. 8

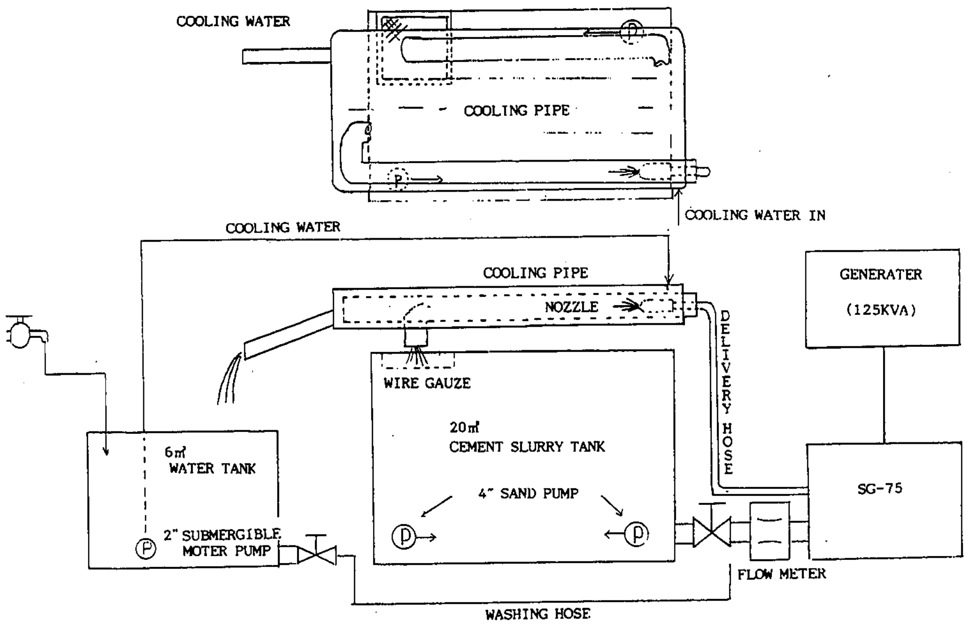

Fig. 9

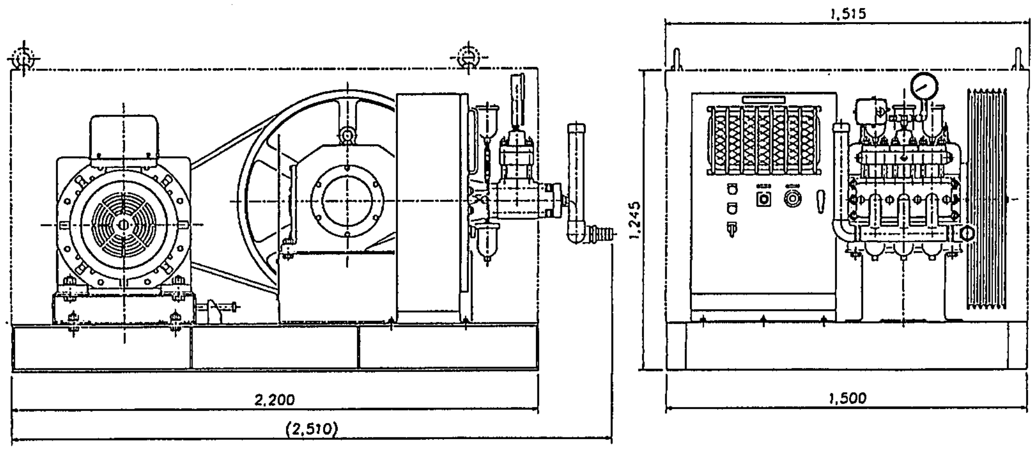

Fig. 10

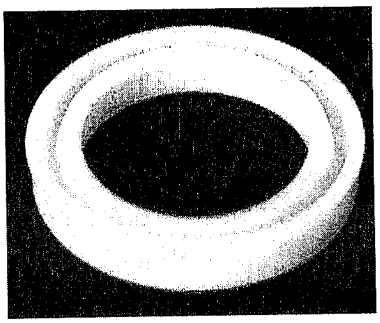

Fig. 11

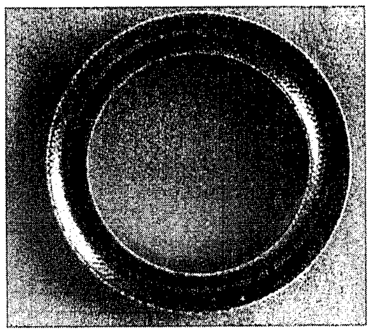

Fig. 12

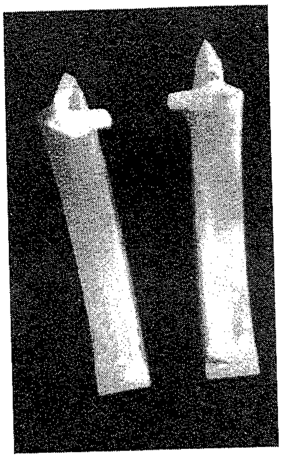

Fig. 13

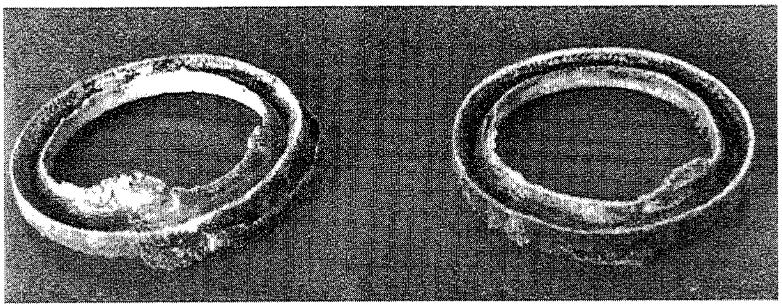

Fig. 14

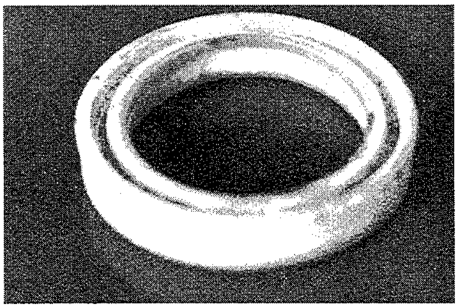

Fig. 15

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Paper **24**

POTENTIALITY OF WATER JET METHOD FOR CUTTING OF SHEET MATERIALS

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ABSTRACT

In manufacturing of many industrial products, the accuracy and rate of working are most important. This paper describes the phenomena or defects caused by water jet cutting and the characteristics of cut edges. Various phenomena were named and classified reasonably being compared with other working methods such as press shearing, metal sawing, machining and beam cutting. The water jet cutting has many individual flaws. Furthermore, the causes and influencing factors of the defects were explained by considering the experimental results of cutting such sheets as mild steel, austenitic stainless steel, extra super duralumin, polypropylene and polyphenylene-sulfide. In conclusion, the water jet of high pressure, short nozzle distance and small amounts of abrasive can cut various material sheets with practically sufficient accuracy.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

In manufacturing many industrial products, the accurate working of materials or product accuracy is most important along with the working rate or productivity. Water jet cutting has been studied mostly on its cutting ability such as equipment, applicability and dynamics (e.g., Freist et al., 1989, and Sano et al., 1990). However, the cutting accuracy has been reported too little to apply the method for manufacturing process (e.g., Blickwedel et al., 1990; Burnham et al., 1989; Hunt et al., 1987; and Matsui et al., 1990). To explore an applicability of water jet cutting to industrial use, authors investigated here the phenomena seen at cutting, especially cutting defects and characteristics of cut edges in comparison with conventional cutting methods.

2. EXPERIMENTAL

2.1 Materials

Five kinds of sheets: cold rolled steel (SPCC, t0.8), 18-8 austenitic stainless steel (SUS304, t0.8), and high-strength aluminum alloy (extra super duralumin A7075, t0.8), and polypropylene (PP, t0.8) and glass fiber reinforced polyphenylene-sulfide (GFRP, tl.8) were mainly tested. As listed in Table 1, the mechanical properties along with structures are quite different from each other.

2.2 Apparatus and Cutting Method

The experiment was done by using a water jet cutting machine: TGM Hydro-Cut System the with the capacity of 392 MPa (usually 314 MPa). In this experiment nozzle diameter is of 0.8 mm and water pressure is of 314 MPa, but cutting rate, free length of jet (nozzle distance, stand-off) and volume fractions of abrasives are variable. The cutting conditions are listed in Table 2. The used abrasives are a mixture of angular oxides (Garnet #120), as shown in Table 3. The specimen sheets were set between blank holders (steel, size: W200 x L200 x T19 open space for cutting: W13 mm x L150 mm). A scheme of the apparatus and the appearance of jet are shown in Fig.1(a) and (b) respectively.

The nozzle was set perpendicularly to the specimen sheet. After the given pressure and abrasive amounts were confirmed, the nozzle was moved at a given rate to a cutting direction until it passed a given cutting length.

2.3 Measurements

The appearance of cut surface and skin were observed. The roughness was inspected by a surface roughness meter, and also the flatness of cut surface was done by a contour measuring device. Measurements of cut edges (section) is illustrated in Fig.2. A microscope with movable stage (accuracy: 0.0l mm) was used to measure the maximum width (W_a) and the minimum width (W_b).

3. RESULTS

3.1 Cutting Phenomena on Materials

A cut surface by water jet cutting is simply illustrated in Fig. 3. Authors discovered typical macroscopic phenomena caused by water jet cutting and their characteristics, which were generally different from those by conventional cutting methods used on production spots. Each phenomenon was reasonably called with such names as shown photographically in Fig. 4. The material and the cutting conditions (t: thickness, p: pressure, h: nozzle distance, v: cutting rate, u: abrasive amounts) of each case are also stated in this figure. It is apparently seen that a few phenomena are similar as those in gas fusing and press shearing, but most phenomena are particular ones of water jet cutting. Each phenomenon can be simply written as follows:

(a) Crack — The phenomenon is very often seen in cutting brittle materials. Most cracks are caused by the first impact of jet, and therefore these can be avoided by reducing the pressure of jet at the starting point of cutting and also by increasing abrasives to improve the cutting ability.

(b) Skin roughening — The phenomenon is characteristic of water jet cutting, related to the increase of roughness of upper surface of material. This is caused by small pits which are formed by scattered jet, collision of abrasives, and rebounded water before penetrating the material. Hence this can be remarkably improved by the decrease of nozzle distance and abrasive amounts, and by the use of surface protection film.

(c) Uncutting — The phenomenon is seen when the jet impact is too small to penetrate the material. By increasing the jet pressure, using more abrasives, slowing down the cutting rate, and finding the optimum nozzle distance, this problem can be solved.

(d) Droop — The phenomenon is characteristic of water jet cutting. By the expanded down-stream of the jet, the material surface and the cut edges are shaved away to an undesirable wide range. The term "droop" is commonly used in press shearing of metal, but that of water jet cutting is not due to plastic deformation by tensile stress. This can be effectively improved if the jet is stabilized more and the nozzle distance becomes shorter.

(e) Curling — The phenomenon is a plastic deformation of the cut edges, which is caused by the bending moment of jet impact. Curling is often seen when cutting a thin metal and a mild metal. To improve this the decrease of nozzle distance and supporting span can be most effective.

(f) Burring — This is also an unique phenomenon of water jet cutting. Though the same term was used in press shearing, this is not caused by the breakage of strained material. Because of the insufficient cutting ability of the jet, the bottom of the material, which is to be removed, is put sideways to stay as fin. This is more often seen in cutting mild or ductile materials such as plastics. Increasing the jet pressure and abrasive amount can become the best way to improve the phenomenon.

(g) Tapering — The phenomenon means that the upper width between the cut edges are different from the lower one. As the down-stream of the jet becomes wider in its diameter and smaller in its power, the cut width tends to distribute through the material. In general, the cut width is increased from the top to the bottom in cutting mild materials, while decreased in hard ones. In order to decrease tapering, the optimization of nozzle distance, pressure, cutting rate and abrasive amounts are most effective.

(h) Exposure of fibers — The phenomenon is also characteristic to water jet cutting. When cutting fiber reinforced materials, reinforcements or harder fillers than the matrix remain uncut. Such a problem can be almost solved by increasing the jet impact and the amount of abrasives.

(i) Luster — The metal luster is observed at the upper part of the cut surface when the material is efficiently smooth cut with the strong pressure of the jet. The phenomenon is similar to the vanish surface seen usually in press shearing. In this part the surface is fairly excellent and also the highly accurate cutting can be expected.

(j) Drag lines — The lines are the curved stripes produced by the jet stream, for which the cut surface become uneven. The same phenomenon is observed in gas cutting as well. Drag lines can be decreased by increasing the cutting ability of the jet and by decreasing the cutting rate.

(k) Pitting — Pitting means the traces of pulled-out reinforcing fibers and also those of abrasive attacks on soft materials. This is an unique phenomenon of water jet cutting. The increase of jet impact and abrasive amounts is believed to solve the problem efficiently.

(l) Groove — The phenomenon is observed when the scattered jet stream removes the central part of the soft material. Grooves are very characteristic of water jet cutting. To prevent this defect, the cutting ability of the jet should be improved and the material should be made thinner. Also, when cutting composite materials, only soft fillers may be removed out by the jet stream. The improvement of the cutting ability of jet can be preventive of the defect as well.

(m) Rust or Stain — The cut surfaces of metals, especially steel, are very fresh and are activated to be covered with rust films at the early stage of cutting. Though the damage is little compared with that of a burn mark due to gas cutting and laser cutting, care should be given to control the product quality.

(n) Unstable cutting path and width — The phenomena means that the cutting width becomes uneven and also the contours of both cut sides are not symmetrical. These are caused by the inaccuracy and some damage of nozzle, which influence the shape and stability and thus the width of the jet.

(o) Residual abrasives — Abrasive particles sometimes get into the top surface and cut edges of soft material in abrasive cutting. The residual abrasives, though not so conspicuously seen, may do damage in following process such as welding. This phenomenon is not shown in the figure.

3.2 Contour of Cut Edge

Fig.5(a)-(e) shows the relationships between cut width and nozzle distance in cutting various material sheets. Generally it is seen that with the small nozzle distance and with the less abrasive amounts, the cut width becomes approximate to the nozzle diameter, however, with no abrasive cutting of high ductile materials such as steels and polypropylene, especially in the case of small nozzle distance, the cutting ability decreases rapidly until the uncutting phenomenon appears.

The examples of contour of cut edge are shown in Fig. 6. It is understood from the figure that generally the cut slant (tapering) tends to be smaller with using a less nozzle distance and more abrasives. With no abrasive the above mentioned uncutting is observed in the figure, too.

3.3 Burr and Surface Roughening

The results of the burring observed are shown in Fig. 7(a)-(d). In cutting all materials, the burr height tends to increase with the increase of nozzle distance. The products with no burr can be manufactured when the nozzle distance is very small. In cutting the polypropylene without abrasives (d), as already shown in Fig. 6, burr becomes extremely large due to the piled up chips. By using abrasives, however, this sheet also can be cut with no burring.

A top surface of cut sheet is remarkably roughened as mentioned above. For example, Fig. 8 shows typically an appearance of 18-8 stainless steel sheet after cutting. In the photograph the change in cut width is clearly seen and the roughening is also observed near the cut edges. The roughness of the cut surface is shown in Fig. 9, when the experiment was carried out at a nozzle distance of 0.5 mm and 5 mm. It is generally seen that the surface roughness is remarkably improved by using the shorter distance and the less abrasives.

4. DISCUSSION

4.1 Classification of Defective Phenomena

Being compared with those in other working methods such as press shearing, metal sawing, machining and beam cutting, observed defects were named and classified reasonably in this paper. It is noted that the water jet cutting owns some individual flaws, as follows:

(a) On the surface of material: cracking, skin roughening, pitting, residual abrasives, unstable cutting path, and unstable cut width, etc.
(b) On the contour of cut edges: uncutting, curling, droop or wear, tapering, exposure of

reinforcements, damage of core material, and burring, etc.

(c) On the cut surfaces: Luster, drag line, pitting, residual abrasives, groove, and rusting, etc.

The causes and influencing factors of each defects were made an assumption considering the observation of phenomena. In conclusion, such defective phenomena can be almost resolved when the cutting conditions are properly chosen.

4.2 Cutting Ability and Accuracy

Water jet cutting is essentially grouped into the cutting process based on material removing. As it is clear from the experimental results, the cutting material can be more easily destroyed and separated by making a nozzle distance longer and by thus making impact on a sheet larger. On the other hand, as a jet diameter expands by increasing the distance from the nozzle, the cut width increases.

It is believed that abrasives contribute to the cutting ability by increasing the jet impact and serving as a tool to cut materials. In this sense, a better result will be expected if abrasives could be hard and tough in mechanical property and very sharp in shape. If abrasives could be supplied in a line, they would cut materials just like a rotating whetstone or a saw. The cutting ability (efficiency for material removing) is generally considered to improve with the increase of the abrasive amounts. However, in the abrasive jet process with no water, the jet impact on a material would decrease and the function for flowing out chips would also decrease due to the lack of water. This would mean that there should be an optimum value in the volume fraction, shape, size, kind and properties such as hardness of abrasives for each of the materials to be processed.

In the experiment, the cut width was generally wider at the top of material edge and narrower at the bottom. The reason is considered to be that the jet impact decreases as the jet goes down through and that the abrasives get globular to reduce its cutting ability. So the heterogeneity of the cut width can be improved when the jet pressure becomes higher and the abrasives are optimized.

Also in the experimental results it is seen that by setting the nozzle distance less than approximately 2.5 mm and by using abrasives, the tapering was greatly improved. In order to have a completely vertical cutting edge, however, one should introduce further finishing techniques such as shaving by an additional abrasive jet.

It was proved that fiber-reinforced materials were cut and such defects as roughening and burring could be resolved as well by using abrasives and making the nozzle distance short. These show the characteristics of this cutting method.

5. CONCLUSION

To investigate the possibilities of precision water jet cutting the experimental study was done: water pressure of 314 MPa, nozzle diameter of 0.8 mm, cutting rate of 0.83 mms^{-1}, nozzle distance of 0.5 ~ 60 mm, abrasives of Garnet #120, and abrasive amounts of 0 ~ 3.33 gs^{-1}. Metal sheets such as mild steel, austenitic stainless steel and extra super duralumin, polypropylene sheets and glass fiber reinforced polyphenylene-sulfide were mainly used.

The cutting phenomena were named being compared with those in other cutting methods and classified, for examples roughening, droop, cut width, tapering, burring and so on. The value of cut width increased with increasing abrasive amounts and nozzle distance. In no abrasive cutting, materials except plastics were not split away. Tapering became little as the nozzle distance decreased, and hence the cut width took almost same value as that of nozzle diameter under the nozzle distance less than 2.5 mm. Burring could be completely controlled by using the abrasive water jet with small nozzle distance, though a polypropylene sheet tends to pile up the chips at the bottoms because of its excessive plasticity. Surface roughening improved in no use of abrasives.

It is concluded that when a small nozzle distance and small abrasive amounts are took in, water jet can cut various material sheets with accuracy enough in practical usage.

6. ACKNOWLEDGMENTS

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Table 1 Mechanical Properties of Tested Materials.

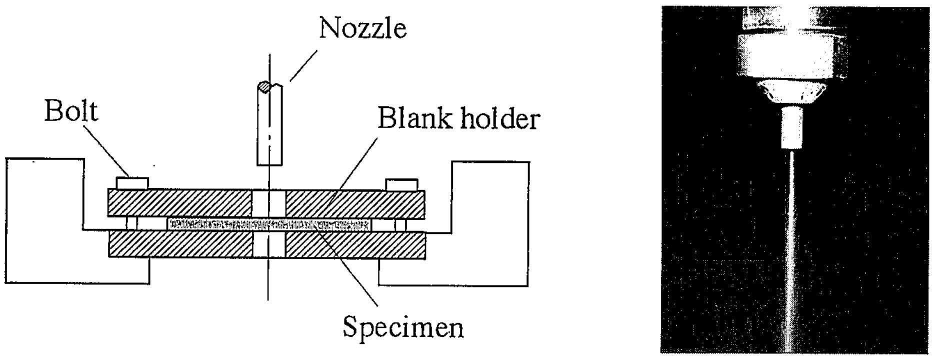
Materials	Yield stress σ_S /MPa	Tensile strength σ_B /MPa	Elongation δ / %	Hardness HR	Young's modulus E / GPa	Structure
Cold rolled steel (SPCC)	210	324	44	HRB46	206	BCC-Metal
18-8 stainless steel (SUS304)	294	578	55	HRC80	193	FCC-Metal
High-strength aluminum alloy (A7075)	107	225	15	HRB16	72	FCC-Metal
Polypropylene (PP)	–	34	600	HRR85	0.1	Polymer
Glass fiber reinforced polyphenylene-sulfide (GFRP)	–	156	1.9	–	12	Composite

Table 2 Experimental Conditions for Water Jet Cutting.

Water pressure	p / MPa	314
Diameter of abrasive nozzle	d / mm	0.8
Cutting rate	v / mm · s^{-1}	0.83
Nozzle distance	h / mm	0.5 ~ 60
Abrasive amounts	u / g · s^{-1}	0 ~ 3.33

Table 3 Composition of Garnet Abrasives Used for Water Jet Cutting.

Component	Content / vol%
SiO_2	40 ~ 41
Al_2O_3	20
MgO	12
Fe_2O_3	12
FeO	9 ~ 10
CaO	2 ~ 3
MnO	1



(a) Setting of specimen

(b) Appearance of jet
(p=147 MPa, u=1.67 $g \cdot s^{-1}$)

Fig. 1 Scheme of Experimental Apparatus for Water Jet Cutting.

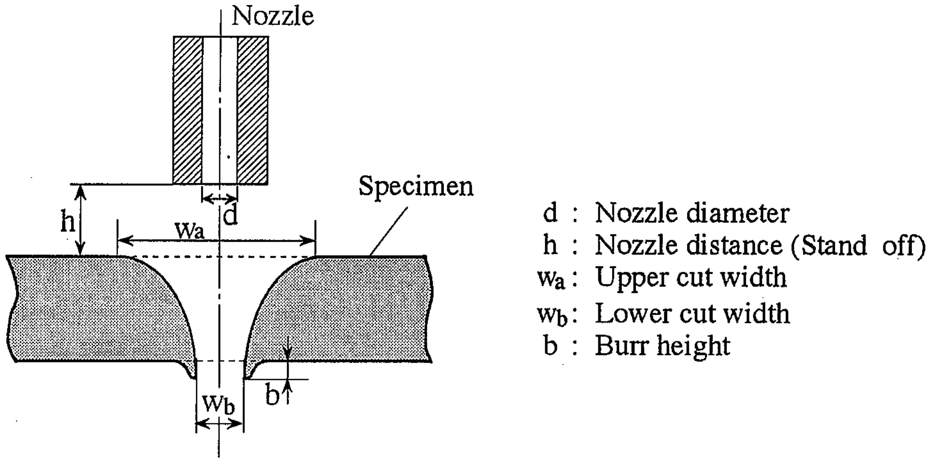


Fig. 2 Illustration of Measurements of Cut Edge by Water Jet .

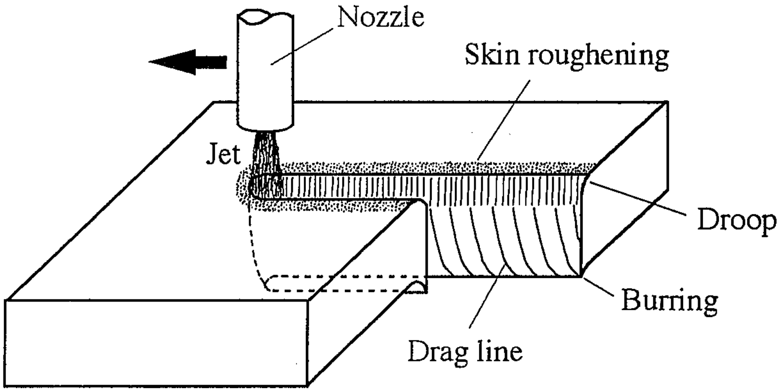
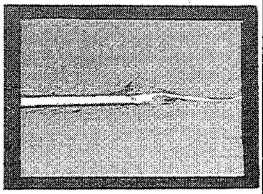
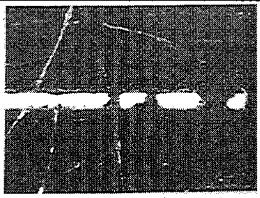
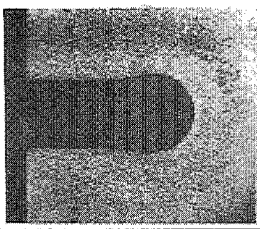
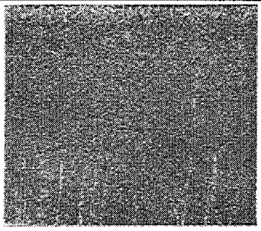
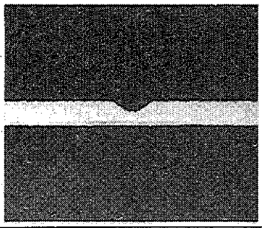
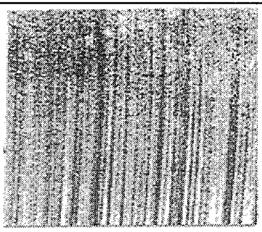
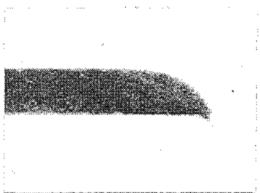
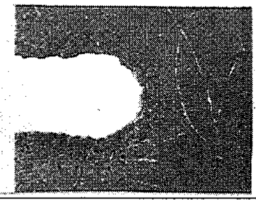
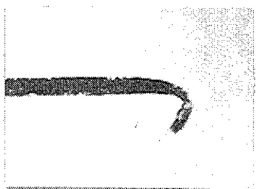
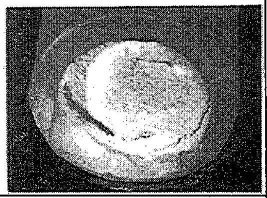
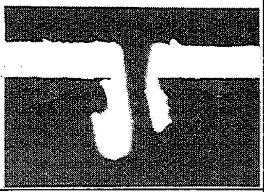
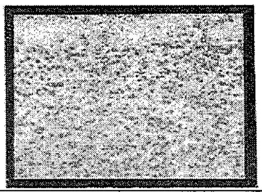
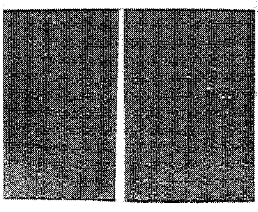
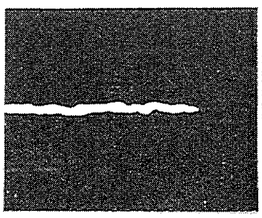


Fig.3 Characteristics of Cut Surfaces Produced by Water Jet Cutting.

Cutting conditions	Phenomenon (view)	Cutting conditions	Phenomenon (view)
(a) Crack (on surface) Glass t 10 p 314 h 5 v 0.83 u 0.33		(h) Exposure of fibers (on surface) GFRP (AG20) t 1.8 p 314 h 0.5 v 0.83 u 0	
(b) Skin roughening (on surface) Aluminum alloy (A7075) t 0.8 p 314 h 10 v 0.83 u 3.33		(i) Luster (on edge) Mild steel (SS41) t 26 p 314 h 2.2 v 0.25 u 3.07	
(c) Uncutting (on contour) Stainless steel (SUS304) t 0.8 p 314 h 60 v 0.83 u 0		(j) Drag lines (on edge) Mild steel (SS41) t 26 p 314 h 2.2 v 0.25 u 3.07	
(d) Droop (on contour) Steel (SPCC) t 0.8 p 314 h 60 v 0.83 u 1.67		(k) Pitting (on surface) GFRP (AG20) t 1.8 p 314 h 60 v 0.83 u 3.33	
(e) Curling (on contour) Steel (SPCC) t 0.8 p 314 h 100 v 0.75 u 4.17		(l) Groove (on contour) Steel(STKM13)/Clay d 27 t 3.5 p 314 h 2 v 0.53 u 3	
(f) Burring (on contour) Polypropylene t 3 p 314 h 3 v 0.83 u 0		(m) Rust (on edge) Carbon steel (S45C) t 10 p 314 h 1 v 0.53 u 3.33	
(g) Tapering (on contour) High alumina fire brick t 59 p 314 h 1 v 0.83 u 3.33		(n) Unstable cutting path and width (on bottom surface) Polymethylmethacrylate t 50 p 196 h 1 v 0.16 u 0.83	

t : thickness / mm p : water pressure / MPa h : nozzle distance / mm
v : cutting rate / $mm \cdot s^{-1}$ u : abrasive amounts / $g \cdot s^{-1}$

Fig.4 Typical Macroscopic Phenomena Produced by Water Jet Cutting.

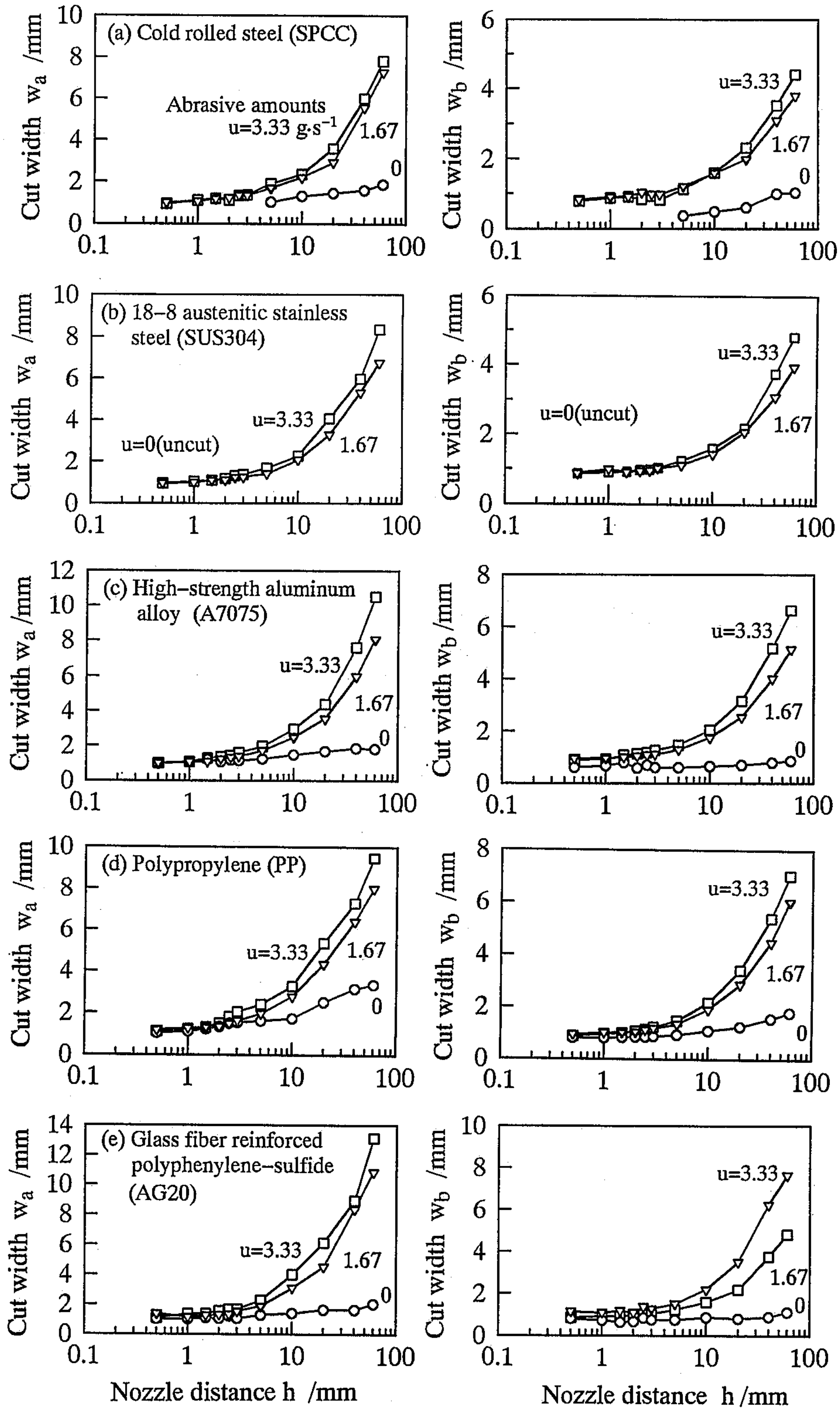


Fig.5 Increase of cut widths with increasing nozzle distance. (Cutting rate $v=0.83\ mm \cdot s^{-1}$)

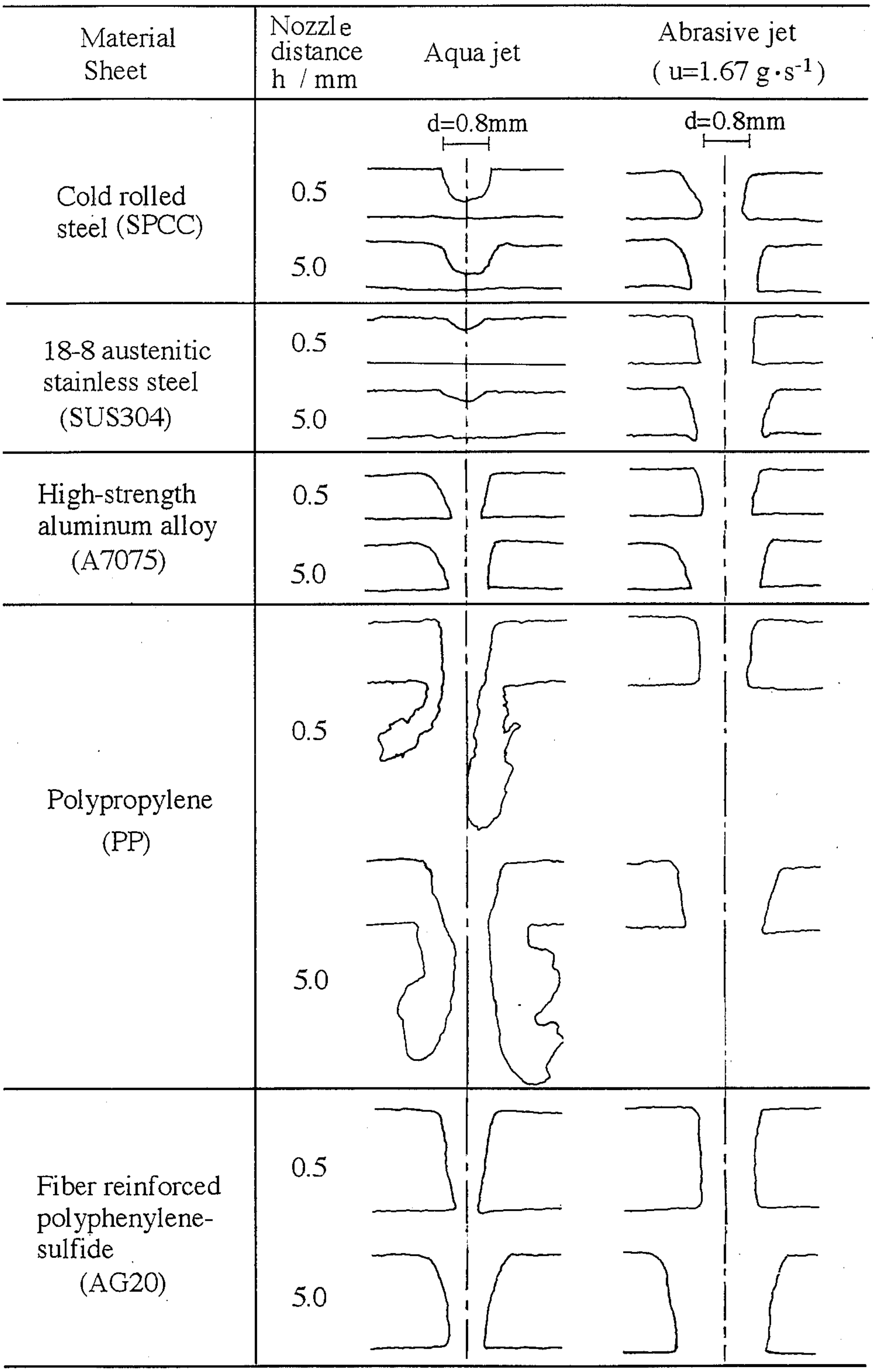


Fig.6 Examples of Contour by Water Jet Cutting of Various Materials. (Cutting rate $v=0.83mm \cdot s^{-1}$)

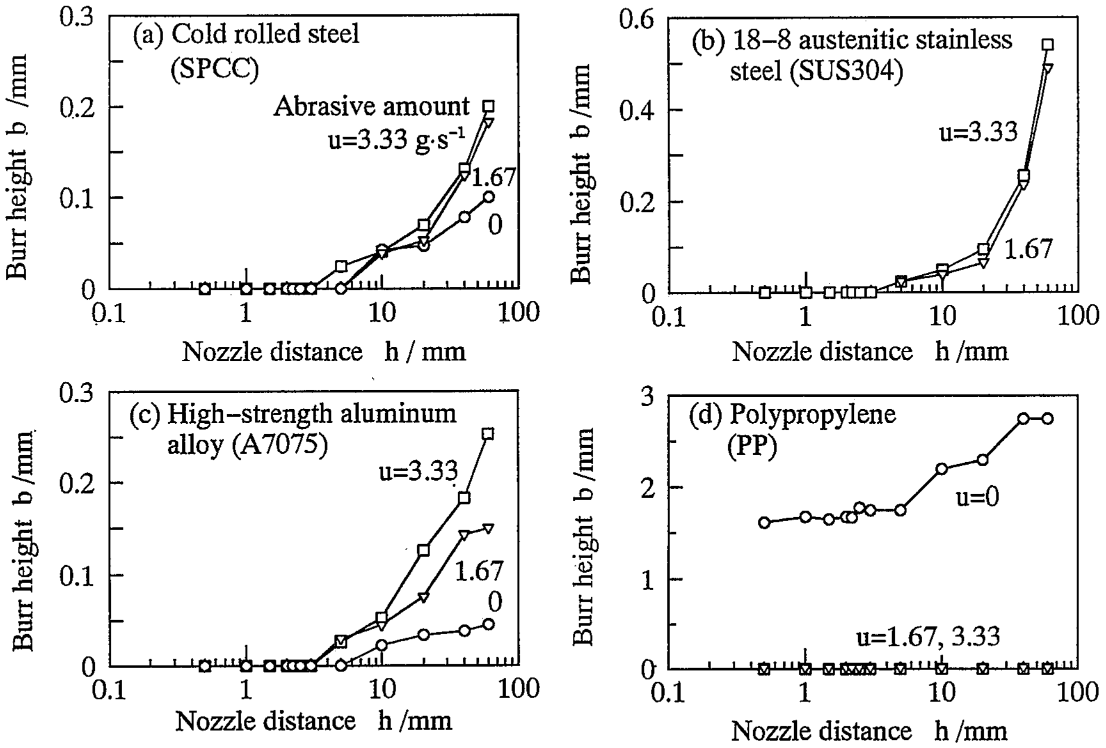


Fig.7 Relationships between Height of Burr and Nozzle Distance. (Cutting rate v=0.83mm·s^{-1})

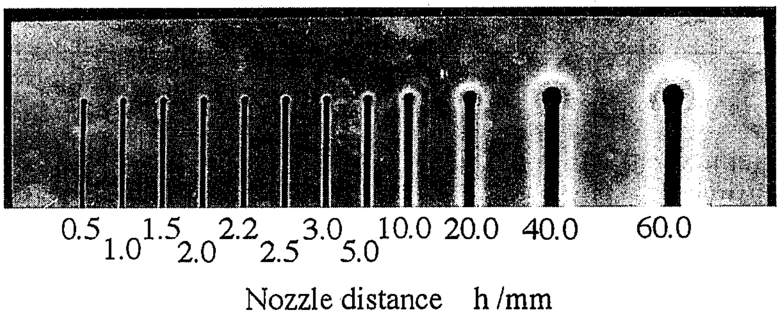


Fig.8 Appearance Change in Upper Surface of Stainless Steel Sheet by Abrasive Water Jet Cutting (u=1.67g·s^{-1}, v=0.83mm·s^{-1}) under Various Nozzle Distances.

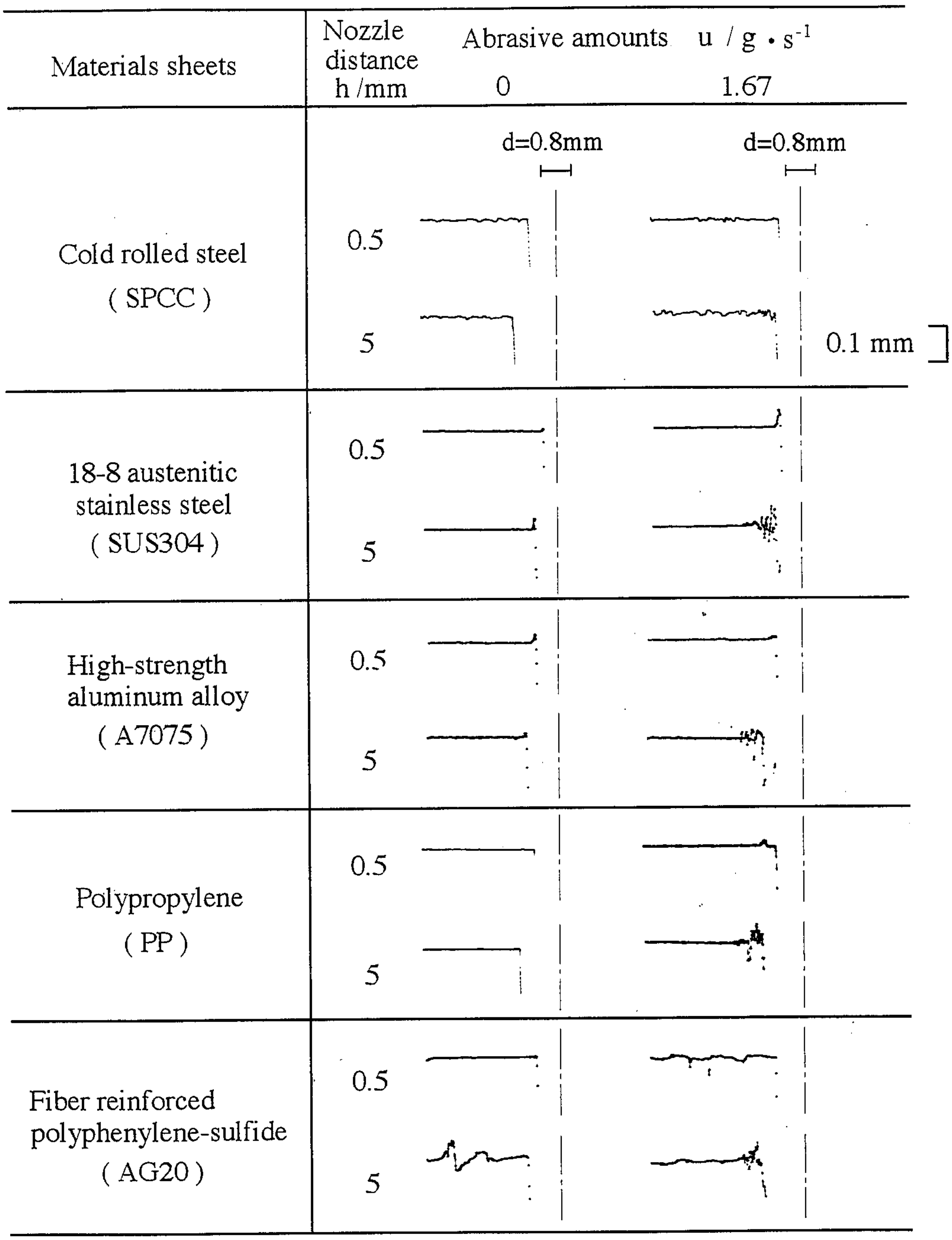


Fig.9 Surface Roughening of Various Material Sheets Produced by Water Jet Cutting. (Cutting rate $v = 0.83 mm \cdot s^{-1}$)

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Paper **25**

A GENERALIZED ABRASIVE WATER JET CUTTING MODEL

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ABSTRACT

A general equation for material cutting by abrasive water jet is developed based on similarities to the structure of the kinetics of chemical reactions. The equation considers the probabilistic character of abrasive water jet erosion by introducing an erosion probability, P_E, which is based on the abrasive particle energy distribution, $g(E_P)$, and the local activation energy distribution of the machined material, $\varphi(E_A)$. This model can be used to calculate cutting depth distributions, f(h). For the case $P_E=0.5$ the model is comparable to conventional non-probabilistic AWJ cutting models. Using the model, the influence of the abrasive flow rate, $\dot{m}_P$, on the machining process is investigated. For low abrasive flow rates and for a reaction power parameter n=1, the influence of all other process parameters on the erosion is linear and does not depend on changes in the abrasive flow rate. For higher abrasive flow rates and for all cases when n<1, these relations are more complex. The depth of cut is determined by the number of impacting abrasive particles and their amount of kinetic energy.

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1. INTRODUCTION

As a new manufacturing process, abrasive water jet (AWJ)-cutting has been very effective in machining difficult-to-machine materials. This cutting technique is one of the most recently introduced machining methods. On the basis of jet generation, abrasive water jets can generally be categorized as injection jets or suspension jets. For practical applications, injection jets are more commonly used. An injection jet is formed by accelerating small (diameters between 50 μm and 1000 μm) abrasive particles (garnet, aluminum oxide, silicon carbide) through contact with a high velocity (up to 800 m/s) small diameter (about 0.2 mm) plain water jet. The mixing between abrasive, water and air takes place in a mixing chamber, and the acceleration process occurs in an acceleration tube, or abrasive water-jet nozzle. The abrasives leave this nozzle at velocities of several hundred meters per second, which leads to the erosion of the processed materials. The process of erosion by abrasive water jets is a very complex event which is not well understood. Modeling of the erosion due to abrasive water jets is a primary requirement for the application of these tools in automated machining, such as estimating the depth of cut in cutting applications. Abrasive water jet cutting is a process which consists of an extremely large number of localized events. As Momber (1993) has calculated, the frequency of abrasive particle impacts can reach as high as 1 MHz. The basic event is the impact of a single abrasive grain which is characterized by its kinetic energy (particle diameter, particle velocity, particle material density) and its shape. One of the basic assumptions of existing analyses in the field of AWJ cutting is the equality of all single events. Measurements of abrasive particle sizes (Simpson 1990, Foldyna 1991) and of abrasive particle velocities (Chen and Geskin, 1991 and Neusen et al., 1992) show that this ideal supposition is unrealistic. The removal of material by abrasive water jets is characterized by the action of particles with different kinetic energies, different shapes and unknown locations. It is a probabilistic process. This assumption is supported by the random structure of the machining results. Zhou et al. (1992) estimated that the surface roughness of AWJ generated kerfs are distributed randomly by a Gaussian distribution. These authors also suggest a relation between energy balance at the point of particle impact and the surface topography statistics. Similar observations were made by Mohan et al. (1995) who measured roughness distributions in different workpiece thicknesses under different process conditions. Investigations from Öjmertz (1993) also show characteristical distributions for the parameters depth of cut, surface waviness, and surface roughness of abrasive waterjet processed materials. Momber (1994), who used an acoustic emission technique to investigate the AWJ cutting process, found that the detected signals follow a Normal distribution which depends on the depth of cut. To illustrate these problems, Fig. 1 shows the structure of cuts in aluminum samples machined by AWJ. It can be seen that the depth of cut randomly varies. The depth distribution of a glass sample cut by an AWJ is given in Fig. 2. It was found by Momber et al. (1995) that the depth of cut distribution is sensitive to the abrasive particle size distribution. These findings are not considered in the up to date modeling of the abrasive water jet erosion process.

Despite the difficulties discussed above, some attempts were carried out to model the process of abrasive water jet cutting as listed in Table 1. The first models in this field (Hashish 1984, 1989, and Tikhomirow et al., 1987) are based on results for dry solid particle erosion. They consider the cutting process as an accumulation of single abrasive impacts. But as an important limitation, Hashish's (1989) model can successful be applied only for materials showing a ductile behaviour. Tikhomirov's (1987) analysis is based on the assumption of fatigue failure of the materials which results in a limitation of his equation for a material group which is sensitive to fatigue. An additional problem of both models is the neglection of the influence of the pressurized water, which may contribute to the destruction process as suggested by Ramulu and Wong (1991). Another group of models is based on energy balances between the available abrasive jet energy and the amount of energy required for material removal (Oweinah, 1989; Blickwedel, 1990; Matsui et al., 1991; and Zeng and Kim, 1992) which may suggest that these models are able to describe the erosion process in a more general form. The most important limitation of the models of Oweinah (1989) and Blickwedel (1990) is the absence of any phenomenological description of the performance. They do not consider the different failure mechanisms for different groups of material, as brittle, quasi-brittle or ductile, and homogeneous or multiphase. The model of Zeng and Kim (1992) is developed for brittle granular materials, such as ceramics, and is not able to give information on the behaviour of most of the metallic materials. The contribution of Matsui et al. (1991) fails, as shown by these authors, for rock materials. In general, their basic assumption of a simplified stress-strain curve may be questionable. All these energy models are also only valid for certain conditions. A third group of abrasive waterjet cutting models contains regression models (Kovacevic et al., 1992 and Chung et al., 1992) which yields good results for a limited range of cutting conditions. But they are not applicable to describe a wide range of materials or cutting conditions. Whereas Kovacevic's (1992) regression function is valid only for concrete materials, Chung's (1992) model can be applied for ductile materials only.

But the most important restriction of all these models is the fact that they give only average values for the target parameters, such as depth of cut. For this reason they are not applicable for advanced machining processes, such as shape milling and 3-D operations, where a shaped cavity with a uniform depth profile must be generated. Here, a model is required which is able to describe the spatial deviations in the depth of cut. Also, because all the models discussed above characterize a certain range of cutting conditions and materials, it may be an ingenious idea to unify these models. This could lead to a generalized model which (a) contains all other models as special cases and (b) considers a wide field of machining applications. Such a generalized model may be an important contribution to the understanding of the material removal process by abrasive water jets.

Based on this introduction, the objectives of this paper are:

- to check and to discuss the validity of applying reaction kinetics to the case of abrasive water jet cutting,
  and
- to develop a probabilistic model for the estimation of the depth of cut in abrasive water jet cutting.

2. REACTION KINETICS APPLICATION TO ABRASIVE WATER JET CUTTING

An early work applying chemical reaction kinetics to problems of material processing was done by Patat and Langemann (1959). They described the behaviour of comminution mills by using the basic equation of reaction kinetics in a modified form. Later, Humphrey (1980) used the transition state theory of chemical reactions for the characterization of erosion wear of ductile materials. In his study, he considered only the case of first order of reactions and did not modify the reaction velocity.

To illustrate this idea, the basic equation for chemical reaction kinetics may be given (Laidler 1950)

$$\frac{dC_1}{dt} = k \cdot C_2^n . \tag{1}$$

Here, C_1 is the concentration of the product per unit surface, C_2 is the concentration of the reactant per unit surface, K is the reaction velocity and n is the order of reaction. The general process of material removal during abrasive water jets is the generation of a certain number of wear particles in a given time period. This number is assumed as the concentration of the product. For a given time period, this number is proportional to the removed material mass m_M. The removed material mass is given by the product of material density and depth, width and length of the cut. If the width and length of the cut created during the cutting process are assumed to be independent of the depth of cut, the depth for a given material can be expressed by

$$\frac{dC_1}{dt} = \frac{dm_M}{dt} \propto h. \tag{2}$$

The depth of cut increases as the number of material particles removed in the time period increases. During the cutting process the target material is subjected to a number of impinging abrasive particles N_P. This number may be considered to be the concentration of the reactant. For a given period of time this number depends on the abrasive flow rate $\dot{m}_P$ only. The higher the abrasive flow rate the larger the concentration of the abrasive particles. Thus,

$$C_2 \propto \dot{m}_P . \tag{3}$$

With Eqs. (2) and (3), Eq. (1) can be rewritten as

$$h = k \cdot \dot{m}_P^n . \tag{4}$$

Here, h is the depth of cut, k is the reaction velocity for abrasive water jet cutting, $\dot{m}_p$ is the abrasive flow rate, and n is the order of reaction for the abrasive water jet cutting process. It can be seen that the models presented in Table 1 can be generalized by Eq. (4). This result suggests the possibility of discussing the abrasive water jet cutting process using the structure of chemical reaction kinetics. It will be the objective of the following paragraphs to discuss the similarities between the abrasive water jet cutting process and the structure of the kinetics of chemical reactions, and to discuss the parameters k and n for the case of abrasive water jet cutting.

According to the transition state theory of chemical reactions one can define a probability, P_E, for which the reaction (cutting process) starts to occur. This parameter depends on the activation energy, E_A. In molecular reaction kinetics this probability can be described by Arrhenius' law (Atkins 1985)

$$k = A \cdot e^{\frac{-E}{R \cdot T}}. \tag{5}$$

The part of this law which is related to the present problem is given by

$$e^{\frac{-E}{R \cdot T}} = P_E. \tag{6}$$

Here, the value E describes the activation energy, E_A, as an energy barrier which must be overcome by the molecules of the reactive agents. The energy potential of these molecules is given by the product R·T, where R is the so called Gas-constant and T is the temperature. The higher the product R·T, the higher the probability P_E that a reaction product is generated. The rate (or velocity) of product formation depends on the value A in Eq. (5). In chemical reactions this parameter is often called the frequency factor which characterizes the number of impacts between molecules. In the present study this constant should take into account the number of abrasive particles which are involved in the erosion process.

3. DISCUSSION OF THE ORDER OF REACTIONS FOR ABRASIVE WATER JET CUTTING

Figure 3 shows typical relations between depth of cut and abrasive flow rate for abrasive waterjet cutting. It is seen that the order of reactions n is a function of the abrasive concentration according to

$$n = f(\dot{m}_P). \tag{7}$$

In general, four different stages of "reaction" can be distinguished in Fig. 3. With a low abrasive particle concentration the progress is linear and an order of reactions of $n=1$ exists. This stage is followed by a transition stage with an order of reactions of $0<n<1$. Here, the progress starts to drop. After this, a range of maximum depth of cut can be found with $n=0$. In the area of large abrasive particle concentrations the material removal starts to drop. This stage is characterized by negative orders of reactions, n<0. Thus the following cases can be described:

$$n=1 \quad h=k\cdot \dot{m}_P\,, \quad \frac{dh}{d\dot{m}_P}=k=\text{const.} \tag{8a}$$

$$0<n<1 \quad h=k\cdot \dot{m}_P^n, \quad \frac{dh}{d\dot{m}_P}>0=f(\dot{m}_P) \tag{8b}$$

$$n=0 \quad h=k, \quad \frac{dh}{d\dot{m}_P}=0 \tag{8c}$$

$$n<0 \quad h=k\cdot \dot{m}_P^n, \quad \frac{dh}{d\dot{m}_P}<0=f(\dot{m}_P) \tag{8d}$$

Eq. (8a) describes the linear relation between both parameters. This case is represented by the models of Oweinah (1989), Blickwedel (1990), Tikhomirov et al. (1987), and Hashish's (1989) model for the deformation wear [see Table 1]. If the reaction velocity k is constant, every increase in the abrasive particle concentration leads to a proportional increase in the material removal. This assumption is supported by results from Geskin et al. (1989) who found that the depth of cut is proportional to the number of abrasive particles at comparatively low abrasive flow rates. In this range the progress of the erosion process k, which contains the influence of other process parameters, is independent of the abrasive flow rate.

The decrease in progress at higher abrasive flow rates, which is described by Eq. (8b), characterizes the fact that not every 'new' abrasive particle contributes to the process. Here geometrical aspects like particle collision and damping start to act. Also, the restricted input energy of the plain water jet is distributed over a higher number of abrasive grains which must be accelerated. This leads to a reduction of the individual grain energies. It can be seen that the parameter k drops as abrasive flow rate increases. This case is represented by the models of Hashish (1989), Kovacevic et al. (1992), Chung et al. (1992), and Zeng and Kim (1993) [see Table 1].

In the stage of Eq. (8c) critical conditions exist. The maximum depth of cut is reached. In this range changes in the abrasive concentration do not influence the machining performance. A further improvement is possible only by raising the reaction velocity k. This case is represented, under some limitations, by the model of Matsui et al. (1991) [see Table 1]. The same relations are valid for the case $\dot{m}_P$=constant.

The last stage, especially the case n< <0, describes the blocking of the abrasive mixing head and of the kerf bottom by too many abrasive particles. This case was not found in any of the selected models.

The authors assume here that most of the cutting and machining applications of abrasive water jets occur in the range of n=1, since this is the most effective range from the point of view of abrasive consumption. Under this assumption Eq. (4) is reduced to Eq. (8a).

Under these conditions it is possible to estimate the parameter k by measuring and calculating, respectively, the progress of Eq. (8a).

4. DISCUSSION OF THE REACTION PROBABILITY FOR ABRASIVE WATER JET CUTTING

As shown in Eqs. (4) and (5) the reaction velocity, k, can be described by an equation of the form

$$k = A \cdot P_E, \tag{9}$$

where A is the collision number and P_E is the reaction probability. The reaction probability, P_E, depends on the energy distribution of the reactive agent, in this case, the abrasive particles.

It must be noted, that Eqs. (5) and (6) are valid in these special forms only for particles whose energies are distributed over a Maxwell-Boltzmann distribution (Lorenz, 1904). This is the case for gas molecules, but also for some technical processes. Mempel (1965), for example, has used this distribution of the balls energy in fragmentation mills. It can be shown that the basic assumption for the derivation of the Maxwell-Boltzmann distribution (the same probability of particle movement in all directions) is invalid for the movement of abrasive particles in a water jet. Consequently, as abrasive particle velocity measurements by Chen and Geskin (1991) and Neusen et al. (1992) have shown, the Maxwell-Bolzmann distribution seems to be invalid for the energy of abrasive grains accelerated by water jet. The results of these authors suggest that a Gaussian distribution should be applied to describe this parameter (see Fig. 4). The kinetic energy of an abrasive particle can be calculated using Eq. (10).

$$E_P = \tfrac{\pi}{12} \cdot d_P^3 \cdot \rho_P \cdot w_P^2 \tag{10}$$

The range of the individual abrasive particle energies in an abrasive water jet may be limited by:

$$E_P^{\min} \le E_P \le E_P^{\max} \tag{10a}$$

Fig. 5 shows the energy range of an abrasive water jet. The kinetic energies of the individual particles range from $E_P^{\min}$=7.5·10^{-4} mJ to $E_P^{\max}$=6.3 mJ. This wide range of energies is the result of the complex mixing and acceleration of the particles in the abrasive cutting head, where they come into contact with the high velocity plain water jet. Assuming a simple momentum transfer between abrasive grain and water jet in the mixing unit, the abrasive particle velocity can be estimated by Eq. (11)

$$w_P = \xi \cdot \frac{1}{1+R_M} \cdot \sqrt{\frac{2 \cdot p}{\rho_w}}. \tag{11}$$

The parameter ξ which describes the mixing efficiency has to be assumed as a local parameter which depends not only on the local flow situation, but also on the hydrodynamical properties of a single abrasive grain, such as drag coefficient. This fact may explain the differences in the particle velocities for a given pump pressure and a given mixing geometry.

Below this velocity, the particles' energies depend on their diameters, as shown in Eq. (10). If the abrasive particle stream hits the material surface, it is characterized by a grain size distribution. The reason for this is the intense comminution of the particles while they pass through the mixing head and the acceleration tube. This was shown by several authors (Simpson 1990, Foldyna 1991). According to Simpson (1990), about 80% of all abrasive particles undergo fragmentation during the mixing process. In Fig. 5, only four different abrasive particle diameters are given.

Both effects - the different local mixing and acceleration conditions, and the abrasive grain fragmentation - may explain the wide range of the abrasive particles kinetic energies.

By assuming a limited diameter range for the impacting abrasive grains, and a constant density for a given abrasive material, a modified energy distribution $g(E_P)$ is assumed where $\overline{E}_P$ is the average particle energy

$$g(E_P)=\frac{1}{\sqrt{2\cdot\pi}\cdot\sigma}\cdot e^{\frac{-(E_P-\overline{E}_P)^2}{2\cdot\sigma^2}} . \qquad (12)$$

In Eq. (12), E_P plays the same role as the product R·T in Eqs. (5) and (6), and describes the energy potential of the impacting particles. For the energy barrier E in Eqs. (5) and (6) a critical energy value of the target material must be defined. A minimum threshold energy is assumed to simplify the problem. This threshold energy, E_A, shall be a material value which must be overcome by the abrasive particle energy, E_p, to start the cutting process. The idea of a critical threshold parameter is also contained in some abrasive water jet cutting models. Blickwedel (1990) and Chung et al. (1992), for example, use a critical pump pressure p_C to describe this assumption (see Table 1). In the present paper, the author defines a minimum area of new generated surfaces, S_n, during the erosion process as a threshold condition. To satisfy the general material removal model in paragraph 2, this area may be identical to the surface of a certain number of removed material particles. The energy which is absorbed by the material during the generation of a new surface is assumed as

$$E_{AB}=E_A=(\gamma_S+E_T)\cdot 2\cdot S_n . \qquad (13)$$

Assuming that E_T is related to the surface energy by $E_T=\chi\cdot\gamma_S$, Eq. (13) yields

$$E_A=\gamma_S\cdot 2\cdot S_n\cdot(1+\chi),$$
$$E_A\propto\gamma_S . \qquad (13a)$$

As Fig. 4 shows, the reaction probability, P_E - in other words the probability that the activation energy, E_A, will be exceeded by the energy potential of an abrasive grain, E_P - can be interpreted as the area which is enclosed by $g(E_P)$ and E_A. This area is given by Eq. (14) which replaces Eq. (6) for the case of abrasive water jet cutting

$$P_E = \frac{1}{\sqrt{2 \cdot \pi} \cdot \sigma} \cdot \int_{E_A}^{E_P} e^{\frac{-(E_P - \bar{E}_P)^2}{2 \cdot \sigma^2}} dE_P . \tag{14}$$

Since Eq. (14) cannot be directly evaluated by integration, the transformation $\kappa = \frac{E_P - \bar{E}_P}{\sigma}$ is introduced, so that

$$P_E = \frac{1}{\sqrt{2 \cdot \pi} \cdot \sigma} \cdot \int_{\frac{E_A - \bar{E}_P}{\sigma}}^{E_P} e^{-0.5 \cdot \kappa^2} d\kappa . \tag{15}$$

This relation is called the Standard Normal Distribution and is widely tabulated (Shooman 1968).

In the case $P_E = P_E^{\max}$, the maximum possible depth of cut will be reached. In the case $P_E = P_E^{\min}$, the minimum depth of cut will be obtained. It has to be distinguished between the three conditions (a) $E_P^{\min} > E_A$, (b) $E_P^{\min} > E_A > E_P^{\max}$, and (c) $E_P^{\max} < E_A$. For the condition (a), every impacting abrasive particle contributes to the erosion process. The result $P_E=0$ is invalid under these conditions. In the case (b), the solution P_E may be possible for some values of E_P. In the case (c), no cutting will occur and the general solution will be $P_E=0$.

5. DISCUSSION OF THE COLLISION NUMBER FOR ABRASIVE WATER JET CUTTING

It is important to note that Eqs. (14) and (15) give only the relative depth of cut or the depth distribution, respectively, for a given abrasive particle energy distribution. They do not allow the calculation of the absolute depth of cut. The estimation of the absolute depth of cut is obtained by combining the erosion probability with the collision number according to Eq. (9). The collision number may describe: (a) the number of impacting particles, N_P, and (b) the absolute energy levels of the impacting particles, ψ. These relations are given in Eq. (16)

$$A = K_2 \cdot t = \psi \cdot N_P . \tag{16}$$

For the discussion of the number of impacting particles it is assumed that every single abrasive particle is able to collide with the surface of the eroded material. For a given abrasive flow rate, a given abrasive grain shape, and a given abrasive grain size distribution, the number of colliding particles, N_P, depends on the duration of the cutting process, t. Thus, $N_P \propto t$. The duration of the cutting process is given by

$$t = \frac{1}{v} \cdot \int dx \,, \tag{17}$$

which after integration from x=0 to x=d_f gives $t = \frac{d_f}{v}$. Here, d_f and v are the diameter and the traverse rate of the abrasive water jet focus, respectively. The number of impacting particles is therefore

$$N_P \propto t = const \cdot \frac{d_f}{v}. \tag{18}$$

A comparison with Table 1 shows that the relation $h \propto v^{-1}$ is in general agreement with the abrasive water jet models having an order of reaction n=1.

The absolute kinetic energy of the abrasive particles is described by the location of the function $g(E_P)$ on the energy axis, as shown in Fig. 5. An increase in E_P leads to a shift in the right direction. As a simplification it is assumed that this movement does not influence the abrasive particle energy distribution but the average abrasive particle energy, $\overline{E}_P$.
As several experimental investigations have shown (Blickwedel 1990, Kovacevic 1992, Momber 1993, Oweinah 1989), the function ψ in Eq. (16) can be expressed by a function $\psi(p)$, where p is the applied pump pressure of the abrasive water jet generation unit. In general, $\psi(p)$ can be written

$$\psi(p) = p^{\phi}. \tag{19}$$

As shown in Table 1, the power exponent lies between $0.79 \le \phi \le 1.25$. For practical applications in pressure ranges between p=100 MPa and p=250 MPa, it can be assumed that $\phi=1$ (Momber 1993). Combining Eqs. (16), (18), and (19), the collision number is

$$A = \frac{p^{\phi} \cdot d_f}{v}. \tag{20}$$

6. SUMMARY AND CONCLUSIONS

- Some analogies between abrasive water jet cutting and the structure of the kinetics of chemical reactions are used to model the abrasive water jet cutting process.

- The general equation for the depth of cut achieved by abrasive water jets derived from the structure of reaction kinetics is given by the equation

  $$h = A \cdot P_E \cdot \dot{m}_P^n = p^{\phi} \cdot \frac{d_f}{v} \cdot \int_{E_A}^{E_P} g(E_P) dE_P \cdot \dot{m}_P^n$$

- The presented equation considers the probabilistic process of abrasive water jet cutting by introducing an erosion probability, P_E, which is based on abrasive particle energy distribution, $g(E_P)$, and local energy distribution of the eroded material, $\varphi(E_A)$. The probability parameter, P_E, describes the relative depth of cut and can be applied to calculate the depth of cut distribution, f(h). For the case of $P_E=0.5$ the model is comparable to conventional AWJ cutting models.

- The model considers the influence of the abrasive flow rate, $\dot{m}_P$, on the machining process as a complex problem and clearly shows that the dynamics of influence of this parameter on the AWJ cutting process depends on the selected abrasive flow range. The influence of four main ranges of the abrasive flow rate, which can be evaluated using a reaction power parameter, n, are found and discussed. For the small abrasive flow rates and when $n=1$, the influence of all other process parameters on the machining process is linear and does not depend on changes in the abrasive flow rate. For larger abrasive flow rates and the cases when $n<1$, these relations are more complex.

- The depth of cut generated during abrasive water jet cutting is determined by a certain number of impacting abrasive particles with a certain amount of kinetic energy.

7. ACKNOWLEDGEMENTS

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9. NOMENCLATURE

A	reaction velocity
b_k	width of cut
C	constant
d_f	abrasive focus diameter
d_W	water orifice diameter
E	activation energy for chemical reaction
E_P	average abrasive particle energy
E_A	activation energy for abrasive water jet
E_{AB}	absorbed jet energy
E_m	Young's modulus
E_P	abrasive particle energy
E_T	energy absorbed by plastification
H	hardness
h	depth of cut
$\dot{m}_P$	abrasive flow rate
$\dot{m}_W$	water flow rate
n	order of reactions
N_m	machinibility number
p	pump pressure
p_C	threshold pump pressure
P_E	erosion probability
R	gas constant
R_W	mixing ratio
s	stand-off distance
S_n	new surface
T	temperature
v	traverse rate
w_P	abrasive particle velocity
β	tensile strength
ε	specific energy
γ_S	specific surface energy
χ	ratio between specific surface energy and plastification energy
η	regression parameter
ρ_P	abrasive material density
σ	abrasive particle energy standard deviation
σ_V	abrasive water jet velocity deviation

Table 1. Models for the Depth of Cut in Abrasive Water Jet Cutting ($h = k \cdot \dot{m}_P^n$).

Author	Basic Equation	n-value
Matsui et al. (1991)	$\frac{10^{4.74}}{v \cdot (H \cdot \varepsilon_S)^{0.67}}$	0
Kovacevic et al. (1992)	$\frac{C \cdot p^{0.79} \cdot s^{0.0068} \cdot \dot{m}_P^{0.1844}}{v^{0.5671}}$	0.1844
Zeng and Kim (1993)	$\frac{N_m \cdot p^{1.25} \cdot \dot{m}_W \cdot \dot{m}_P^{0.343}}{C \cdot d_f^{0.618} \cdot v^{0.866}}$	0.343
Hashish (1989)*	$\frac{C \cdot d_W \cdot w_P}{2.5 \cdot w_C} \cdot \left(\frac{14 \cdot \dot{m}_P}{\pi \cdot v \cdot d_W^2 \cdot \rho_P} \right)^{0.4}$	0.4
Chung et al. (1992)	$\frac{(p - p_C) \cdot \dot{m}_P^{0.6}}{v \cdot b_K}$	0.6
Blickwedel (1990)	$\frac{C \cdot (p - p_C)}{v^{0.86 + \frac{2.09}{v}}}$	1
Oweinah (1989)	$\frac{w_P^2 \cdot \eta \cdot \dot{m}_P}{2 \cdot v \cdot b_k \cdot \varepsilon}$	1
Hashish (1989)**	$\frac{2 \cdot (w_P - w_C)^2 \cdot \dot{m}_P}{\pi \cdot d_W \cdot v \cdot \sigma_f}$	1
Tikhomirov *et al.* (1987)	$CONST \cdot \sqrt{\pi \cdot \rho_P^C} \cdot d_{cont}^2 \cdot (w_P \cdot \sin\alpha)^3 \cdot \frac{\dot{m}_P}{M}$	1

* "cutting" wear

** "deformation" wear, neglecting wall friction

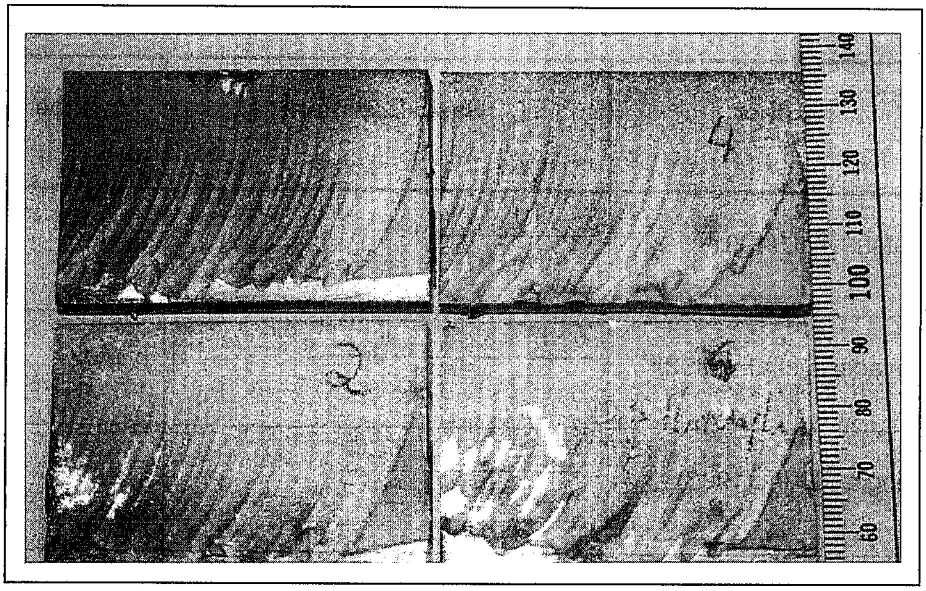

Figure 1. Depth of Cut Structure in Aluminum Samples Cut by Abrasive Water Jet.

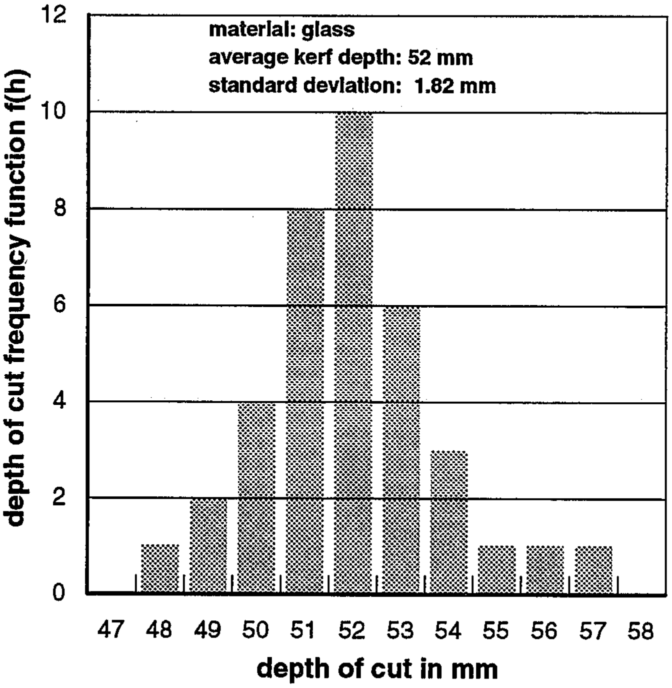

Figure 2. Depth of Cut Distribution in a Glass Sample Cut by Abrasive Water Jet.

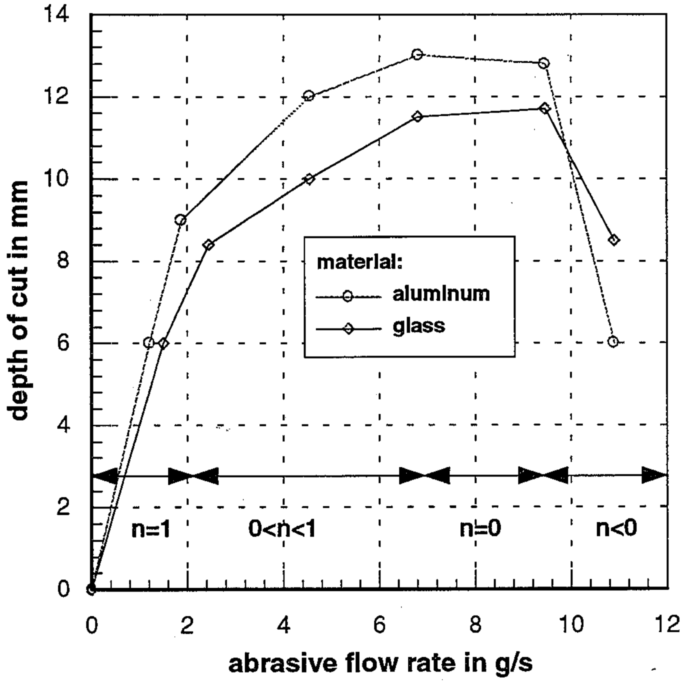

Figure 3. Relation Between Abrasive Flow Rate and Depth of Cut in Glass and Aluminum.

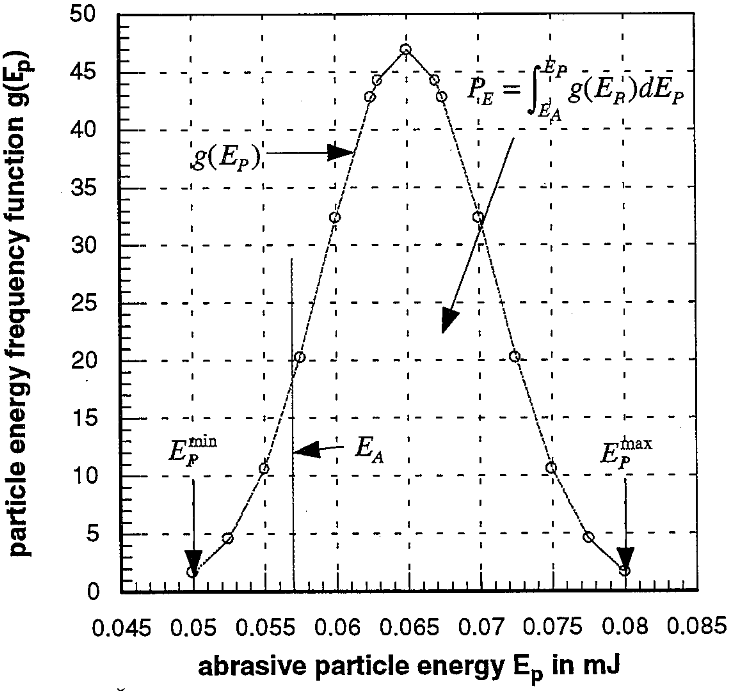

Figure 4. Energy Distribution of Abrasive Particles in an Abrasive Water Jet [Based on Measurements from Chen and Geskin (1991)].

d_P=0.1 mm, w_P=250 m/s, σ_V=41.4 m/s

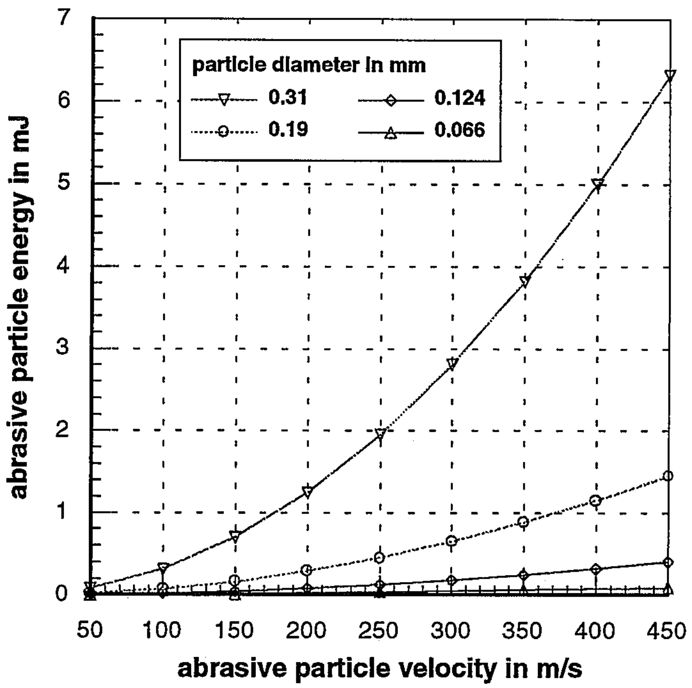

Figure 5. Range of Single Abrasive Particle Energies in an Abrasive Water Jet [Based on Measurements from Chen and Geskin (1991)].

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Paper 26

DEVELOPMENT OF AN AWJ DEEP HOLE DRILLING SYSTEM FOR METALS

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ABSTRACT

A study was conducted to determine the overall feasibility and to validate drill head concepts for drilling deep holes (2.5 m [8 ft] long with about 19-mm [0.75-in.] diameters) in refractory metals using novel abrasive-waterjet (AWJ) approaches. Only relatively short holes (a few centimeters deep) were drilled to demonstrate the drill head geometry with the understanding that the drill head concept can be adapted for long holes (over 2.5 m). Two basic drill head concepts were found feasible. In the first, a rectangular-shaped AWJ with a radial power gradient was used. By rotating the workpiece, the drill only needs to be axially advanced into the hole. In the second concept, a rotary drill was used with a rotation axis radially offset relative to the workpiece axis of rotation. A modified concept using an oscillating jet rather than a rotating jet was also demonstrated to be feasible, but proved to be more complex than the simple nonrotary head method. It was demonstrated that high-quality holes (straight and smooth) can be drilled with either tool.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

Many materials have been cut with AWJs, including hard steels, titanium, aluminum, cast iron, high-strength composites, armor-layered glass, ceramics, rocks, and steel-reinforced concrete. AWJs have also been investigated for some machining operations such as milling, turning, and drilling. This work, however, is to determine the feasibility of using abrasive-waterjets for the deep drilling (several meters) of tungsten, tungsten-molybdenum, and other chemically inert refractory metals. The specific objectives were to ascertain the most promising AWJ-based deep drilling concept(s), determine the effect of AWJ parameters on the drilling rates, and address the economics of AWJ deep hole drilling.

2. ALTERNATIVE TECHNIQUES

Other nonconventional machining methods that have been considered for the deep hole drilling application are discussed here. Electrical discharge machining (EDM) is one alternative to conventional machining, especially for fragile tungsten parts or when difficulties are encountered in conventional machining. A practical material removal rate for EDM ranges from 20 to 2000 mm^3/hr (Yih and Wang, 1979). This relatively low volume removal rate translates into an exorbitant machining cost for the required tubes and piping. For example, a 0.5-m (1-ft) long, 19-mm-diameter hole in tungsten will require over 60 hours of EDM machining time. Another disadvantage of EDM lies in the thermal effects of the process, which can lead to microcracks in the fully dense tungsten.

Electrochemical machining (ECM) has also been used in the past for hard-to-machine materials. However, ECM is inherently an extremely slow process with poor dimensional stability. In addition, the hazardous wastes generated in the process are undesirable, especially in light of today's strict environmental laws.

Another machining method that seems to have potential for refractory metals is laser machining (Frye and Polk, 1986). The geometry of the hole that can be drilled by lasers, however, is limited by several factors. If the power density is too high to drill a deep hole, the plume of vapor above the work surface absorbs and scatters the laser radiation, causing the process to go out of control. If the power density is reduced to counter this effect, an undue portion of the energy is conducted from the drilling zone, leading to a large heat-affected zone and poor energy efficiency.

3. TEST SETUP AND RESULTS

Figure 1 shows the different deep hole drilling head concepts. A three-axis gantry robot was used to axially traverse the drilling head onto the rotating workpiece. The rotation of the workpiece was provided by a DC servo motor controlled by a computer for accurate control of rotational speed. An intensifier-type, high-pressure pump supplied the drill head with high-pressure water. A small hopper was mounted on the manipulator arm to furnish the drilling head with abrasives, which were metered accurately using a simple orifice plate. The drilling process was conducted inside a shroud tank, and all the influents were pumped out of the tank using a commercial sludge pump. With this setup, the drilling operations were conducted accurately in a very well-controlled environment. The specific drill head geometries and associated results are described below.

3.1 Drilling with Oscillating Jets

Drilling tests were conducted in stainless steel 15-5 to study the pattern of the oscillating jet coverage over the workpiece. Figure 2 shows cross-sectional sketches of example holes drilled with the oscillating jet concept. Figure 3 shows pictures of different holes drilled in these tests.

A computer program was written to model the kinematics of the jet coverage process and to predict the cross-sectional hole geometry. This prediction was based on a simplified analysis (Hashish, 1984) and is only aimed at guiding the experiments.

Figure 4a shows a computer printout of a jet path over the workpiece. Observe that, with the speed combination shown, no hole can be drilled; rather, the jet will engrave a "flower" shape into the workpiece. Reversing the rotational speeds gives the pattern shown in Figure 4b, which again is not suitable for hole drilling. Altering the rotational speed by only 5% will result in the coverage shown in Figure 4c, which can be used to drill a hole. Fast coverage over the entire drilling face is important to prevent the creation of high peaks and valleys that will deflect the jet and introduce other effects.

The most important conclusion from the kinematic modeling is that the ratio of nozzle frequency to part rotational speed should not be an integer value. In fact, an imprecise rotation speed will be beneficial for achieving even coverage.

3.2 Drilling with a Fan AWJ

An AWJ nozzle was modified to incorporate a mixing tube with a rectangular opening. The rectangular hole of the nozzle was manufactured by grinding a 10-mm (0.40-in.) wide and 1.5-mm (0.06-in.) deep groove in a tungsten carbide strip and then brazing another strip on it. This method allowed a quick and relatively inexpensive way to evaluate this concept. Multiple parallel waterjets were used to accelerate the abrasives in the rectangular mixing tube. The waterjet orifices were not of the same size. The larger-diameter jet was mounted on the outside. This provided a power gradient compatible with the kinematic needs of drilling. Optimization of power distribution by selecting orifice sizes was done on a limited scale. Figure 5 shows pictures of the rectangular AWJ at 379 MPa (55 ksi).

Tests were conducted using the nozzle in Figure 5. The rotation of the workpiece under the axially fed rectangular jet produced holes of varied sizes depending on the location of the jet relative to the centerline of rotation. Figure 6 shows selected cross-sectional sketches of different hole geometries along with the parameters used for the drilling tests. Tungsten was drilled at the rate of 116 mm/hr (4.56 in./hr) using two 0.254-mm (0.01-in.) diameter waterjets, which are equivalent in power to the single 0.33-mm (0.013-in.) diameter jet used in the previous oscillatory test. Observe that the drilling rate for tungsten dropped from 159 mm/hr (6.27 in./hr) to 116 mm/hr. This reduction is expected because the jet is spread over a larger area in a rectangular mixing tube. However, the reduction in drilling rate was not proportional to the reduction in energy density. This is encouraging because, with optimized power distribution and with the use of more jets, higher drilling rates can be achieved. Obviously, this drill head concept is advantageous because no drill rotation is needed.

It is concluded here that the fan AWJ drill concept is technically feasible for tungsten drilling. It is also a feasible concept for practical implementation with reduced motion requirements. Optimization of power distribution is important for high volume removal rates.

3.3 Drilling with a Rotary AWJ

Instead of oscillating the AWJ over the rotating workpiece, as discussed above, a rotary, radially offset AWJ was found to be easier to implement. Figure 1 shows the concept of operation of this nozzle.

A computer program was written to animate the jet coverage over the workpiece. Figure 7 shows two examples of computer output after different intervals of exposure. Full coverage of the drilling face can be achieved at many different combinations of AWJ and workpiece rotational speeds. However, similar to oscillating nozzles, the variation of speeds within say 5% will enhance the coverage process. This alleviated the need for very precise control over the rotational speed.

Extensive parametric testing was conducted using this drilling concept. Figure 8 shows sample cross sections of holes drilled with the rotary AWJ at different parameters; the parameters are listed on the figure. The effect of radial offset is evident from tests 3, 4, and 5. A zero offset means that only a radial groove will be cut with a diameter equal to that of the drill (ignoring the effect of standoff distance), and the drill cannot be advanced. An offset that is larger than the radius of the drill will result in the machining of a ring in which the drill can still be advanced. In this case, the hole diameter will be larger than twice the drill diameter. To reduce the hole size, the radial offset should be slightly smaller than the drill radius. Consequently, the diameter of the drill should be approximately equal to the radius of the required hole.

The drill head that was built in this study is 13 mm (0.5 in.) in diameter and, thus to produce a 19-mm-diameter hole, a radial offset of 3.2 mm (0.125 in.) is required. The central core that will result due to this offset is mathematically equal to 3.2 mm. However, due to jet spreading, continual drill axial advance, and return flow, no core may form at all. In fact, the formation of a central core is not significant for through-hole drilling.

The angle of the AWJ selected in this study was 3 degrees. Although this was found to be adequate, increasing the jet angle may result in faster drilling rates.

It is concluded here that the rotary AWJ drill is technically feasible and more efficient than the nonrotary rectangular drill. The angle of the AWJ needs to be increased for faster drilling rates. The necessary hardware components, such as abrasive swivels, water swivels, and mixing nozzles, are all developed.

4. OBSERVATIONS AND REMARKS

The following general observations and remarks on drilling with AWJs are made based on the Phase I test results.

Holes with relatively thin walls can be drilled with the AWJ drill. For example, a 0.38-mm (0.015-in.) thick wall has been machined in a solid rod. The axial uniformity of the thickness varied within 0.025 mm (0.001 in.) only over the relatively shallow hole depth. For drilling thin wall tubing (or precise hole diameters) over longer distances, a control system must be used. This control system will sense the drilling rate (or wall thickness) and adjust the drill advance rate.

To control the hole diameter, the drilling rate (the advance rate of the cutting face) must be matched to the advance rate of the drill. For example, a drilling rate that is higher than the advance rate will result in hole enlargement. Figure 9 shows an example of an enlarged diameter hole. Observe the symmetry of the produced hole. Also observe the central core that is continually removed as the drill advances. In our tests, a trial-and-error approach was adapted to determine the drilling rate and then to adjust the advance rate. When these rates were matched, hole diameters were controlled.

The AWJ-drilled holes are relatively smooth with a typical roughness of Ra = 1.6 microns (68 μin.). All drilled holes exhibited high qualitative features. No pitting or deformation was observed in any hole. Microscopic inspection of hole walls did not show any anomalies or surface integrity degradation.

The spoils generated by the AWJ drilling process consist of water, abrasives, and the target material debris. The water constitutes over 96% by volume of the spoils. The abrasive particles are broken down to finer sizes. Consequently, recycling the abrasives is not technically feasible.

5. ECONOMIC ANALYSIS

The cost analysis was based on the following assumptions:

Cost of machining system	$250K
Pump cost	$1000/horsepower
Power cost	$0.10/kW
Nozzle replacement cost	$5/hr ($200 nozzle with 40-hour life)
Abrasives	$0.26/kg ($0.12/lb)
Pump maintenance	$4/hr
Interest rate	10%

Lifetime of equipment	10,000 hours
Payoff period	5 years
Residual value	$0
Drill head lifetime	500 hours
Disposal cost	$0.5/mm^3 ($0.05/ft^3)

Figure 10 gives an hourly cost breakdown showing that the dominant cost is due to the manipulator. The projected hourly operation system cost is about $67. The cost of drilling per meter depends on the drilling rate. Figure 11 shows the total hourly cost for different drilling rates. For tungsten drilling at 700 mm/hr (1 ft/hr), the cost per meter will be $223. For a 2.5-m-long rod, the drilling cost will be around $575 and the drilling process can be completed in about 8 hours.

6. CONCLUSIONS

- Three deep hole drilling concepts were tested and all proved to be technically feasible. The nonrotary fan AWJ drill is less efficient than the focused rotary AWJ drill (or oscillatory drill), although it is the simplest.
- It is projected that tungsten rods can be drilled at rates of 700 mm/hr and at a cost of about $67/hr, and thus at $223/m. A 2.5-m-long rod can then be drilled at a projected cost of $575.
- The AWJ deep hole drilling process is suitable for a wide range of materials. The holes drilled with the AWJ process are of high quality with a typical surface finish of 1.6 microns.

7. ACKNOWLEDGMENT

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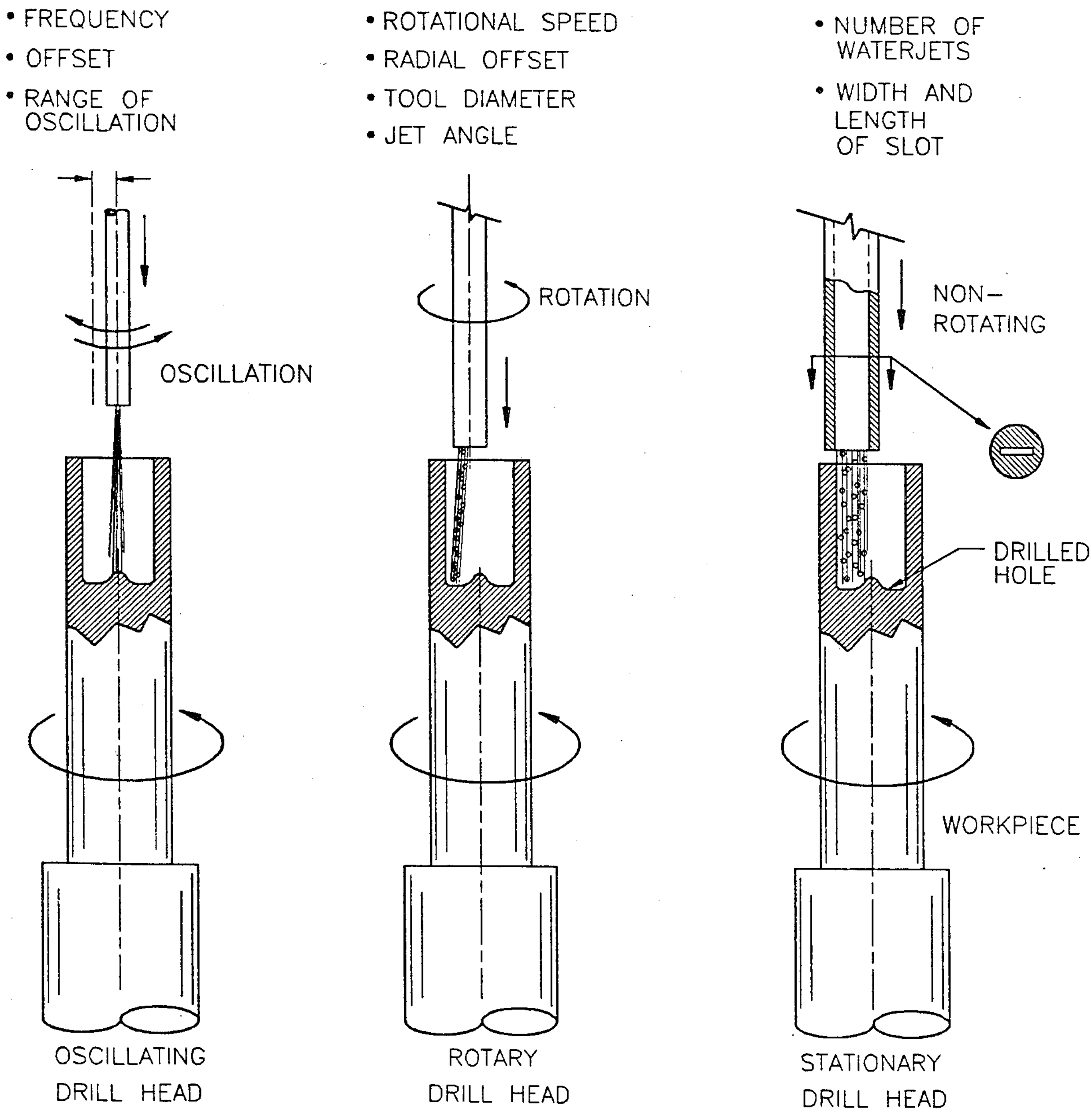
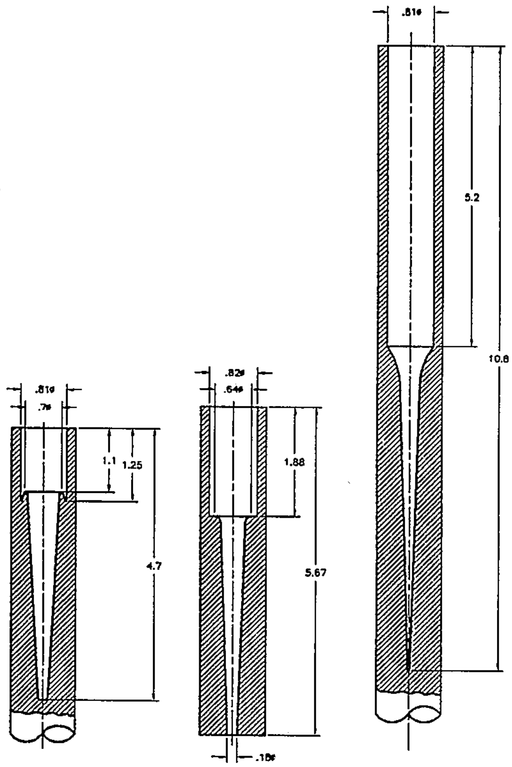


Figure 1. Concepts of Deep Hole Drilling and Their Kinematic Parameters



N = 600 rpm N = 1050 rpm N = 3000 rpm

Figure 2. Cross Sections of Example Holes Drilled in Steel with an Oscillating Jet Drill Head.
Pressure = 50 ksi, traverse rate = 0.1 in./min, drill rpm = 205,
nozzle diameter = 0.013 in., and mixing tube diameter = 0.047 in.

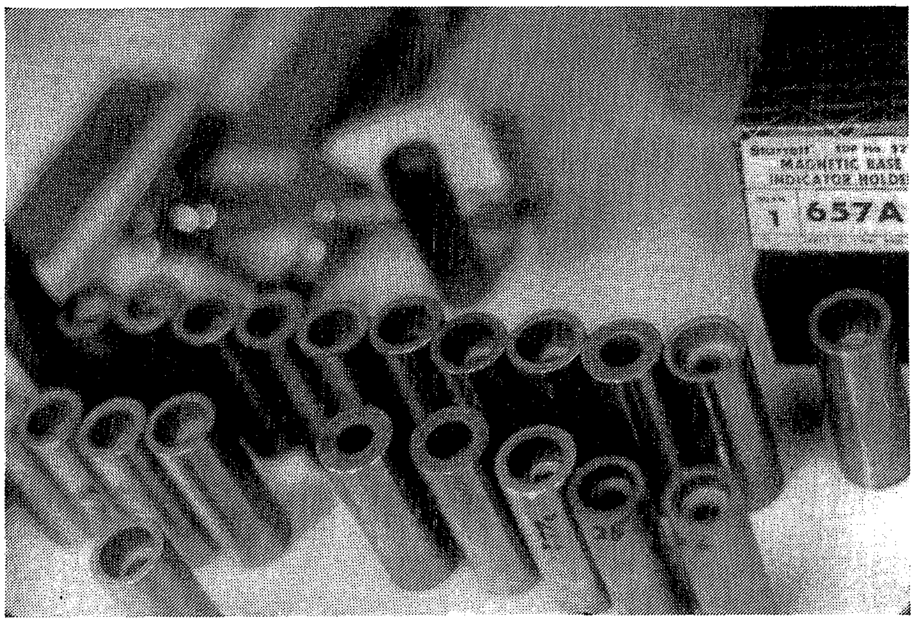
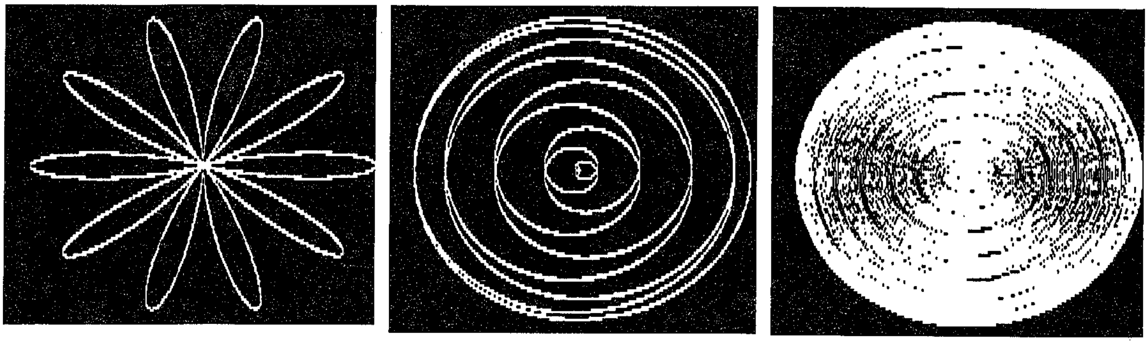
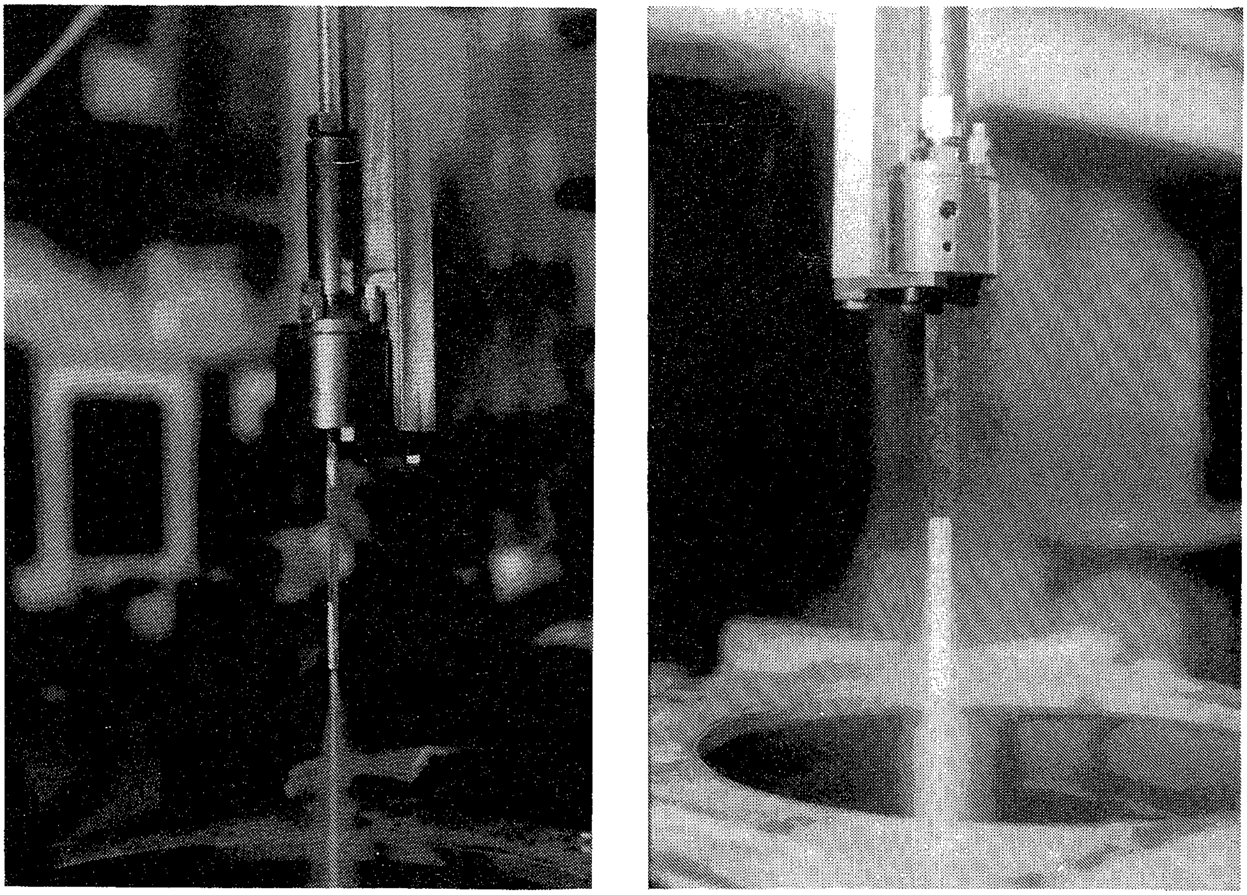


Figure 3. 0.75-Inch (19-mm) Diameter Holes Drilled with Oscillating Jet Drill Concept in 1-Inch (25.4-mm) Diameter Steel Rods



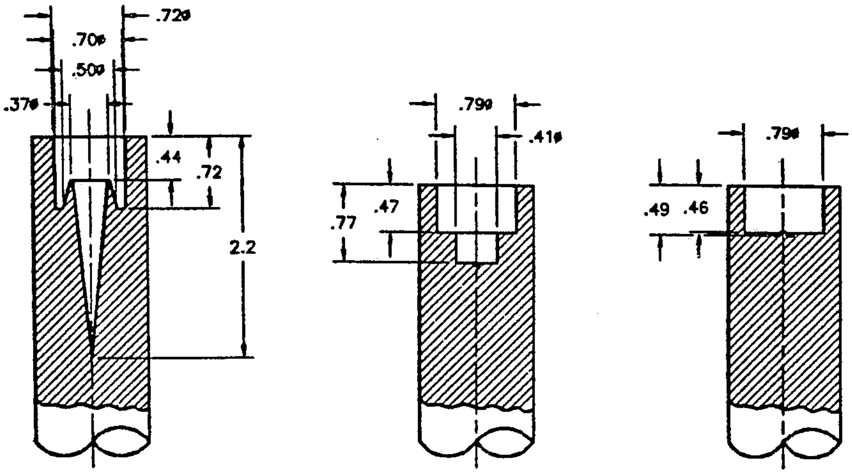
a. rpm1 = 100, rpm2 = 1000 b. rpm1 = 1000, rpm2 = 100 c. rpm1 = 1000, rpm2 = 105

Figure 4. Pattern of Oscillating AWJ Path over a Rotating Workpiece



a. Side view b. Front view

Figure 5. Rectangular AWJ Nozzle

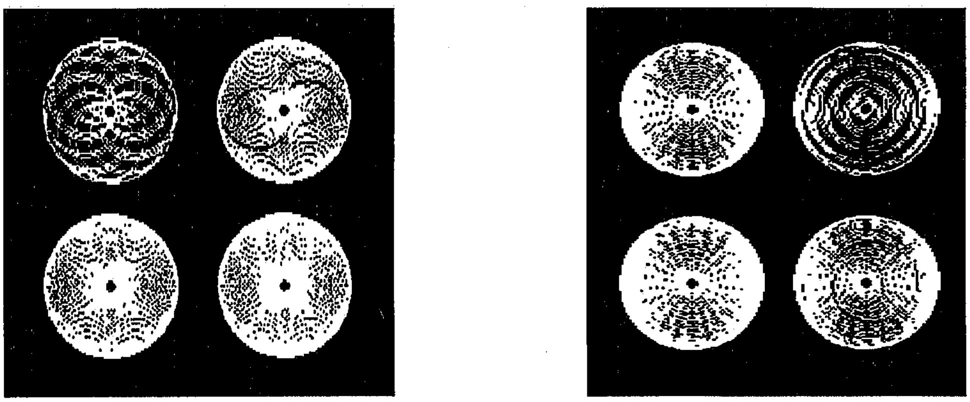


N (rpm) = 600
offset (in.) = 0.12

N (rpm) = 1050
offset (in.) = 0.1

N (rpm) = 3000
offset (in.) = 0.1

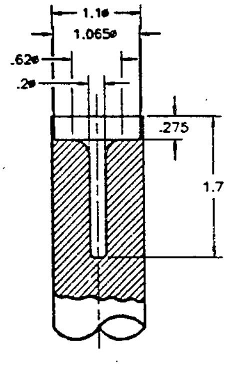
Figure 6. Cross Sections of Example Holes Drilled in Steel with a Nonrotary Rectangular AWJ. Pressure = 50 ksi, nozzle size = 0.063 in. wide by 0.40 in., traverse rate = 0.1 in./min.

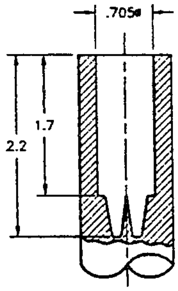


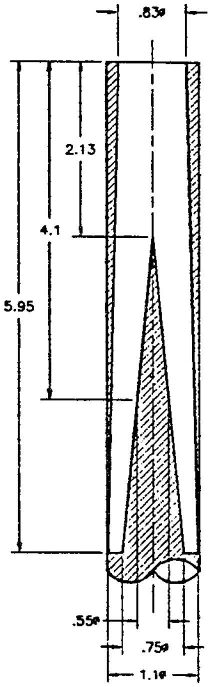
a. rpm1 = 500, rpm2 = 110

b. rpm1 = 110, rpm2 = 500

Figure 7. Computer Animation of Rotary AWJ over Rotary Workpiece







Mixing tube diameter = 0.04 × 0.12 **0.047** **0.125**

Figure 8. Cross Sections of Example Holes Drilled with a Rotary AWJ. Pressure = 35 ksi, drill rpm = 325, nozzle diameter = 0.013 in., and rod rpm = 600.

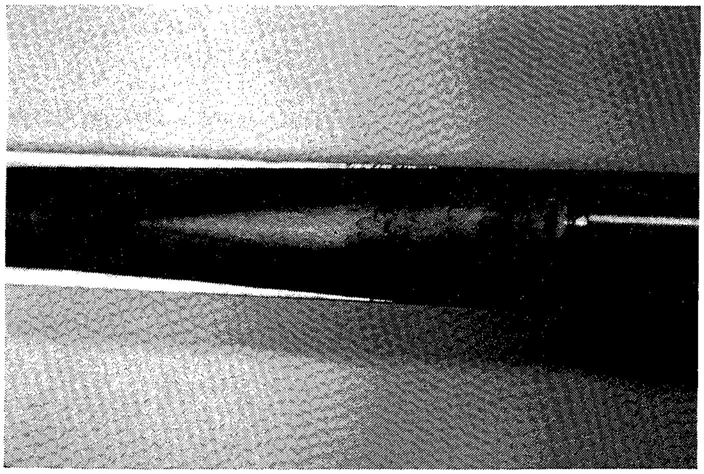


Figure 9. Hole Divergence Due to Slow Advance Rate

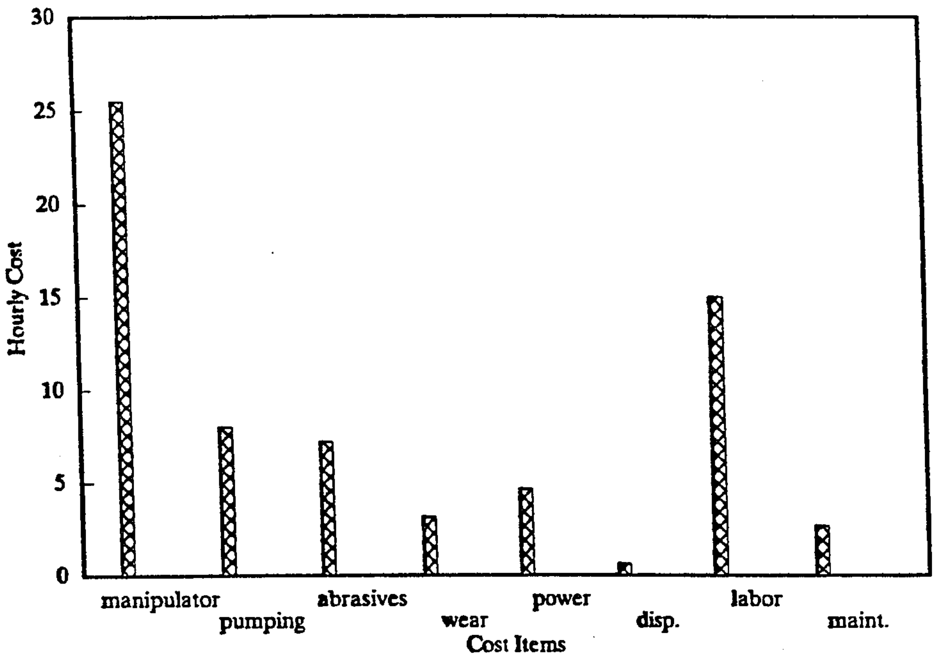


Figure 10. Hourly Cost Breakdown of AWJ Drilling Operation

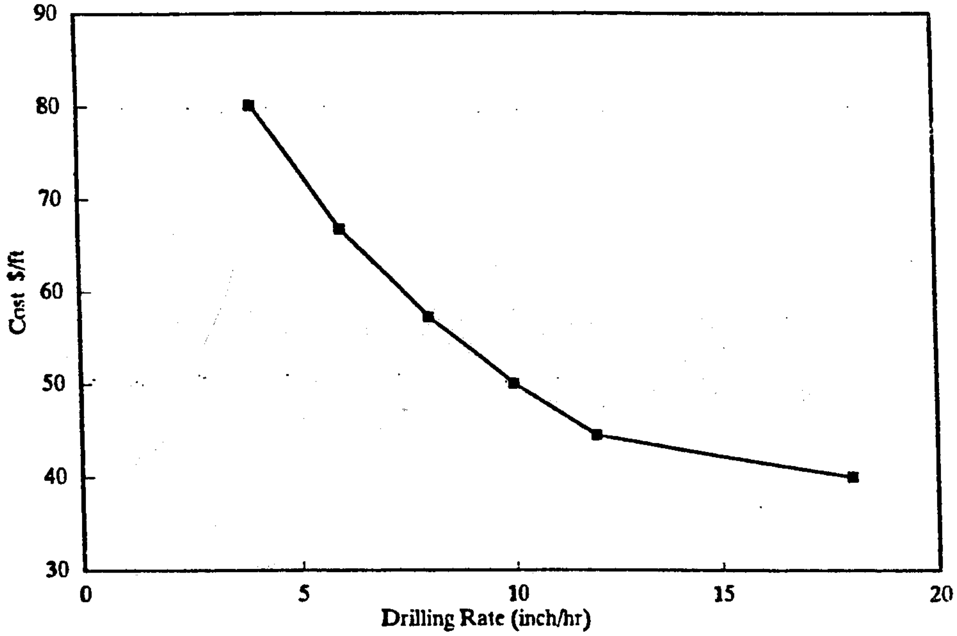


Figure 11. Drilling Cost per Foot Versus Drilling Rate

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ABRASIVE WATERJET MACHINING OF TITANIUM ALLOY

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ABSTRACT

A titanium alloy (Ti-6Al-4V) was machined with an Abrasive Waterjet (AWJ) using a variety of process conditions. The effects of AWJ machining on the surface texture, microstructure, and residual stress state of the machined surfaces were studied and compared with the surfaces generated by conventional slab milling, and surface grinding. Although the two traditional processes provided the highest machined surface quality, an average roughness near 2 μm was achieved with the AWJ. Residual stress measurements from x-ray diffraction imply that AWJ machining induces a tri-axial stress state due to the abrasive particle trajectory during material removal. Furthermore, the residual stresses in the plane of the free surface are compressive. The magnitude and direction of the residual stress was found to depend on the choice of operating parameters. Residual stresses formed during AWJ machining of Ti-6Al-4V are compatible with those achieved from conventional milling, and are more desirable than the nature of those received from grinding.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

Within the last decade there has been tremendous growth in both Abrasive Waterjet (AWJ) technology and its application within the manufacturing environment. Over this period of time, the AWJ machining process has proven to be amenable for cutting both homogeneous and advanced heterogeneous materials [1-6]. However, the AWJ is still considered a supplemental method of manufacturing and is employed only when conventional net-shaping proves insufficient. This has hampered its application for net-sectioning of common structural alloys, where in fact its use may prove advantageous. Consequently, limited work has been performed regarding the influence of AWJ machining on the surface mechanics of popular monolithic alloys.

The intrinsic mechanisms of material removal of a cutting process are responsible for the surface characteristics including the general lay, surface roughness, and residual stress state. Surface roughness is of critical concern and is generally minimized or limited to a predetermined magnitude with the appropriate choice of cutting process and operating conditions. Minimizing the surface roughness serves to eliminate high stress concentrations caused by the microscopic surface geometry. The quality of surface finish generated with AWJ machining has been reported in the literature for a variety of materials [7-10]. In fact, empirical models for the surface quality of AWJ machined stainless steel [8] and Graphite/Epoxy composites [9] have been developed which allow tailoring of the surface finish in terms of the cutting parameters.

Residual stresses induced during machining are the result of plastic deformation, local heating during material removal, and the elastic recovery process. The surface finish and nature of the residual stresses have pronounced effects on the component performance through their influence to the ensuing formation and propagation of cracks from the machined surface [11]. A compressive residual stress will have a beneficial effect, whereas tensile residual stresses often have detrimental effects to the fatigue properties. Extensive studies have been conducted for processes like grinding, to evaluate the magnitude and orientation of the residual stress field [12,13]. With our present knowledge on the ability to tailor the surface finish in AWJ machining, it would appear that perhaps the same is true of the residual stress field. Although the transient state of stress in AWJ piercing of polymer materials has been documented [14], no studies have reported the nature of the residual stress field caused by AWJ machining. Furthermore, a thorough comparison of AWJ and conventional machining of monolithic alloys in terms of the surface quality and state of residual stress has not been made.

Therefore, the purpose of this study was to examine the influence of AWJ machining on the surface properties of Ti-6Al-4V and elucidate the differences from those of conventional processes. The morphology of the machined surfaces was analyzed using electron microscopy and surface profilometry. Residual stress measurements were made using x-ray diffraction. AWJ machined surface properties of the titanium are compared with that of traditionally milled and ground surfaces in terms of texture, microstructure, and residual stress.

2. EXPERIMENTAL

2.1 Material

A hot rolled 0.5 m square, 16 mm thick plate of titanium alloy (Ti-6Al-4V) was obtained for this investigation. The specific composition of the alloy was chosen due to its widespread use in the aerospace industry and its acute propensity for work hardening. Pertinent material properties for the Ti-6Al-4V plate are listed in Table 1.

2.2 Equipment

Abrasive waterjet machining was conducted with a Powerjet model machine with a 20-35 waterjet pump. The system was modified with a Hardinge milling machine table and two Dayton DC motors with Model 6x165 motor controllers to provide bi-axial power feed. The primary components of the nozzle assembly used in this study consist of a 0.3 mm sapphire jewel which transforms the high pressure water into a collimated jet and a 1.0 mm internal diameter carbide focusing tube, 44 mm in length. All experiments were performed with garnet abrasives. Conventional milling was conducted with a Bridgeport milling machine and grinding of the samples was conducted with a conventional table surface grinder.

Topographical analysis of the machined surfaces was conducted with profilometry, scanning electron microscopy, and x-ray diffraction. Surface profilometry was conducted with a SurfAnalyzer™ 4000 profilometer using a 5 µm diameter probe and electron microscopy was conducted with a Jeoul JSM scanning electron microscope. Residual stress analysis was obtained via x-ray diffraction with a Phillips diffractometer consisting of a 1830 Generator and PW1710/00 Diffraction Control Unit. Peak intensities and plane spacing were determined using PC-STRESS, a residual stress measurement and analysis software [15].

2.3 Procedure

An experimental design was used in machining titanium samples with the AWJ incorporating a variety of process conditions. A three-level, nine-run design matrix with 27 independent parametric combinations was chosen. With replication, a total of 54 cutting tests were performed. Following AWJ machining, the quality of all the machined surfaces was examined. Three specimens that exhibited minimal evidence of jet induced waviness were identified for further analysis. Three additional samples were prepared with traditional machining process for a comparison to the AWJ samples: one from conventional slab milling with a carbide end mill, and two using surface grinding. One of the ground specimens was subjected to a full anneal heat treatment [16] to serve as the control sample for residual stress measurements. Process conditions for the AWJ machined, milled, and ground samples are listed in Table 2.

Surface profilometry was performed to evaluate the surface texture of all machined samples, including the 54 AWJ samples, in addition to the milled and ground specimens. Three profiles were obtained and averaged from each of machined surfaces in directions parallel and perpendicular to the dominant lay. All measurements were conducted with a 3.5 mm traverse length, and 0.8 mm or 3.5 mm cutoff lengths according to ANSI B46.1-1985. The larger cutoff length (3.5 mm) was equivalent to the traverse length of the measurement and used to indicate the degree of large wavelength surface asperities filtered out by the standardly used shorter cutoff length. Profiles were obtained perpendicular to the dominant lay imposed from each method of machining. The average surface roughness (R_a) and average peak to valley height (R_y) were calculated in addition to the probability density, cumulative distribution, and power spectrum density of the profile heights. Scanning electron microscopy was used to analyze the machined surface microstructure typical of the three material removal processes.

Residual stress measurements were derived from calculations of plane spacing according to Bragg's Law as outlined in [17]:

$$n\lambda = 2d\sin\theta \qquad (1)$$

Bragg's Law represents the relationship between plane spacing "d" and the x-ray incidence and refraction angle (θ) in terms of the incident x-ray wavelength (λ). A tri-axial stress-strain analysis was chosen based on the high probability of the presence of the shear components ε_{13} and ε_{23} attributed to the abrasive jet loading trajectories on the kerf wall as shown schematically in Figure 1. The machined surface and diffractometer coördinate systems used for the residual stress analysis are shown in Figure 2. Diffraction peaks were recorded with the diffractometer at $\pm\psi$ tilts of 0°, 20.7°, 30°, 37.76°, and 45° at ϕ angles of 0°, 45°, and 90°. A total of 30 measurements of peak location were recorded for each of the 6 samples. Copper k_α radiation was used for this investigation with a wavelength of 1.54060A° which permitted diffraction of the 213 Miller indices hkl peak at large ψ tilts. Hence, the plane spacing d_0 was indicated by the position (2θ) of the diffraction peak from the hkl reflection of each material according to Bragg's law. All peak intensities were corrected for Lorentz polarization and background intensity using a linear correction. Peak positions were calculated using both parabolic fit and center of gravity methods. In general, the center of gravity calculated peak position provided the most consistency with ψ tilt and was therefore used in calculating the respective strains. The strain field in the plane of the specimen surface was obtained through the independent plane spacing measurements $d_{\phi\psi}$ as given by [17] in equation (2).

$$(\varepsilon_{33})_{\phi\psi} = \frac{d_{\phi\psi} - d_0}{d_0} = \varepsilon_{11}\cos^2\phi\sin^2\psi + \varepsilon_{12}\sin2\phi\sin^2\psi + \varepsilon_{22}\sin^2\phi\sin^2\psi$$
$$+ \varepsilon_{33}\cos^2\psi + \varepsilon_{13}\cos\phi\sin2\psi + \varepsilon_{23}\sin\phi\sin2\psi \qquad (2)$$

Unstressed lattice spacing d_0 for the titanium alloy was determined from diffraction measurements of the fully annealed sample. To dissect the 6 independent strain components, a_1 and a_2 as shown in equations 3, and 4, respectively, are plotted as a function of the ψ tilt for each specimen orientation (ϕ).

$$a_1 = \frac{1}{2}\left(\varepsilon_{\phi\psi+} + \varepsilon_{\phi\psi-}\right) = \left(\frac{d_{\phi\psi+} + d_{\phi\psi-}}{2d_o} - 1\right)$$
$$= \left(\varepsilon_{11}\cos^2\phi + \varepsilon_{12}\sin 2\phi + \varepsilon_{22}\sin^2\phi\right)\sin^2\psi + (1 - \sin^2\psi)\varepsilon_{33} \qquad (3)$$

$$a_2 = \frac{1}{2}\left(\varepsilon_{\phi\psi+} - \varepsilon_{\phi\psi-}\right) = \frac{d_{\phi\psi+} - d_{\phi\psi-}}{2d_o}$$
$$= \varepsilon_{13}\cos\phi\sin|2\psi| + \varepsilon_{23}\sin\phi\sin|2\psi| \qquad (4)$$

This approach assumes that ψ splitting occurs due to the presence of the two shear strains ε_{13} and ε_{23} and their transformation dependence on the term $\sin 2\psi$ given in equation 2 [17]. The terms $d_{\phi\psi+}$ and $d_{\phi\psi-}$ represent the plane spacing measured at both positive and negative ψ tilts. With the unstressed lattice spacing d_o known from the annealed sample, the component ε_{33} can be determined using equation 3 from the intercept of a_1 vs. $\sin^2\psi$ where $\psi = 0°$. With ε_{33} known, the strain components ε_{11}, ε_{22}, and ε_{12} can be acquired from the slope of a_1 at ϕ angles of 0°, 90°, and 45°, respectively. The components ε_{13} and ε_{23} are obtained from the slope of a_2 vs. $\sin 2\psi$ for ϕ of 0°, and 90°, respectively. The residual stresses were calculated from the strains using Hooke's Law assuming isotropic conditions. An analysis of anisotropic behavior of the lattice planes associated with cold working of Ti-6Al-4V has shown that errors are limited to less than 0.8% [18].

3. RESULTS AND DISCUSSION

The macroscopic features of the machined Ti-6Al-4V surfaces obtained from AWJ machining, slab milling, and surface grinding were distinctly different. Both the milled and ground samples exhibited a highly uniform surface with little evidence of a prominent lay direction. However, the AWJ machined specimens exhibited a prominent lay consistent with the jet penetration direction. A comparison of the surfaces is shown in Figure 3.

3.1 Surface Finish

The quality of the AWJ machined, slab milled, and ground surfaces of the titanium samples in terms of standard roughness parameters are outlined in Table 3. Machined surface quality is inferred by the relative magnitude of the average surface roughness (R_a), peak to valley height (R_y), root mean square roughness (R_q), and skewness. For the milled and ground specimens the measurement direction was perpendicular to the direction of rotation of the cutter, whereas for the AWJ machined specimens the measurement direction was perpendicular to the jet penetration axis. Slab milling and grinding provided the best surface finish of the three processing methods respectively, with average roughness (R_a)

less than 1 μm. The average roughness parameters of the AWJ machined samples ranged from 6 to 10 times the magnitude of finish received from the slab milling process. However, the R_a of the three chosen AWJ machined samples ranged from 2.5 to 3.1 μm, which is extremely low considering the operation was used synonymously for sectioning and finishing. The lowest surface roughness of the 54 AWJ machined samples was 1.9 μm. Probability density of the profile height and the cumulative height distribution of the machined surfaces are shown in Figure 4(a,b). Abrasive waterjet machining imposed a much more random distribution in profile height compared to the other two processing techniques as indicated by the wider variation in profile height about the mean line in Figure 4(a), and the higher slope of the cumulative height distribution in 4(b). All of the cutting processes induced a moderately negative skewed surface profile suggesting that the surfaces are characterized by high plateaus with interspersed valleys. The difference in AWJ operating parameters for samples (a-c) and corresponding limited response of the surface strata indicates the multiplicity in the appropriate choice of operating conditions for a desired surface quality. Invariably, the use of smaller garnet abrasive sizes for the specimen AWJ (c) produced the best surface finish of the three cutting conditions. A representative power spectrum density resulting from AWJ cutting with conditions (a-c), slab milling, and grinding are shown in Figure 5(a-e). The wavelength or period of the prominent surface feature is indicated by the reciprocal of the frequency at the point of maximum amplitude. All three of the techniques generated a very low frequency (large wavelength) periodicity on the machined surface; typical wavelengths from a survey of all measurements for each of the samples varied between 1.5 and 3 mm. The amplitude of the periodicity of the AWJ samples was considerably greater than that exhibited by the ground and milled samples due to the larger peak to valley height as noted in Table 3. The lack of small wavelength periodicity of the AWJ machined samples confirms that the abrasive removal process was random in nature. The presence of large wavelength periodicity can be attributed to either machine vibration [19] or the dynamics of the cutting process encountered during jet deflection induced waviness [20].

3.2 Microscopy

A microscopic examination of the machined surfaces was conducted with the use of a scanning electron microscope. For each of the three AWJ machining conditions, micrographs of the machined surface were obtained at three depths of jet penetration from the point of jet entrance including 50 μm, 6 mm, and 15 mm. Micrographs from the machined surface of specimen AWJ (a) are shown in Figure 6 (a-c) for the three depths of inspection and are representative of characteristics of all the titanium samples. Significant degrees of plastic deformation were evident near the jet entrance which has been previously termed in the literature as the Initial Damage Region (IDR) [21,22]. Features of the machined surface within this region consisted of an irregular structure which appears to have been formed from the repeated bombardment of abrasive particles, plastic embrittlement, and subsequent erosion. The extent of this zone from the jet entrance, which is primarily governed by the standoff distance and degree of jet expansion prior to impact, did not vary significantly between the three AWJ machined specimens. The length of the IDR from the point of jet entrance was limited to approximately 125 μm along the kerf depth. However, specimen AWJ (a) exhibited the most pronounced damage due mostly to the large abrasive particles and the high jet pressure used in obtaining this sample. The enhanced jet pressure and abrasive particle mass are able to deliver more kinetic energy for plastic deformation. Characteristics of the machined surface from the end of the IDR to the point of jet exit were extremely different from those within the region of jet entrance. The two views in Figure 6 (b) and (c) for AWJ (a) are representative of the typical features noted on each of three AWJ machined samples, despite the difference in operating parameters. Throughout the penetration depth, no distinct differences were noted except for the gradual increase in abrasive deflection with depth of jet penetration.

Machined surface features highlighted in Figure 6 are also representative of those noted from inspection of samples which exhibited waviness patterns, or more appropriately the presence of the Rough Cutting Region (RCR) [20,22]. Within the RCR of the titanium samples, no difference in material removal features were noted. In general, a decrease in abrasive path length and increase in path randomness was noted with increasing depth of cut due to the loss in jet energy with penetration depth. Figure 7(a,b) shows magnified views (x1500) of the slab milled and ground titanium samples. In comparison to the AWJ machined surface, the slab milled and ground samples exhibited a much more regular surface on the micro level which is indicative of the defined path of the tool. The abrasive removal imposed by grinding in Figure 7(b) appears more rugged than that of the milled sample as would be expected from the coarse nature of the grinding wheel and continuous oblique cutting edge of the end mill.

An example of the interaction of a singular abrasive particle and the titanium alloy along the kerf wall is shown in Figure 8. The particle signature discloses the abrasive path during the progression of plowing and chip formation. The abrasive penetration and subsequent material removal in AWJ machining discontinues when the energy available for micromachining related deformation is less than that required to overcome the increasing resistance of the workpiece invoked through work hardening. From the scale of the micrograph it can be inferred that the depth of the wear crater highlighted in Figure 8 is between 10 and 20 μm; the geometry of this crater is consistent with the average of those noted throughout this study. The trajectory of the particle implies that a significant tangential force component was imparted to the workpiece during its interaction with the kerf wall. Based on the evidence of plastic deformation and knowledge of the abrasive particle cutting force components, AWJ machining should induce a surface residual stress.

3.3 Residual Stress Analysis

In the determination of stresses within a deformable body, the components normal to the free surface are zero, by definition. However, the strains calculated from plane spacing displacements via x-ray diffraction are averaged over the x-ray penetration depth. Therefore, it is necessary to estimate the depth of penetration over the irradiated volume. The depth of penetration is dependent on the focusing position (ψ), based on the increase in absorption with x-ray path length. Absorption between the workpiece and x-rays serves to attenuate the intensity with depth. The greatest depth of penetration occurs with no ψ tilt (ψ=0). At this position the total intensity diffracted by the surface of the titanium as a fraction of the total diffracted intensity (G_x) is given in equation (5) where 'x'

$$G_x = 1 - e^{-2\mu x/\sin\theta} \qquad (5)$$

represents the depth of penetration and μ is the linear absorption coefficient. From the weight fraction of the elements present in Ti-6Al-4V [23], the total absorption was found to be μ_t = 90.25 mm^{-1}. Using G_x = 99% for the effective depth of penetration, the depth of copper k_α penetration in the titanium samples was 12.8 μm. Hence, the stresses calculated from the residual strains in this study represent an average of the residual stress state over a depth of approximately 13 μm from the machined surface.

Representative plots of the plane spacing ($d_{\phi\psi}$) vs. $\sin^2\psi$ for AWJ (a) and the milled specimen are shown in Figure 9(a,b), respectively. Within the bounds of errors in measurement and dissection of the diffraction peak positions, the "d" vs. $\sin^2\psi$ plots are essentially linear and no ψ-splitting was apparent. Linear behavior and the lack of ψ-splitting from equation (2) suggests that the components ε_{13} and ε_{23} are relatively insignificant. Strains were calculated from the plane spacing using equations (2) and (3) and the value of d_0 obtained from the annealed sample. The unstressed lattice spacing from the annealed sample was 0.81713 A° and the literature cited value was 0.81532 A° [18]. The difference in lattice unit cell dimensions could be due to the instability of the alpha and beta phases of Ti-6Al-4V, and the lack of knowledge concerning the prior processing temperatures of the "as received" plate. It is believed that separation of the two phases occurred during the final heat treatment , thus providing a different plane spacing. Therefore, the value of plane spacing from the literature was used in calculating machining induced strains. The strain tensors for all of the machined specimens are shown in Table 4. The corresponding residual stress tensors for each of the machined surfaces are listed in Table 5. All of the AWJ machined specimens (a-c) exhibited a significant compressive tri-axial field over the x-ray penetration depth of 13 µm. The nature of the residual stress field received from the milled sample is similar to that received from AWJ machining. However, diffraction measurements from the ground surface of the Ti-6Al-4V imply that the resulting state of residual stress is tensile.

The effect of AWJ process conditions on the magnitude of the surface displacements and residual stress field is readily apparent from Tables 4, and 5. The large abrasive particles sizes (#50 garnet, 350µm)) used in conditions (a) and (b) resulted in much larger degrees of shear deformation along the jet path. The largest in-plane shear strain ε_{12} and corresponding shear stress σ_{12} was generated from the use of #50 garnet and a jet pressure of 240 MPa. In contrast, the lowest degree of shear strain was generated with the #100 Garnet on the machined surface of the sample AWJ (c). Braski [24] also noted that the deformation and corresponding residual stress increased with abrasive size when shot peening Ti-6Al-4V sheet. The benefits in the case of AWJ machining is that net-sectioning and surface treatment was performed in a single operation. Furthermore, although the surface finish obtained from each of the three different parametric combinations was similar, the residual stress field was significantly different. This would allow tailoring of both the surface finish and residual stress for optimum component performance.

One of the most interesting features of the residual stress field is that the lower jet pressure used in AWJ (b) produced a 30% higher degree of surface displacement perpendicular to the jet direction than condition (a); specimen AWJ (a) was obtained with the same grit size and a jet pressure more than twice that of AWJ (b). The difference in surface displacement component ε_{11} is most likely caused by the enhanced jet deflection due to the lower jet energy in AWJ (b), hence causing the abrasive path to skew away from the jet nozzle axis. In support of this, the surface displacement parallel to the jets' primary axis ε_{22} from condition (b) is lower than the corresponding component generated with AWJ (a) cutting conditions. The principal stress tensor and the orientation with respect to the samples coordinate system are listed in Table 6. Milling with the carbide end mill induced the maximum compressive residual stress of all three processing techniques studied. Abrasive waterjet machining conditions (a) and (b), both of which used #50 garnet, resulted in similar magnitude compressive principal components; AWJ (a) with the highest jet pressure resulted in the highest maximum shear as expected. In comparison to the other two parametric combinations, specimen AWJ (c) exhibited principal stresses nearly half the magnitude of those generated with the larger grit size. In contrast to AWJ machining and milling, the principal stresses are tensile and their orientation coincides with the grinding direction.

4. SUMMARY AND CONCLUSIONS

A titanium alloy of composition Ti-6Al-4V was machined with the use of the abrasive waterjet (AWJ), milling machine, and surface grinder. A comparison of the machined surface characteristics from the three shaping techniques was conducted using surface profilometry, scanning electron micrography, and residual stress measurement. Based on this analysis, the following conclusions were made;

1. A high quality surface finish was received from AWJ machining of the titanium alloy, with an average surface roughness as low as 2µm. Three completely different parametric combinations were used in producing nearly equivalent surface quality, hence indicating the dexterity in AWJ machining. The traditional methods of machining including milling and grinding produced a better surface finish with average roughness values of 0.4 and 0.7 µm respectively.

2. All three cutting processes induced a negative skewed surface profile with a very low frequency (large wavelength) periodicity. The most dominant wavelength for all the cutting techniques ranged between 1.5 and 3 mm.

3. From a microscopic analysis of the AWJ machined surfaces, no change in material removal mechanisms occurred below the initial damage region (IDR) despite the cutting parameters or macroscopic surface features. Material removal of the Ti-6Al-4V in AWJ machining consisted primarily of micromachining chip formation and plowing mechanisms.

4. Residual Stress Measurements using X-Ray diffraction implied that the stress tensor of an AWJ machined surface is tri-axial. Furthermore, the magnitude of the stresses are highly compressive, and are similar to those induced by conventional slab milling. Grinding of the Ti-6Al-4V generated tensile residual stresses.

5. The highest compressive residual stress in AWJ machining was received with the use of the largest grit size (#50 garnet, 350µm). Conversely, the lowest residual stresses which were less than half the maximum values were generated with the smallest grit size (#100 garnet, 135µm).

6. The principal stress direction does not correspond with the jet penetration direction in AWJ machining. However, the orientation of the maximum shear stress coincides with the jet path along the kerf wall.

5. ACKNOWLEDGMENTS

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Table 1 Material Properties for Ti-6Al-4V

Composition (Vol. %)			
90% Titanium, 6% Aluminum, 4% Vanadium			
Material Properties			
Density (g/cm3)	**Modulus** (GPa)	**Yield Strength** (MPa)	**Ultimate Strength** (MPa)
4.43	113	1055	1165

Table 2 Cutting Conditons

Test	Jet Pressure (MPa)	Standoff (mm)	Garnet #/size #/(μm)	Traverse Speed (mm/s)	Abrasive Flow Rate (grams/s)
AWJ (a)	207	2.5	50/350	0.7	10
AWJ (b)	138	2.5	50/350	0.7	10
AWJ (c)	207	2.5	100/135	0.7	10
Milling	Slab machined with a 4-flute carbide end mill using finish machining conditions, 0.5mm depth of cut, 70mm/min cutting speed(≈0.05 mm/tooth) and liberal lubricant.				
Grinding	Ground with SiC/Al203 mixture, #46 mesh, general purpose wheel (DA46-H9-V20) at 3450RPM, 12μm depth of cut, manual feed, and dry conditions (no lubricant).				

Table 3 Surface Roughness of the Machined Samples

Specimen	Ra (μm)	Ry (μm)	Rq (μm)	Skew
AWJ (a)				
0.8mm cutoff	3.0	18.8	3.9	-0.5
3.5mm cutoff	4.6	33.9	5.8	
AWJ (b)				
0.8mm cutoff	3.1	17.6	3.9	-0.7
3.5mm cutoff	6.5	42.1	8.3	
AWJ (c)				
0.8mm cutoff	2.5	13.1	3.1	-0.8
3.5mm cutoff	5.8	34.0	7.4	
Slab Milled				
0.8mm cutoff	0.4	2.3	0.6	-0.6
3.5mm cutoff	0.7	4.5	0.9	
Ground				
0.8mm cutoff	0.7	4.9	1.0	-0.3
3.5mm cutoff	1.1	9.5	1.5	

Table 4 Strain Tensors from Diffraction Measurements

Specimen	Strain Tensor (10^-3)			Specimen	Strain Tensor (10^-3)		
AWJ (a)	-2.44	-9.14	0.00	Milled	-1.49	-9.96	0.00
	-9.14	-2.42	0.00		-9.96	-4.24	0.00
	0.00	0.00	2.17		0.00	0.00	2.70
AWJ (b)	-3.23	-8.58	0.00	Ground	4.18	-0.88	0.00
	-8.58	-2.24	0.00		-0.88	-0.31	0.00
	0.00	0.00	1.99		0.00	0.00	-0.52
AWJ (c)	-1.51	-6.20	0.00				
	-6.20	-1.13	0.00				
	0.00	0.00	1.52				

Table 5 Residual Stress Tensors for the Different Machining Conditions

Specimen	Stress Tensor (MPa)			Specimen	Stress Tensor (MPa)		
AWJ (a)	-451	-385	0	Milled	-402	-419	0
	-385	-449	0		-419	-634	0
	0	0	-63		0	0	-49
AWJ (b)	-590	-362	0	Ground	658	-37	0
	-362	-506	0		-37	280	0
	0	0	-149		0	0	-37
AWJ (c)	-229	-261	0				
	-261	-197	0				
	0	0	26				

Table 6 Principal Stress Tensors

Specimen	Stress Tensor (MPa)		
AWJ (a), θ = 44.9°	-65	0	0
	0	-835	0
	0	0	-63
AWJ (b), θ = 41.7°	-184	0	0
	0	-912	0
	0	0	-149
AWJ (c), θ = 43.2°	48	0	0
	0	-474	0
	0	0	26
Milled, θ = 37.3°	-83	0	0
	0	-953	0
	0	0	-49
Ground, θ = 0°	661	0	0
	0	276	0
	0	0	-37

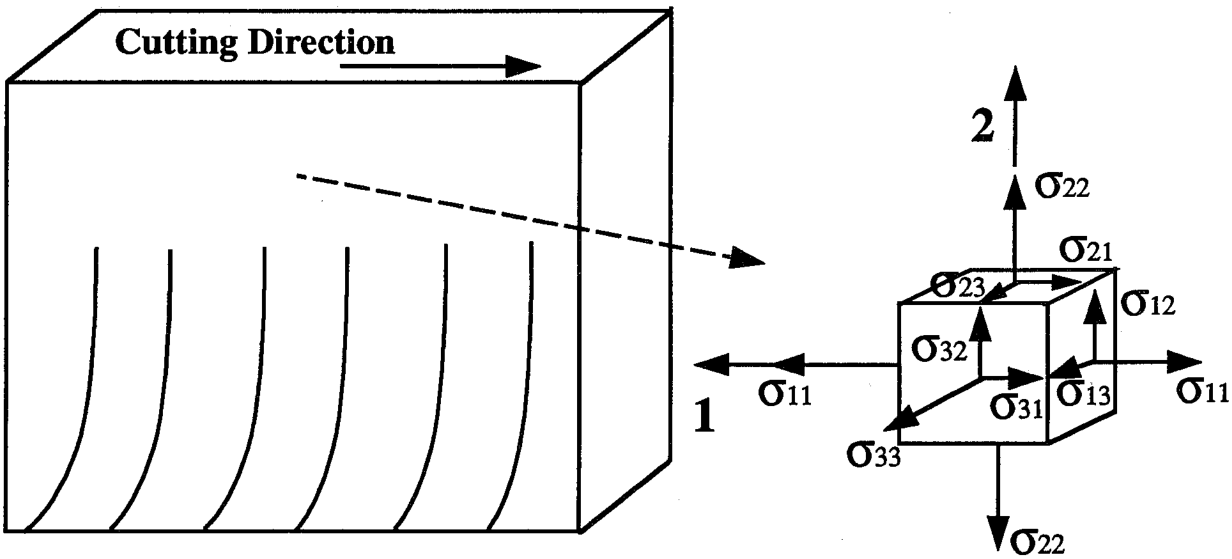


Figure 1 Stress Components of the Machined Surface

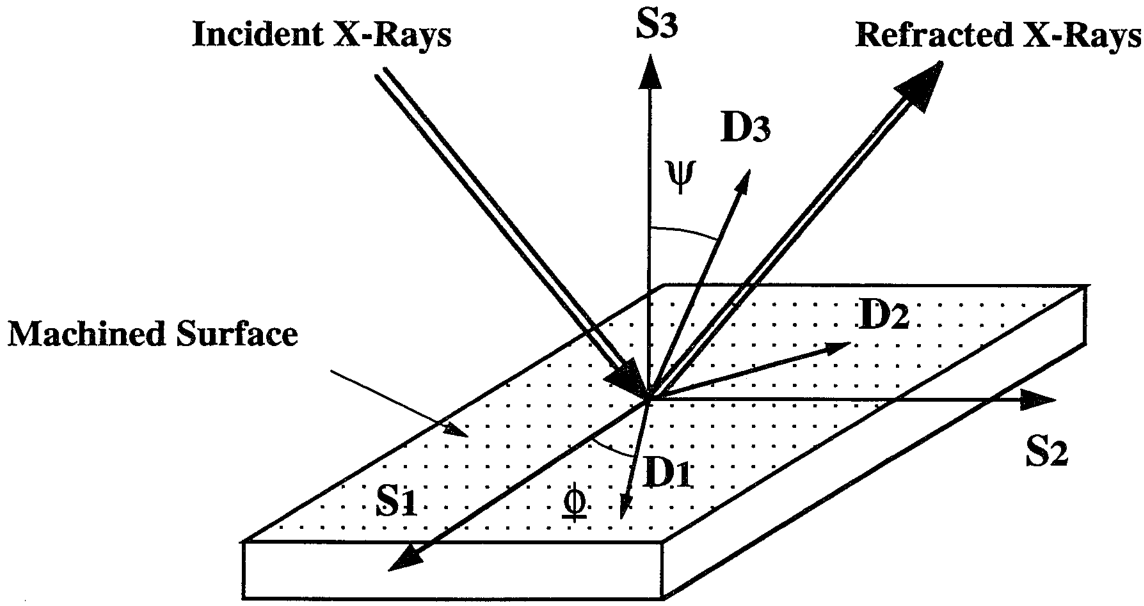


Figure 2 Sample and Diffractometer Coordinates

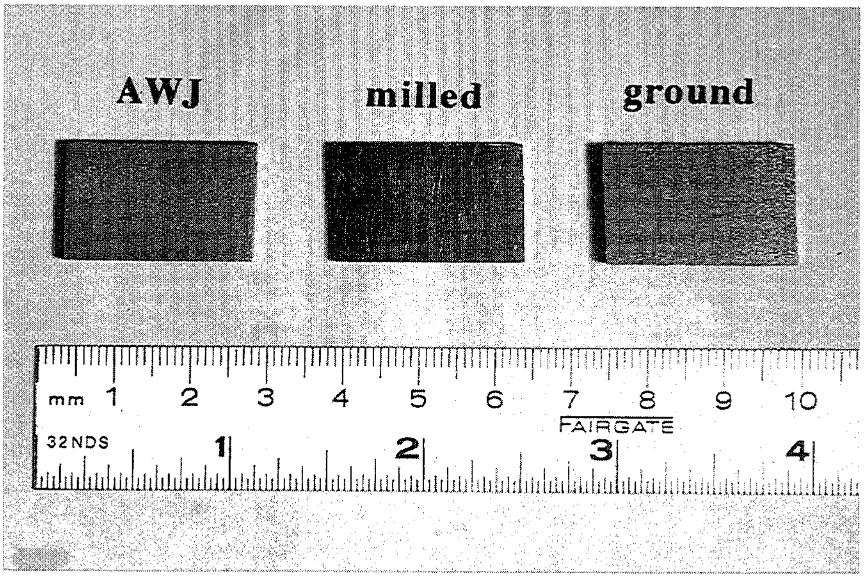
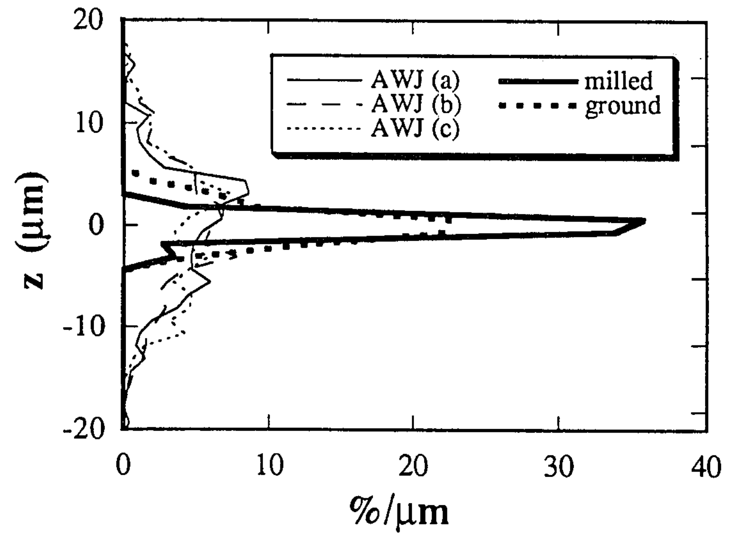
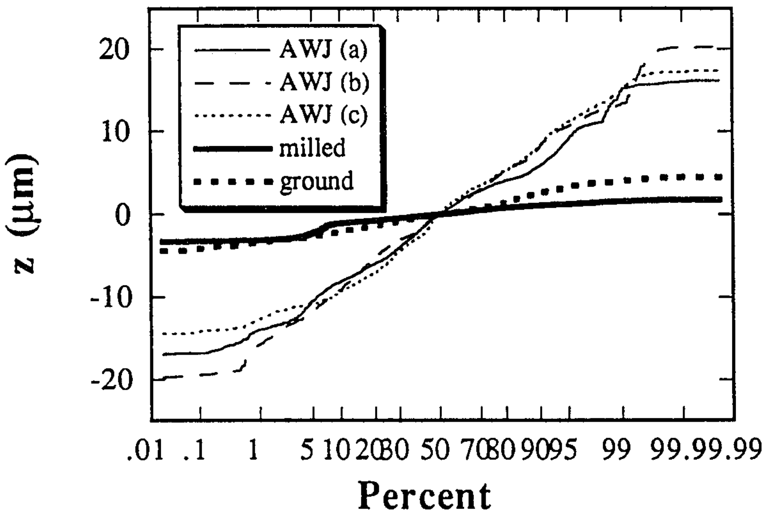


Figure 3 Machined Specimens

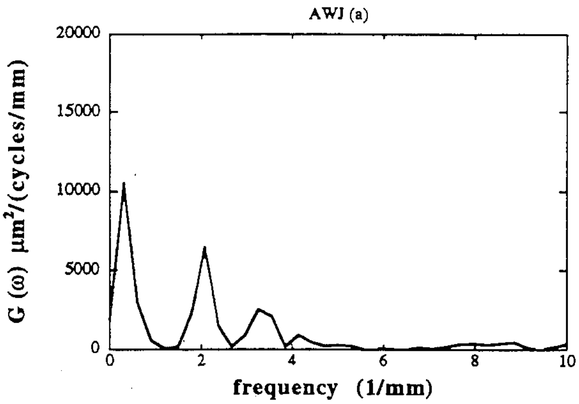


a) probability density

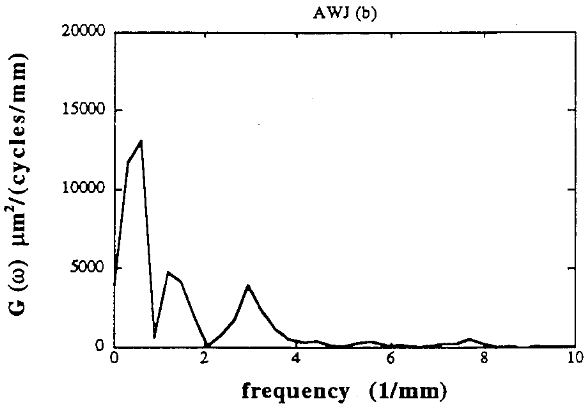


b) cumulative height distribution

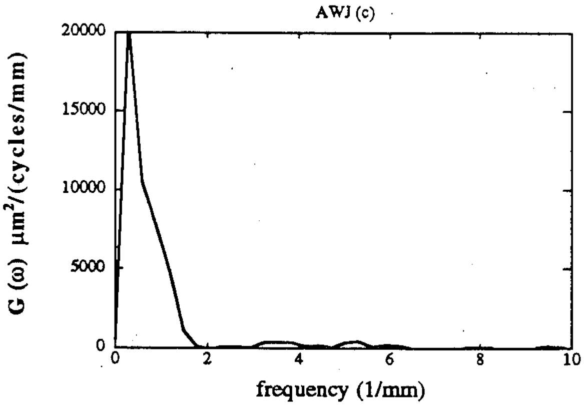
Figure 4 Probability Density and Cumulative Height Distribution of the Samples



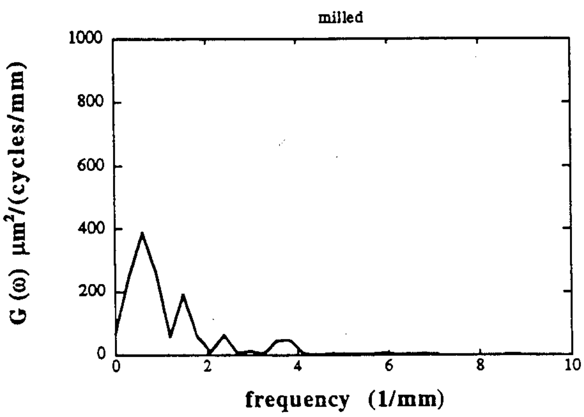
a) AWJ (a)



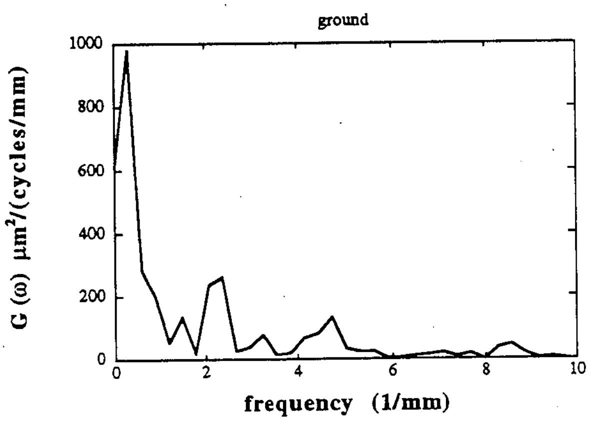
b) AWJ (b)



c) AWJ (c)

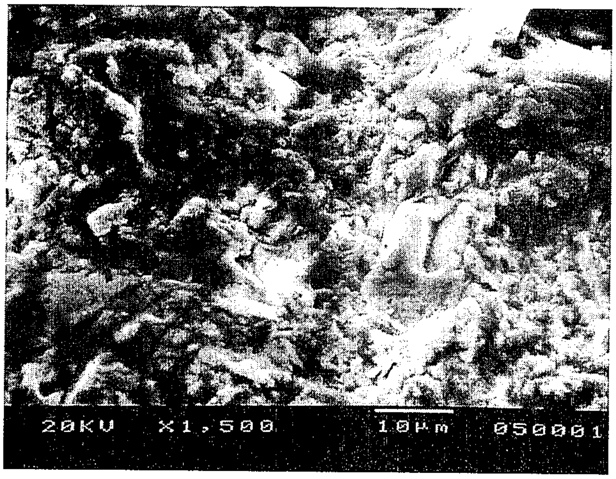


d) milled

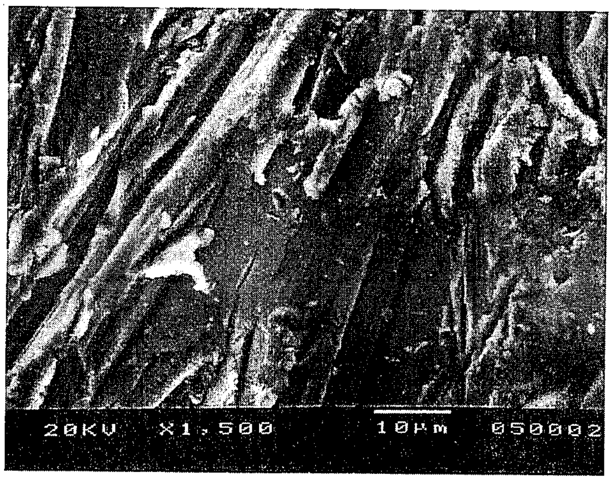


e) ground

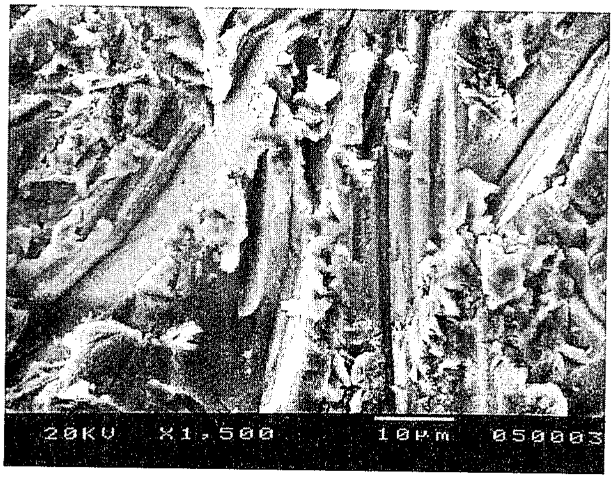
Figure 5 Power Spectrum Density of the Machined Surfaces



a) 50 µm from jet entry



b) 6 mm from jet entry



c) 15 mm from jet entry

Figure 6 Micro View of AWJ Machined Ti-6Al-4V
Machining Conditions: AWJ (a); 207 MPa pressure, 2.5 mm standoff, #50 garnet, 0.7 mm/s traverse speed, 10 grams/sec abrasive flowrate.

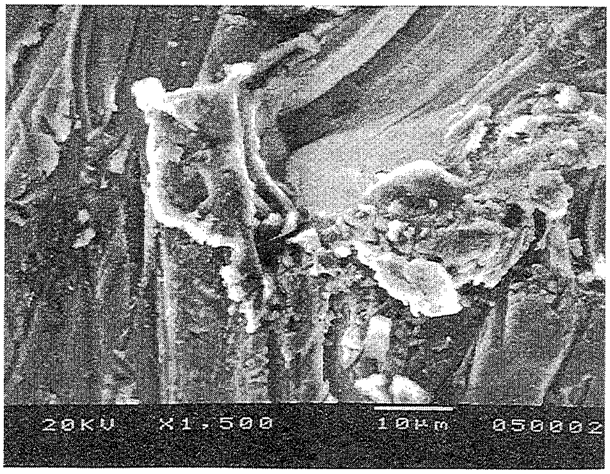
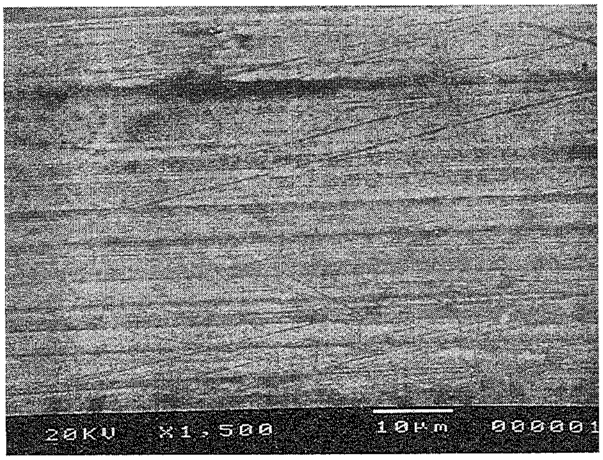
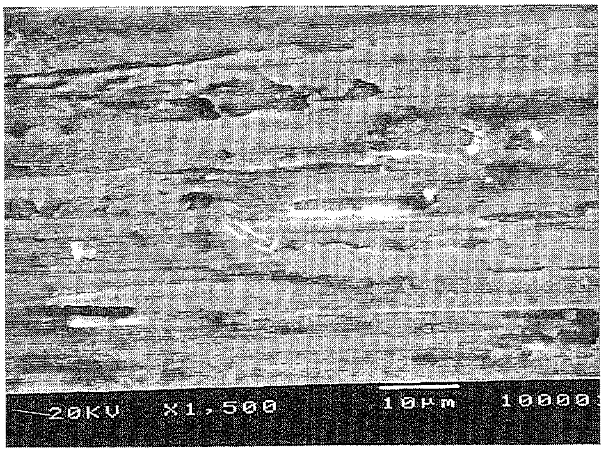


Figure 8 Chip Formation and Plow Tracks in AWJ Machining (AWJ(a))

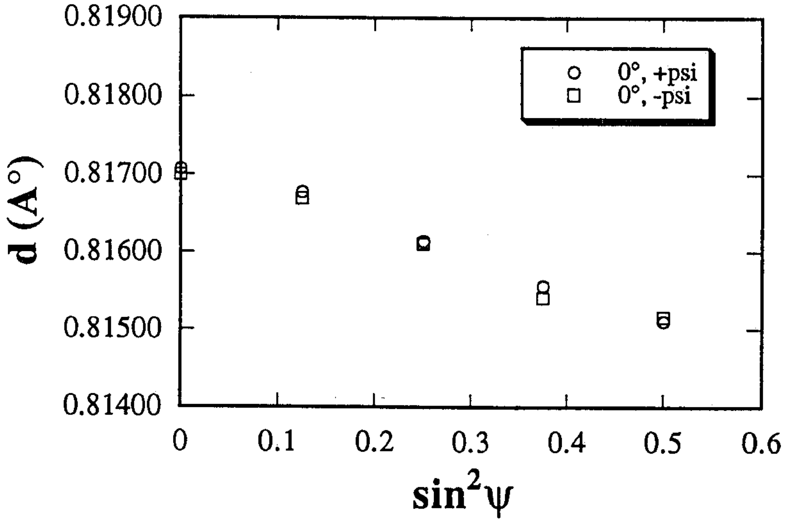


a) milled

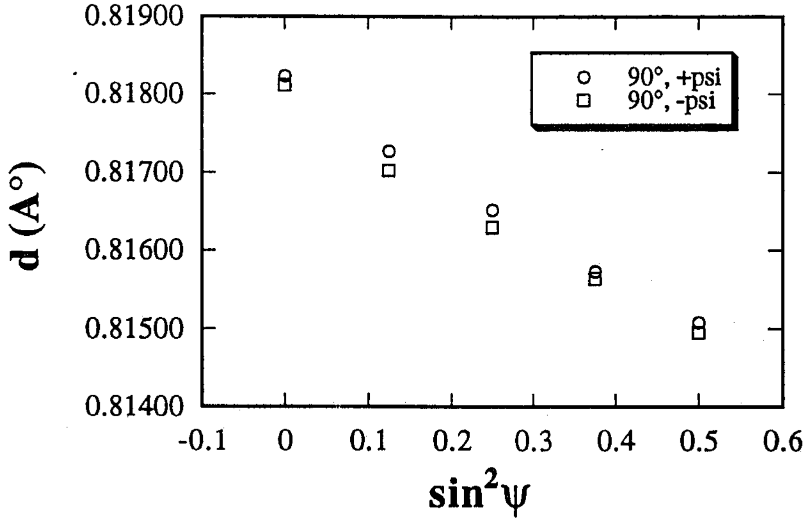


b) ground

Figure 7 Micro View of the Traditional Machined Surfaces



a) specimen AWJ(a) with $\phi = 0°$



b) milled specimen with $\phi = 90°$

Figure 9 Plane Spacing and Lack of ψ Splitting from Diffraction Measurements

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Paper **28**

DEVELOPMENT OF THE CUSP MINING TOOL FOR AUTOMATED UNDERGROUND EXCAVATION

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ABSTRACT

Previous work has shown that the use of a waterjet slot to create a free surface in a rock face will allow subsequent excavation of large fragments of rock, weighing up to 2000 lb. A self-propelled slotting and drilling tool with capabilities for splitting and fragmenting the rock has been developed, known as the CUSP Miner (for Cut and Split).

The slotting tool uses an abrasive waterjet for both cutting the slot and drilling the rock. Particular problems with lance stabilization have been identified and the design enhanced to overcome these for surface operation.

The low reaction force of the abrasive waterjet produces a sufficiently low reaction force that the machine can be automated both for steering and for operation of the hydraulic arm. The robotic system will use a combination of sensors to form a detailed picture of the rock face to be excavated. Ultimately the computer will then form an operational plan which it will use to control the robot tooling to achieve the maximum possible rate of excavation.

Organized and Sponsored by the Water Jet Technology Association.

1. INTRODUCTION

1.1 Previous Work on the Cut and Split Excavation Method

The Cut and Split Method of rock excavation was initially developed for use in creating space for a new theater underneath the Gateway Arch in St. Louis, Missouri (Yao et al., 1991). The rock was first drilled within 60 to 90 cm of a free face, then the rock was split using a hydraulic feather splitting tool. The developed crack usually did not liberate the rock and the split was then followed by activation of a light duty impact breaker which was inserted into the bore hole. Activating the splitter generally broke the rock from the solid within a minute. The rock was broken into large pieces, weighing up to a ton. These pieces were loaded out using an overhead tram and 1 cubic meter buckets. A total of 2100 m^3 were removed. An abrasive waterjet was used to trim the walls to within 5 cm of the existing foundation width over a height of up to 4.5 m.

At the time of the Arch project, all steps of this operation were performed manually, requiring tremendous amounts of set up time. For this technique to be of more value, an automated robotic platform is the logical choice for drastic improvements in process speed. The machine being built to improve this process bears the name CUSP Miner (CUt and SPlit Miner).

2. OBJECTIVE

This vehicle was developed for use in the excavation of any type of rock. The abrasive jet drill used on this machine is capable of drilling over 122 cm/min in dolomite, and 15 cm/min in basalt. It uses a 35 MPa (5000 psi) waterjet with directly injected abrasives (Fairhurst et al, 1986) for drilling and slotting of the rock face. The low thrust forces of this waterjet drilling system allows the use of a lightweight mechanized vehicle for the application of the abrasive jet within the working area. The small size of the vehicle makes it capable of working in more confined areas than conventional automated drilling equipment. The robot in **Figure I** is approximately the size of a conventional automobile.

All of the heavyweight components of the system reside elsewhere on the site. For portability a large capacity water tank, a generator, and a high pressure water pump were mounted on the bed of a semi trailer (see **Figure II**).

The use of steel shot as an abrasive allows recycling of the abrasive using a magnetic separation system, and a continuous operation of the system. The abrasive is separately charged into a pressure vessel (**Figure III**) from which it is metered into the high pressure line. Two cylinders are used so that one can be charged while the second is in use. The water, rock chips, and abrasive are returned by a vehicle mounted jet pump. When they are returned they are fed into the funnels on the top of the injection apparatus.

The vehicle is powered by a three cylinder, 13.4 kW (18 hp) diesel engine, driving a hydraulic system that powers propulsion and drill manipulation. The body, with tank treads, is from a Snowcat all-terrain vehicle. The flexible 6 axis arm can position the end effector to work on walls, ceilings, or floors. The arm has a 180 degree sweep from side to side and a reach of 2.5 m. This arm can be used in a slotting configuration to cut on floors (**Figure IV**) or walls or as a drill.

The techniques which have been developed and separately operated must now be distilled into an orderly formulation that can be executed autonomously by a controlling computer. The control program must continuously adapt to the changing environment in real time for the project to be worthwhile. This is the goal of the CUSP Miner Automation Project. A human operator can drive the vehicle and perform all the operations but the human operator will get tired and require rest stops. A human operator is also likely to "eyeball" each operation, resulting in a less than optimal rate of excavation due to repeated correction of placement of the tool and latency periods while trying to determine the next slot or drill placement.

Proposed applications for the equipment as described above include coal mining, gold mining, and excavation in delicate environments. One particular application intends to use the equipment to perform excavation of rock in a cave where the delicate geology prohibits use of more violent techniques.

3. EQUIPMENT DESIGN

3.1 Mechanical Aspects

The CUSP Miner was built around the basic platform of a Snowcat Snowmobile. It consists of a dual rubber track design. The vehicle is driven in traditional tank tread fashion, that is thrust steering by individual control of the tracks. The master plan of the CUSP Miner is shown in right isometric view in **Figure V.**

The platform was modified extensively in a number of ways. First, a three cylinder diesel engine was substituted for the existing gasoline engine to result in a safer emissions combination for humans working underground. The engine is to be regulated by the controlling computer and drives a hydraulic pump from which all motor power is derived for the tracks and arm and drill mechanisms. The arm is a 6 degrees of freedom unit with the addition of a flexible end effector that can be used as either a drill or slot maker. Currently the end effector requires manual retooling in order to switch configurations between drill and slotting applications.

The drilling and slotting tooling at the end of the arm uses high pressure abrasive waterjets to cut the rock. The drilling bits have three tungsten carbide nozzles with a polycrystalline diamond insert. The use of this arrangement results in drilling speeds three times conventional drilling rates.

Each hydraulic assembly will be actuated by servo valves which will be driven by a host computer. The resulting movements will come from either control algorithms in the software or by movements directed by the human operator, giving the option of either automatic or manual operation.

3.2 Computer Control and Electrical Configuration

The control software resides on a Macintosh PowerBook 520c at a remote site and will be tied to the robot by a serial cable link. The remaining control electronics are located in a watertight box on the robot itself.

Each joint on the arm has a sensor for internal feedback of position or angle. Bending joints use the voltage drop across a potentiometer to measure angles. Each of the track assemblies will have movement measured by an incremental encoder because the important consideration in that case is how much the tracks move relative to each other.

In order for the CUSP Miner to interact effectively with its environment, an array of external sensors which attempt to give redundant data is necessary. The imaging system currently scheduled to be implemented is to use an array of ultrasonic range finders supplied by Polaroid to produce a three dimensional map of the surroundings. There will need to be a range finder for coarse mapping and a sensor for detailed mapping. Coarse mapping is used to determine position inside of the mine at large. Detailed mapping will be used to produce a close picture of the particular rock face that the CUSP Miner is currently working on. It is from this picture that decisions on tool placement will be made.

3.3 Software Design

The central control program for the CUSP Miner is being written in Symantec Think C++ 7.0 for Macintosh. There are several functions of the control software. They are to provide an interface to the user, to serve as a coordinator for complex motor control, to take in and process sensor data to produce a mathematical model of the environment for the robot, to allow the robot to navigate its environment, and ultimately to form and execute operation plans to achieve the maximum possible rate of excavation of a rock face.

3.3.1 User Interface

The control program layout to the user is fairly simple and easy to use. There are separate windows for graphic display of arm telemetry and vehicle mounted user controls as well as a command line window from which commands and equipment status requests can be issued at the prompt. In each of the telemetry windows the current status of the device being monitored is displayed. At present the arm is represented as a stick figure drawing with key locations labeled. The status of the driver's controls is displayed also. There will also be a window to display what the robot perceives as the world in front of it as interpreted by the navigational and rock face mapping sonar. The data will be displayed as a surface map.

3.3.2 Motor Coordination

The arm used on the CUSP Miner for the drilling and slotting operations has 6 degrees of freedom built into the arm and wrist. The end effector has tool feed and tool rotate functions. The forward kinematics of the waterjet boom arm, yielding the position and orientation of the end effector, given a set of control variables, are derived in the following manner.

The waterjet boom link frames diagrams are shown in **Figure VI** and **Figure VII**. Each of the values d_3, d_5, a_6 in the link frame diagrams remain constant in all configurations. The value d_6 changes depending on the configuration, but is treated as a constant in the calculations. The values q_1, q_2, q_3, q_4, q_5, q_6, and d_7 are treated as variables in the calculations. The primary difference between the slotting and drilling configurations is that the waterjet lance directions differ by 90°. The link parameter table for the arm excluding the end effector is shown in **Table I** from which we determine the "A" matrices from which we calculate the forward kinematics of the arm. The base form of the A matrix is shown in **Equation 1**.

Equation 1.

$$A_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Using this basic form we determine A matrices for each of the links A_1 through A_6 as shown in **Equation 1** through **Equation 7**. For brevity, $\sin q_1$ and $\cos q_1$ are written as S_1 and C_1 respectively. The A matrixes for the end effector in the slotting and drilling configurations are shown in **Equation 8** and **Equation 9**, respectively.

Equation 2. Equation 3. Equation 4. Equation 5.

$$A_1 = \begin{bmatrix} C_1 & 0 & S_1 & 0 \\ S_1 & 0 & -C_1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad A_3 = \begin{bmatrix} C_3 & 0 & -S_3 & 0 \\ S_3 & 0 & C_3 & 0 \\ 0 & -1 & 0 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad A_4 = \begin{bmatrix} C_4 & 0 & S_4 & 0 \\ S_4 & 0 & -C_4 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad A_4 = \begin{bmatrix} C_4 & 0 & S_4 & 0 \\ S_4 & 0 & -C_4 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Equation 6. Equation 7. Equation 8. Equation 9.

$$A_5 = \begin{bmatrix} C_5 & 0 & -S_5 & 0 \\ S_5 & 0 & C_5 & 0 \\ 0 & -1 & 0 & d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad A_6 = \begin{bmatrix} C_6 & 0 & S_6 & a_6C_6 \\ S_6 & 0 & -C_6 & a_6S_6 \\ 0 & 1 & 0 & d_6 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad A_{7slot} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & -1 & 0 & d_7 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad A_{7drill} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_7 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The T matrix for the entire boom excluding the end effector is calculated in **Equation 10.**

Equation 10.

$$T_{boom} = A_1A_2A_3A_4A_5A_6A_7$$

The complete T matrixes for the waterjet boom in slotting and drilling configurations are calculated by substituting in for A_7 the appropriate end effector matrix, A_{7slot} or A_{7drill} respectively.

While in slotting configuration, the approach vector must lie parallel to the slot length and the orientation vector points at the rock face. The tool is initially placed at the midpoint of the slot on the rock face. While in the drilling configuration, the approach vector points at the rock face as the machine drills into the rock. The variable d_7 is treated as a constant for the initial placement of the drill before tool feed is engaged. This constant is the minimum length that the drill can occupy, i.e. the drill is totally retracted.

3.3.3 Sensor Data Interpretation

The robot will use a combination of sensors to form a detailed picture of the rock face to be excavated. The primary sensors used will be an array of ultrasonic range finding units each tuned for a different purpose. Coarse mapping of the environment around the robot is necessary for basic navigation through the mine or tunnel.

Each cluster of sensors is to be mounted on a motorized platform that allows accurate orientation of the sensors, performing basically the same function as a human head does when aiming eyes and ears. A map of the surroundings can be plotted by rotating the sensor cluster about the yaw axis and taking readings at each of some angle increment. Cartesian coordinates are calculated from the distance retrieved from the ultrasonic range finder, Ud, and from the yaw and pitch angles at which the sensor transducer is pointed when the reading is gotten.The map of the environment for the robot is stored as a sparse array. Each element in the array is a point that was detected as an obstruction by the ultrasonic range finder.

3.3.4 Vehicle navigation

There are a few basic exercises the CUSP Miner will perform when navigating a mine or tunnel. The robot will generally move in one of three ways: rotating about its own axis, traveling in a straight line, and traveling in a curved path. For the robot to rotate about its own axis, it must first determine if the solid of rotation of its own body ranging from the start and stop angles of the rotation is free of obstructions. For the robot to travel in either a straight or curved path, it must plot this path forward from the beginning and ending coordinates and then determine if there are any obstructions in this intended path. Essentially the robot must plot a hollow corridor to follow.

To maintain accurate movements along these intended paths, the treads will be driven by the speeds of the tracks relative to each other. The straight path becomes an instance of the curved path with the curvature being zero. Differential track speed will be continuously monitored and corrected as the robot proceeds along the path. Uneven surfaces certainly will cause difficulty in this respect as slippage occurs, so the best way to determine the true heading will be to use solid state gyroscopes to determine orientation. Course corrections will be made according to those readings so that the intended path can be followed.

4. STREAMLINING THE EXCAVATION PROCESS

The excavation process consists of 4 types of activities. These are drilling, slotting, splitting, and rock removal. First the slot is cut across the rock face then several holes are drilled on either side of the slot at regular intervals as shown in **Figure VIII**. A feather wedge splitter is used to create cracks from each hole to the slot. The final extraction uses a lightweight impact breaker. The chunks that fall out must now be hauled away.

4.1 The First Step in the CUSP Process - Drilling

The drilling arrangement is the most straightforward of the four. First the arm positions the tool with the drilling lance angled perpendicular (or approximately perpendicular) to the face. The high pressure water pump is brought up to the pressure appropriate to the type of rock to be cut. The tool rotation is started and then feed through a friction drive mechanism starts up. Once the maximum hole depth is reached, the drill bit tool is retracted and the arm is withdrawn from the hole.

4.2 The Second Step of the CUSP Process - Slotting

Slotting of a rock face is accomplished with a reconfiguration of the same tooling used for drilling. The feed is still about 6 feet but the water jet lance is shorter and arranged perpendicular to the feed direction. The water jet is brought up to pressure and the lance is moved across the surface of the face. Then the lance is moved into the depth of the slot made by the first pass and another pass is made to increase the depth as shown in **Figure X**. The lance moving across the scar of a previous cut is shown in **Figure IX**. This is repeated until the lance has cut to its full depth.

Particular problems with lance stabilization have been identified and the design enhanced to overcome these for surface operation. When in the slotting arrangement, a point of concern is the occurrences of the slotting tool snagging itself in the irregularities in the previous pass of the slot being cut. In case of a snagging situation, strain sensors indicate to the robot that it should back off the feed in that direction and make a shallower pass in order to cut out the ridges and continue to make complete passes. The ideal circumstances for cutting a slot are to run the cutting lance across the surface to receive the slot and to have a perfectly smooth channel in the rock as a result. **Figure XI** shows this ideal situation when cutting a slot in rock.

4.3 The Third Step in the CUSP Process - Splitting

At this time a human operator must place the feather wedge splitter into each hole and start and stop the hydraulic control of the splitter. This splitter will be placed on a second arm on the machine at a later time. The rock will crack towards the free face that was just created by the slot. As you can see in the top right corner of **Figure IX**, a clean flat edge remains where the rock was removed. After the initial cracks are made in the rock, a hydraulic impact breaker is used to propagate the cracks further, separating the rock chunks from the rock face more completely.

4.4 The Last Step in the CUSP Process - Rock Removal

At this point in the development in the project, there are only plans for automating the process for examining the rock face, making the cuts, and breaking out the rock. Between cycles of said process the rock must be hauled away by human driven machinery such as a small tractor or Bobcat. After the debris of each excavation cycle is cleared away, the process can begin again.

5. FIELD TRIALS

Use of the CUSP Miner equipment in the field revealed a few of the strengths and weaknesses of the process and of the equipment.

5.1 Testing at the Sandstone Quarry

The first attempts at using the machine to excavate a volume of rock were made in a sandstone quarry just outside of Rolla, MO. The machine was first tested for drilling ability by drilling horizontal holes in a rock face. These were straight holes 3 cm in diameter and 2 meters deep drilled with a rotating waterjet drill bit with polycrystalline diamond drill bit inserts and without abrasives in the jets.

The first difficulty noticed with the drilling was the problem of stabilization of the drilling lance tip on the rock face. The drilling lance is mounted on a linear feed track which has a spike on the front end, to allow the sash to "sting" into the rock. Before drilling is begun, the spike is thrust towards the rock face in order to anchor the drilling rig. Because the high pressure water jets come out of the drill bit at angles, the jets torque the arm from side to side as the drill bit rotates resulting in the drilling lance having a tendency to "walk" across the surface of the rock face before penetration begins. This anchor is intended to suppress this, but is not always successful if the spike cannot be well anchored in the rock face. Once the drilling lance penetrates the rock face, the lance remains stable for the duration of the hole drilling.

Next slotting was attempted. The slots made were cut into the floor of the quarry and made in about eight passes 2 meters wide. Each pass deepened the slot by approximately 5 cm. It is in these tests that the problem of the "snagging" on the rock made itself apparent. To overcome this problem, a hydraulic cylinder was placed at a leverage point on the lance in order to determine the torque on the lance created by the lance moving through the slot. Whenever the lance gets snagged a moment is created on the lance which can be measured by the change in pressure on the hydraulic cylinder. These pressure readings will be used by the software to control the feed on the slotting tool to back off and try again so the equipment does not damage itself.

5.2 Testing at the UMR Experimental Mine

Additional testing is in progress at a quarry at the UMR Experimental mine. The rock at this site is composed of dolomite and was penetrated at a much slower rate despite the use of silica sand abrasives. The problem of the "walking" drill bit was more pronounced in this rock because the rock was harder and did not allow the spike to anchor into the wall as well. A better abrasive such as steel shot would have improved penetration and reduced the "walking" of the drill bit substantially. The faster the initial break in the surface, the less chance of "walking" occurring.

6. CONCLUSIONS

Several things have been learned from the development of the CUSP Miner thus far. The difficulties associated with the irregularities in the rock causing the "snagging" in the slots and the "walking" of the drilling lance caused by the waterjets torquing the arm over to the side, add complexity to the control software to compensate for the real world differing from the mathematical model stored in the computer.

The course of action intended from what has been learned so far is to further enhance the stabilization of the waterjet lance during performance of these activities. The primary concerns are the moment produced by the waterjets on the lance and the moment produced by the rock inhibiting movement of the lance.

7. ACKNOWLEDGMENTS

Thanks are extended to the Generic Mineral Technology Center - Mine Systems Design and Ground Control of the Virginia Polytechnic Institute and the U.S. Bureau of Mines as the major source of funding of the CUSP Miner project.

Thanks to Dr. Peter C. Y. Ho of the UMR Computer Science Department for his instruction on robotic control geometries.

Thanks to James A. Nowacki, CPG of R.E. Blattert & Associates - Geologic / Environmental Consultants for the donation of sandstone used in our drilling and slot cutting trials with the CUSP Miner.

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14. FIGURES, TABLES, AND ILLUSTRATIONS

Table I. Waterjet Boom Link Parameter Table.

Link	**Variable**	a	**a**	**d**	**cosa**	**sina**	
1	q1		90°	0	0	0	1
2	q2		90°	0	0	0	1
3	q3		-90°	0	d3	0	-1
4	q4		90°	0	0	0	1
5	q5		-90°	0	d5	0	-1
6	q6		90°	a6	d6	0	1

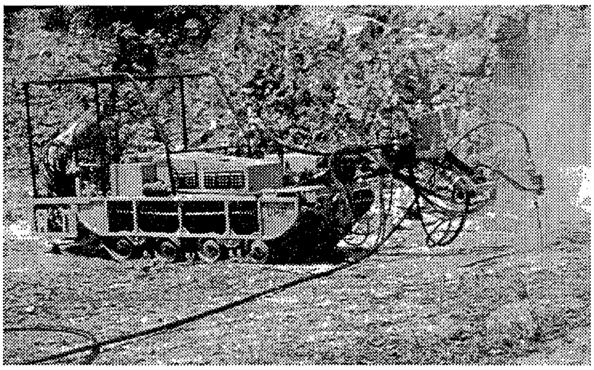

Figure I. Photograph of the CUSP Miner on a surface test.

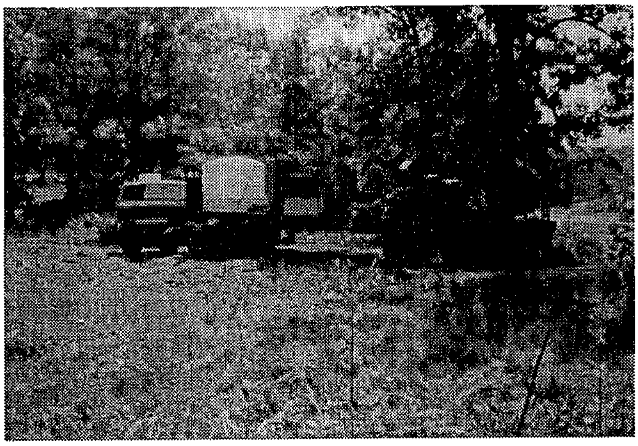

Figure II. Photograph of Support Trailer with Pump, Generator, and Water Supply Tank.

Figure III. Photograph of Diajet Abrasive Injection Apparatus.

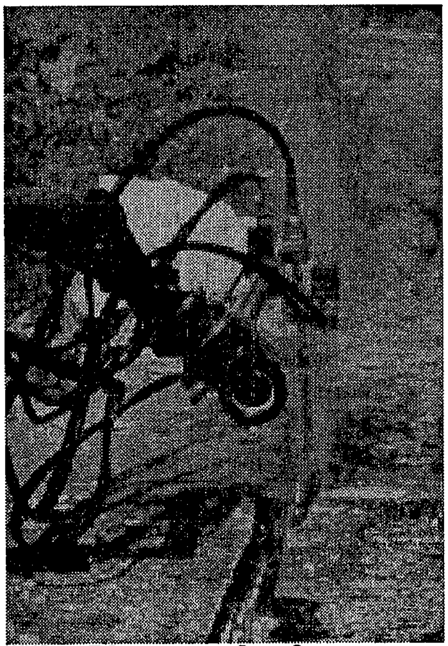

Figure IV. Photograph of slot cutting in progress.

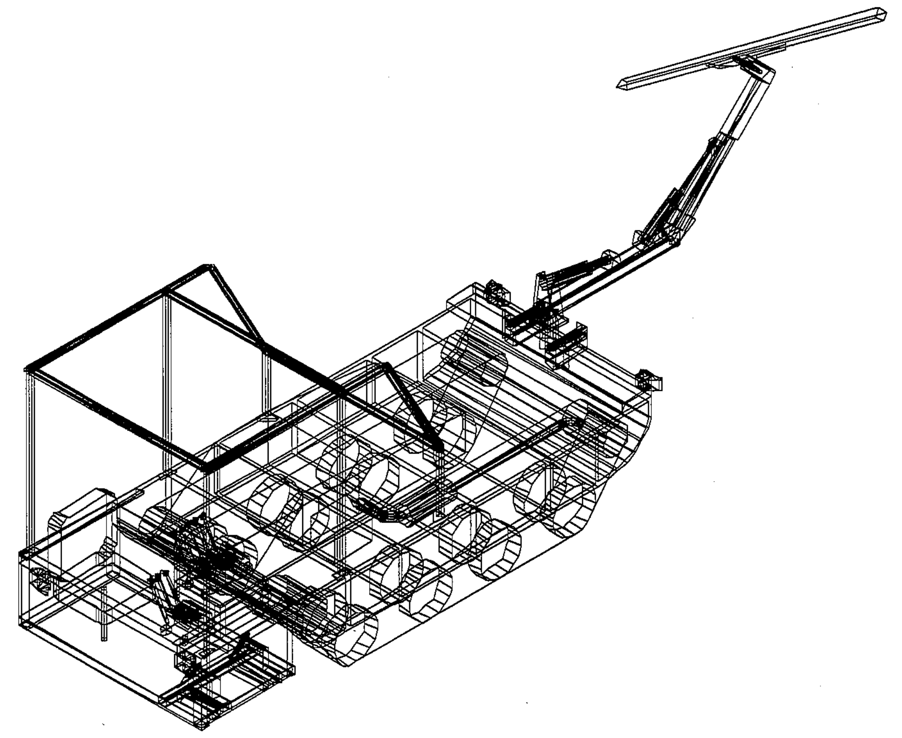

Figure V. Illustration drawn in MiniCAD 5.0 of CUSP Miner shown in right isometric view.

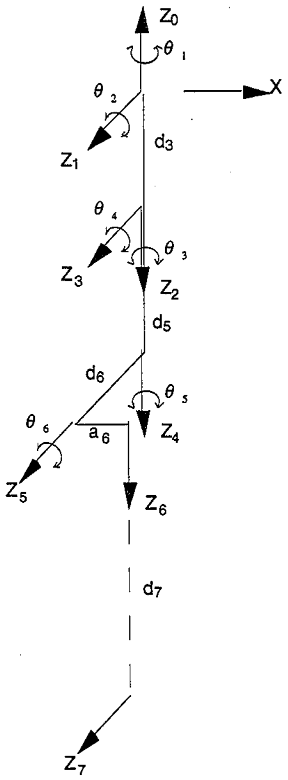

Figure VI. Waterjet Boom Link Frames Diagram for Slotting Configuration.

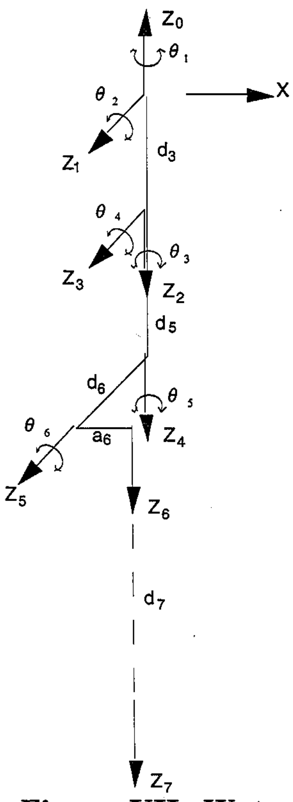

Figure VII. Waterjet Boom Link Frames Diagram for Drilling Configuration.

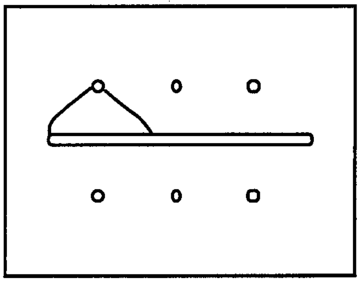

Figure VIII. Excavation Pattern

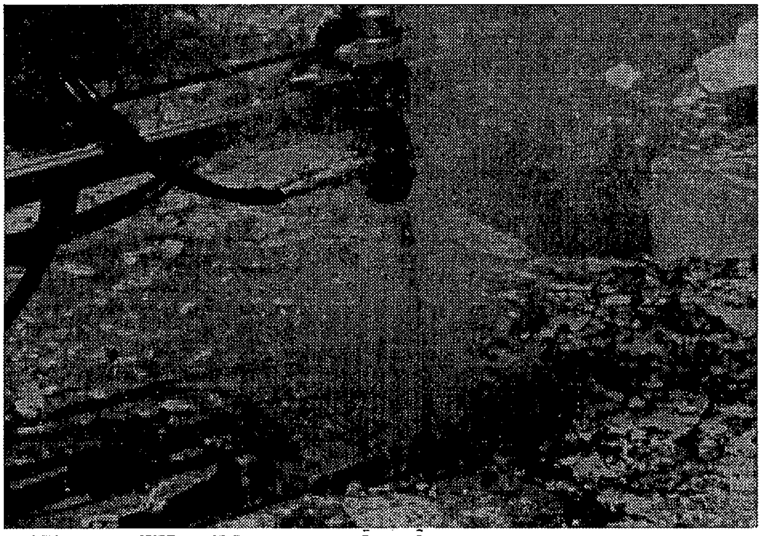

Figure IX. Photograph of Waterjet Slot Cutting.

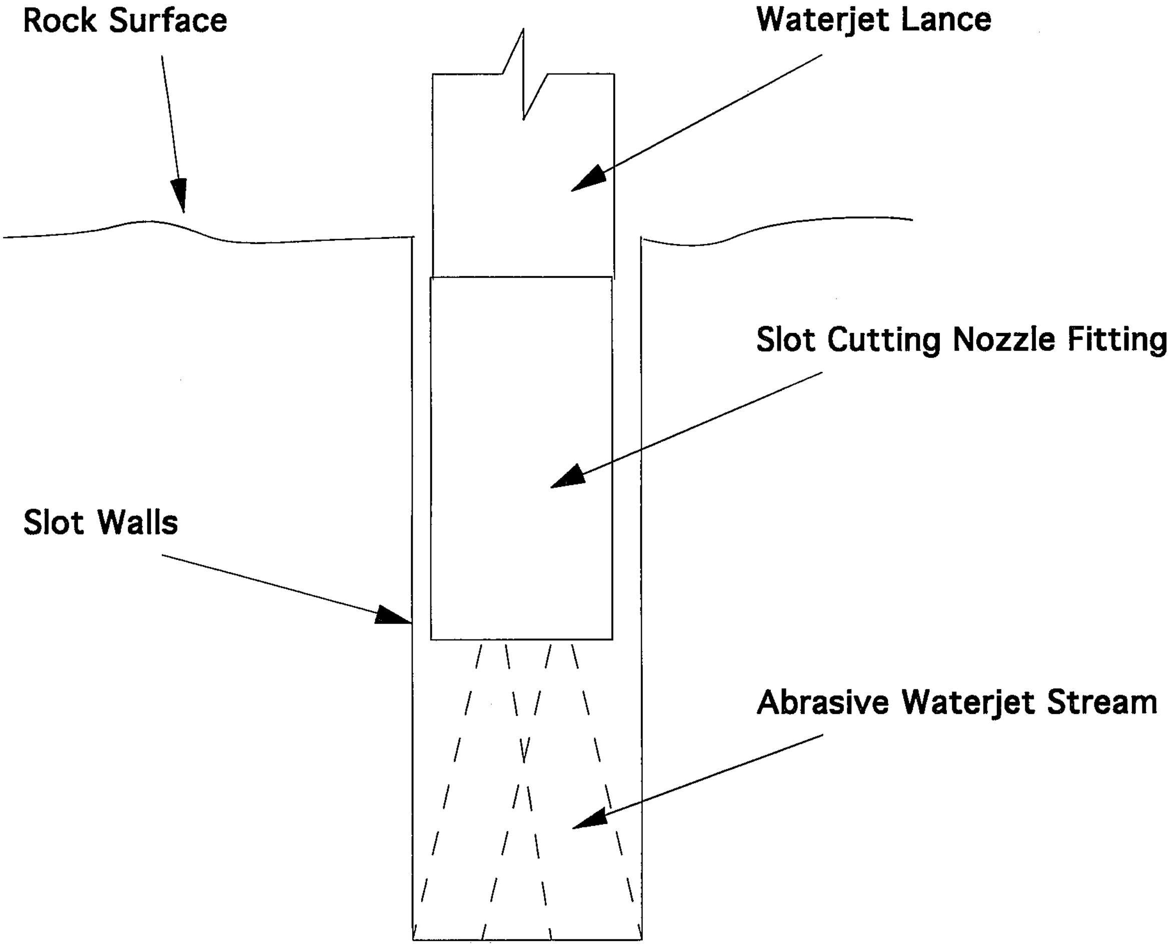

Figure X. Illustration of Slot Cutting by Multiple Passes of Rotating Abrasive Waterjet Lance.

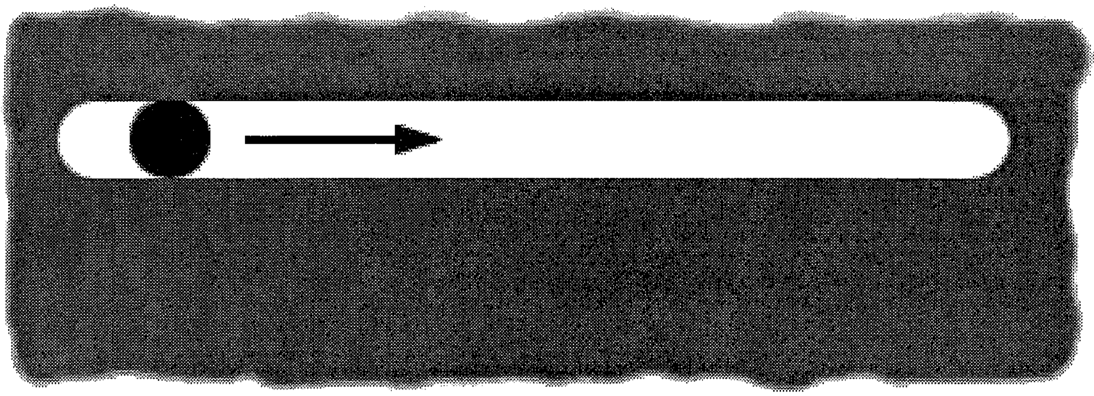

Figure XI. Illustration of Moving cutting lance through scar of previous slotting pass in best case scenario.

8th American Water Jet Conference
August 26-29, 1995: Houston, Texas

Paper **29**

HYDRO-DEMOLITION AN ALTERNATIVE METHOD FOR CONCRETE REMOVAL

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ABSTRACT

What is vital for the success of Hydro-demolition technology is to focus on the long term benefits - as applied to concrete repair. Research and development has improved dramatically in most aspects of concrete repair - new materials, new methods, new types of protection for reinforcing steel, a better understanding of the corrosion mechanism, new sealers and membranes all contribute to long lasting repairs. When dealing with structures having service lives measured in decades, it would be a serious error to discount or overlook this non-destructive removal method... simply because the emerging technology seems complex, perhaps misunderstood and at present exhibits slightly higher short term costs. It is well known in the construction industry that impact percussion tools generate damage that often extends well beyond the proposed repair area and can further accelerate deterioration which may affect the performance of the overall structure. To draw comparisons to conventional removal methods (i.e., jackhammers, hydraulic rams, planers and scarifiers) is difficult since the primary reason for selecting hydro-demolition is the need for non-destructive, non-impact, structurally safe concrete removal.

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1. INTRODUCTION

1.1 Hydro-Demolition?

Definition - Removal of concrete by a wide variety of pressurized water equipment.

2. BACKGROUND

Before 1900	Early placer mines used volume pressurized water to separate overburden from ore.
1937	Russian engineers developed a water canon which,when point loaded, fractured hard rock.
1950's	Hand held water blasting and steam tools were used for cleaning in many industries: - Mining - Petro-chemicals and Oilfields - Marine - Pulp and Paper
1961	The Swedish, Italians and Germans began using pressurized water on construction retro-fit projects namely surface prep on bridge decks, piers, wharfs and other tasks related to concrete repair or restoration.
1963	In North America, Dr. Franz and others were experimenting with water cutting of the frozen tundra and discovered that by entraining abrasive into the water stream, the tundra cut quicker. This lead to many early experiments using pressurized water/sand to cut other materials (concrete, stone, composites and metal).
1967	Improved pumps and hand held tools were becoming more common and as pump pressures increased, concrete was being removed to varying degrees.
1970	Early in the '70s the first semi-automatic positioning beams were used to hold and position water-jets. Pump manufacturers (European & American)were modifying equipment to increase pressures and flows.
1980	Water cleaning and surface preparation was becoming a preferred cleaning method in all types of industries.
1985	Ten to fifteen manufacturers worldwide were producing 10,000 psi to 15,000 psi pumps of various flow rates using hand held and push tools to clean and in some cases remove concrete; however, safety concerns, work place hazards and production rates demanded automated systems.

1986 Water Jet technology flourished, with Hydro-demolition systems gaining acceptance in Canada and the US.
Most manufacturers were producing new nozzle designs, higher rated pumps, better hose, and improved applicator systems which generally consisted of:
- Diesel Engine
- A Pump (15,000 PSI to 30,000 PSI)
- Remotely operated control system

1990 Water-jetting technology continues to improve, pumps, high pressure hoses, robotic applications and associated parts are more reliable.

Robotic applications of Hydro-demolition systems have completed many concrete removal tasks safely and efficiently.

Controlled removal of various depths are achieved on horizontal, vertical and overhead surfaces:
- Bridge decks
- Parkades (suspended slabs)
- Dam walls and slopes
- Pier faces and caps
- Expansion joints
- soffit and capitals
- cement and grain silos
- Hole boring (various sizes)

Today systems generally consist of:
- Larger diesel engines with silencers
- Higher pressure pumps (to 60,000 psi)
- Remote controlled applicators
- Waste water collection systems
- Vacuum removal of cut debris

1994 To Date Improving water-jet technologies will result in:
- Quieter systems
- Less water consumption
- Higher pressures
- Improved robotics and positioning devices
- "ph" balance recirculating waste water processing system
- Reduce cement paste to cake for re-cycle
- Increased removal rates result in lower costs

3. WHY USE HYDRO-DEMOLITION?

In considering the use of Hydro-demolition systems as an alternative method for concrete removal some concerns included in the condition survey would be:

- Size of project & expected performance life
- Production rates required by schedule
- Structural condition of the structure under repair
- Noise and dust requirements
- Compliance with environmental health and safety, general public
- Water supply
- Waste water treatment
- Repair materials and strategy

4. BENEFITS OF HYDRO-DEMOLITION TECHNOLOGY

In using Hydro-demolition technology you can achieve the following benefits:

- Removes unsound concrete selectively without damage to adjacent areas.
- Descales, cleans and clearances reinforcing, in one operation without disturbing the reinforcing grid.
- Creates an edge with slightly under cut vertical, for improved consolidation of repair material.
- Saves labor and reduces costs.
- Eliminates structural vibrations as well as dust and high noise levels.
- **Achieving an adequate bond between repair materials and existing concrete is a critical requirement for durable repairs.**
- The condition of the interface zone where the repair material joins the substrate forms the foundation of the repair.

The mechanical anchorage interlock is further improved in several ways:

- A roughened, relieved profile increases the bond line contact area.
- The sound, fracture free, exposed washed aggregate allows bonding agents and slurries to adhere.
- Opening the pore structure of the cement paste removes laitance, contaminates, fines etc.
- Seeks out hidden points of weakness (i.e., cracks, voids, honeycomb).

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8th American Water Jet Conference
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Paper 30

MULTIPURPOSE MOBILE PLANT FOR DEMILITARIZATION

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ABSTRACT

Demand for demilitarization equipment that is capable of being taken to site, used and then taken off site with the minimum of delay is increasing. The flexibility of such equipment is of paramount importance, the ability to cope with a varying stock of munitions with safety and environmental considerations being of primary concern.

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1. MUNITIONS DISPOSAL IS A PROBLEM THAT IS INCREASING

1.1 Why?

There is a general easing of tension between countries.

There is a reduction in armed forces strength and thereby material strength reduces alongside it.

Weapons obsolescence is increasing as weapons technology increases.

To be able to continue with the sales of munitions, policies of manufacturers will include buy back of old munitions on a new for old basis.

Storage and maintenance is becoming more and more expensive.

Environmental pressures are causing governments and companies alike to look very seriously at previously ignored problems, such as dumped offshore munitions, buried munitions, old stored munitions and the particular problem of the unknown and then discovered munitions.

All of these reasons and others are resulting in increased pressure to find economic, environmentally friendly, safe methods of disposal of the ordnance.

There are methods available which will help in the reduction of some of the vast quantities of munitions that exist, but special technologies and techniques have had to be developed and they do not always suit all situations and problems.

A way forward that meets the criteria of safety with economy and with considerations for the environment has had to be developed and **ALBA INDUSTRIE** have risen to meet that challenge.

2. ALBA INDUSTRIE DISPOSAL PHILOSOPHY

1. **All considerations must be given to ensure that the disposal/destruction of the munitions is environmentally acceptable and economically viable.**
2. **Munitions of varying types, sizes and shapes can be catered for.**
3. **The optimization of the equipment is considered from the use of the best technology, processes and systems available at the time.**
4. **Relevant legislation, regulations, local considerations and area compliances are met and adhered to when developing a concept and subsequently a demilitarization system.**

The disposal therefore represents a complex and complicated process where deactivation and demilitarization takes place.

To accomplish this task a requirement for buildings, installations and facilities has to be made, these buildings being constructed to exacting standards with regard to safety in the processing of explosives.

In all cases special working practices have to be adopted and adhered to, these all adding to the expense and costs involved in a project of this nature.

3. ALBA INDUSTRIE DESIGN CONCEPT

Based upon:

Safety aspects based upon possible problems with:

- Transportation of munitions to licensed site.
- Possible secondary handling problems. (Old munitions, discovered munitions etc.)
- Personnel activities, requirements and availability.
- Possible secrecy problems.
- Environmental problems with movement of munitions from a tolerant site to a site where activities of EOD may cause concerns because of materials arriving on a regular basis.
- Transportation of munitions can put the population at possible risk.

4. TAKE THE EQUIPMENT TO THE PROBLEM. NOT THE PROBLEM TO THE EQUIPMENT

This concept means that by being mobile, savings in setting up and running a purposely built site are made.

Safety considerations are easier to make as the sites where the munitions are kept are usually remote.

Environmental issues can be dealt with on a local level and on a temporary basis with best available techniques being employed for site cleanup on finishing the munitions disposal.

All items are self contained, this means ease of use, ease of maintenance, remote operation is made easy by setting the equipment where it is required, with control cabins and personnel well away from problem areas.

Handling equipment can be designed to cater for all types and sizes of munitions, such as:

- Bombs
- Mines
- Rockets
- Ammunition
- Detonators

- Packaging

5. MOBILE PLANT DESCRIPTION

The system can be designed as big or as small as is required because of its unit construction concept.

By utilizing standard ISO containers, "block building" of a system tailored to suit specific needs can be achieved.

6. BASIC UNITS

6.1 Cold Cutting Supply Unit

This unit is the heart of the system and basically consists of a high flow, high pressure pump driven by a diesel or electric motor, dependant upon requirements.

The EXCALIBUR suspension jet abrasive delivery unit with the pressure capability of 300 to 1000 bar pressure and up to 2.00 mm jet size, plus the various control flow valves and filtration devices that regulate flow and pressure.

6.2 Cutting Unit

This unit contains the cutting table and head with manipulatory control. The manipulator being designed as simply as a single axis passing head cutter with basic standoff initial position control of the cutting nozzle, or as complicated as a multi-axis manipulation system with 3 or more fully controllable axis via the computerized axis drives.

The unit can be designed to accept pre-loaded pallets of munitions which can be loaded and locked into position within the confines of the container or as a separate container which fits up alongside the axis unit.

In both cases the water/abrasive slurry catcher is sited underneath the work area and again can be containerized for ease of transportation and use.

The cutting unit and loader/catcher units can all be used in an alternative loading schedule if so required, that is where the munitions can be conveyored in, positioned, cut and removed in one pass through the units. It depends upon the requirement of the particular client as to how the load/unload sequence is formulated.

By keeping the cutting unit as a totally separated construction, we maintain its flexibility for accepting vastly differing munitions. As different as basic artillery shells up to large diameter rocket motors. All can be cut with the same unit but under different operating parameters.

6.3 Catcher Unit

The collection unit is sited directly underneath the cutting area, and basically consists of a stainless steel tank with protection baffles and plates inside it to protect it from the jet. Full co-ordinate location positions for the incoming munitions whether on a pallet or directly fed via a conveyor unit with fixed beam positions.

The unit is covered to prevent over spray and splash and is water washed to keep any washed out explosive within the confines of the tank area.

Spent slurry falls directly underneath the unit positions and is taken away by a slurry pumping system along with explosive fines to the water settlement and recycling unit.

6.4. Water Settlement and Recycling Unit

Again, this can be as simple or as complex as the client requires it to be or, as the system requires it to be.

A basic settlement system is comprised of a number of water tanks arranged so that water cascades from the first tank through to the last tank over a period of hours so that suspended particles settle out. The final tank is a holding tank which supplies the pump after filtration prior to recycling.

Initially the spent abrasive and explosive fines can be pumped into a slurry holding tank which basically has a sufficiently large enough capacity to hold semi-solids from a number of hours of pumping. This tank is sited over the initial water tank so that the water drains through allowing the slurry to drain off so that it can be transported and either dumped or burnt off through a high temperature furnace to rid itself of any explosive content and the abrasive can be recycled after the addition of new unused abrasive directly into the suspension jet delivery module.

The alternative is to pump the spent slurry into a hydrocyclone separator mounted directly over the initial tank. The hydrocyclone will separate out semi-dry sludge from the water. The sludge can then be transported directly away for dumping or further processing for possible recycling.

These tanks, and hydrocyclone, again are mounted inside ISO containers so that they can be transported and used easily once on site.

6.5 High Pressure Water Washout Unit

This unit takes care of washing out explosive material from munitions that have been opened. By opened the meaning is that the fuse has been removed either by unscrewing it from the main body of the shell or, in cases where this is not possible due to the design of the munitions or age where the fuse has seized in the shell case or where a cut has been made across the rear of the munitions allowing internal access.

The munitions can again be loaded via a pallet containing several pieces or alternatively on a fixed index conveyor system.

Placed over a catcher tank unit the system drives into the exposed inner of the munitions, a rotating high pressure water jet lance which scours the inside of the munitions and removes all of the contained explosive.

The specially designed and developed lance is centered up inside the shell case with a device which locates on the edges of the shell and seals it off so that all the removal is sucked out via a suction line directly to a separator unit

All of the operations once the munitions are in place are fully automatic so that each shell is entered, purged of its contents, and flushed out fully before an index to the next shell takes place.

The resultant sludge is pumped directly to the next stage of the process.

6.6 Explosive Sludge Separator/Water Recycle Unit

This unit is used for dewatering the explosive sludge.

It consists of a central sludge distribution system over a moving belt filtration band which automatically dewaters the sludge allowing the sludge to move towards the end of the unit and tip into a container ready for further processing.

The water is collected in a stainless steel tank underneath the band unit and is pumped out to filtration units prior to storage and re-use.

Again mounted inside an ISO container, this unit can be configured to process various levels and hourly quantities of explosive sludge.

6.7 Filtration Units

The water emerging from the separator system is circulated through a series of filters and a heat exchanger to cool it to a re-usable level, and then finally pumped to a tank receiver ready for re-use.

The filtration units can be containerized or alternatively dependant upon processing levels can be mounted directly onto the input side of the water circuits to the main pump container.

Again dependant upon processing levels it may be required to have two main HP pump sets, one for the supply to the slurry suspension jet, and purely for cutting purposes, and a second for the high pressure and flow for the washout unit.

By utilizing two pumps, simultaneous cutting and washout can be achieved. Also by keeping the abrasive slurry water recycling separate from the washout separation and recycling unit means that either or both systems can run.

6.8 Control

A control cabin directly accepting information from each of the satellite units controls the system; CCTV linking is provided for direct observation under operation.

Each unit can be manually operated if so required but only under guidance and control from the main operations area.

Safety for personnel is paramount; a key card system is used to ensure that personnel such as fork lift truck operatives are out of the area at minimum safe distances prior to start up of any of the system; if key cards are in place at any of the loading/unloading stations and not in the safe distance log in stations then the system is not capable of being started.

The units as satellites communicate via leads running directly back to the control cabin so that full system integrity is maintained.

All service connections such as high pressure hoses, air, water feeds and returns are located within channel sections which can stay on ground level or be buried if so required, again maintaining the integrity of the system.

The nature of the cutting and flushing equipment is such that remote operation is guaranteed, suspension jet units of the type indicated can and have operated successfully at up to 1000 meters away from the cutting heads.

This means that site operation can be easily achieved without vast expense at having to provide accurate sitting positions.

All operations can be moved away from sensitive areas if so required, the system becoming self sufficient with the use of diesel pumps and generator power.

Inaccessible sites become accessible.

Fast response units become a reality.

Uncovered hazards become problems that are easily solved.

Offshore recovery also becomes possible, because the systems are made in stainless steel, able to stand up to the ravages of sea water-plus an added bonus-the systems themselves are capable of being run on sea water so no supply problems, and as the units are self contained and fully isolated, environmental pollution is minimized.

7. CONCLUSIONS

The mobile systems as provided by ALBA industries can be tailored to suit individual needs, they can be as simple, or as complex as is required.

They can be added to as the system and the requirements made of it are developed thus keeping expenditure down to levels that can be afforded.

Previously thought access and process problems become achievable goals and the environmental problems that usually run in parallel become problems that can be overcome.

Rapid response to a critical problem becomes achievable and affordable.

Personnel become used to operation and control of hazardous items giving confidence to end users of the systems.

Deteriorating stockpiles of unwanted munitions can be processed with little impact on the environment.

8. SITE REFERENCES

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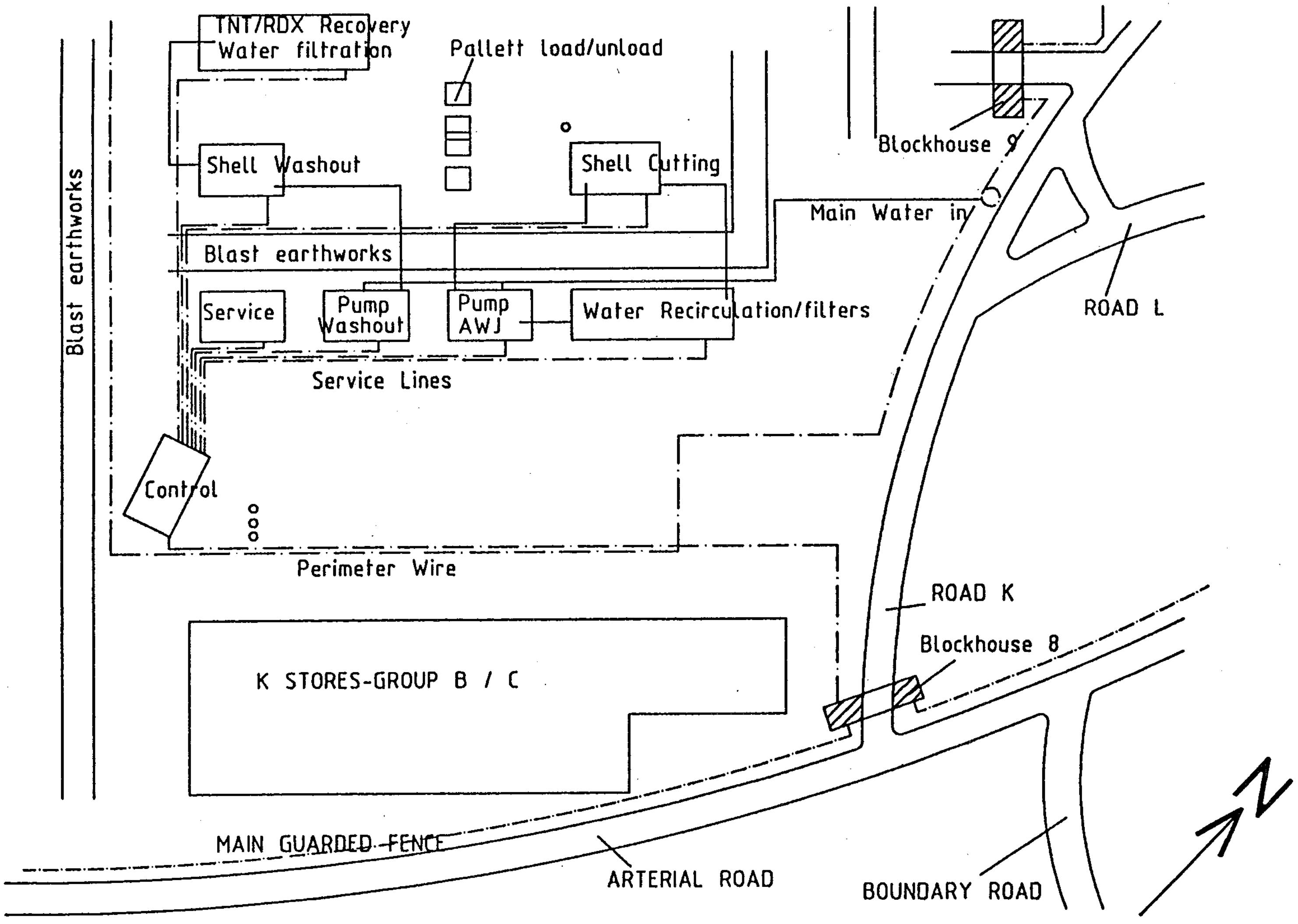
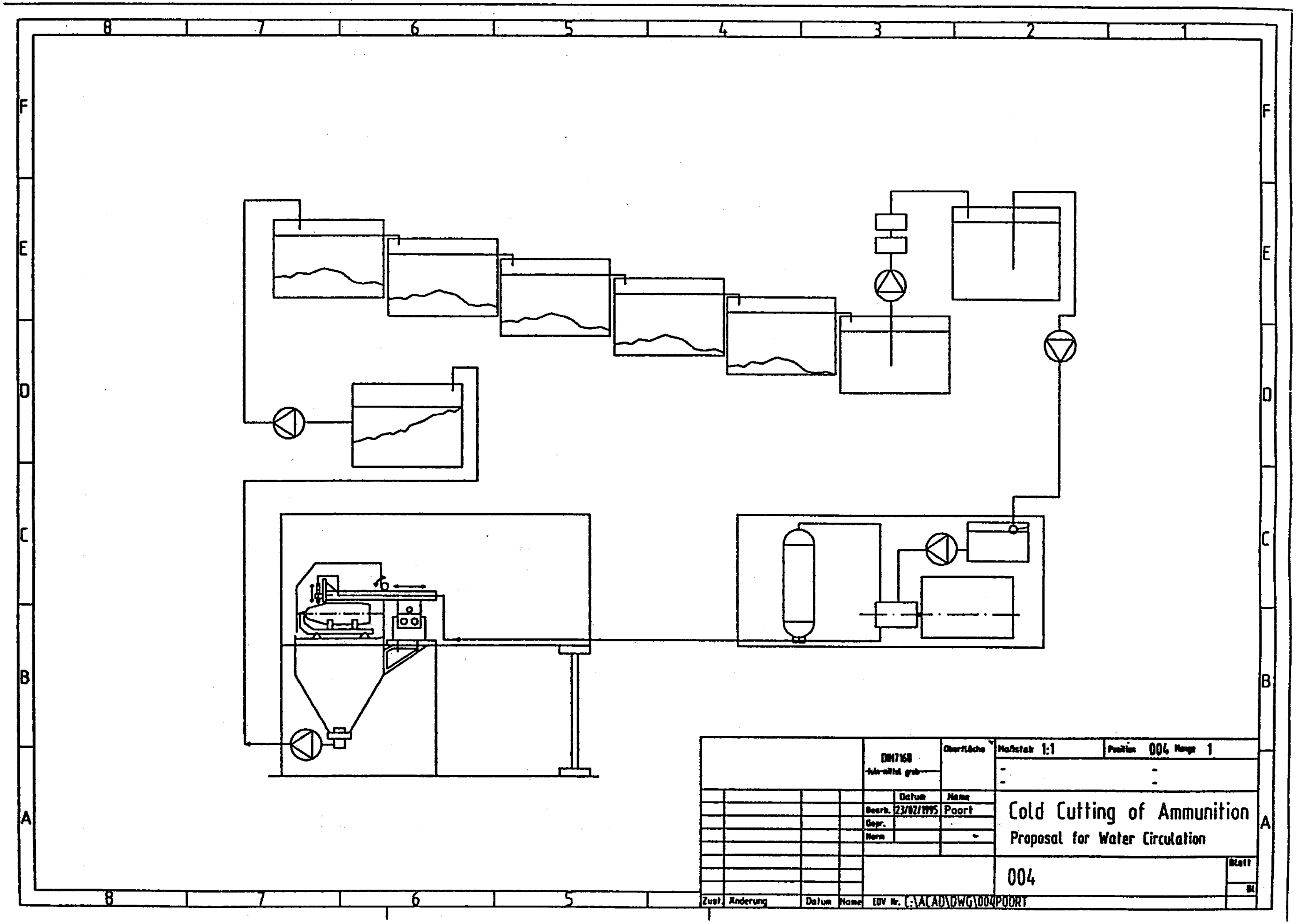


SITE LAYOUT:GROUP B/C MUNITIONS:RECOVERY AREA DELTA: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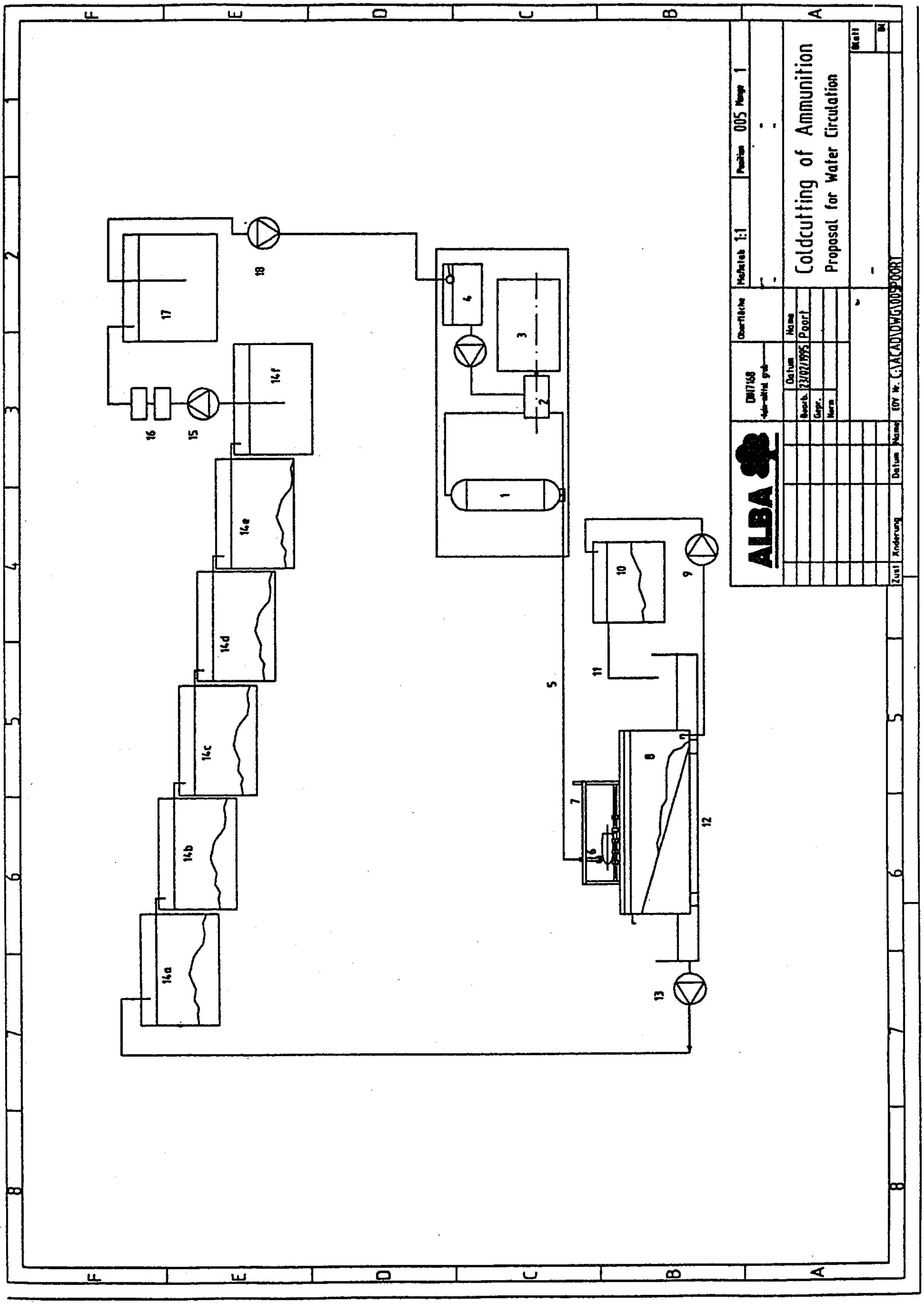
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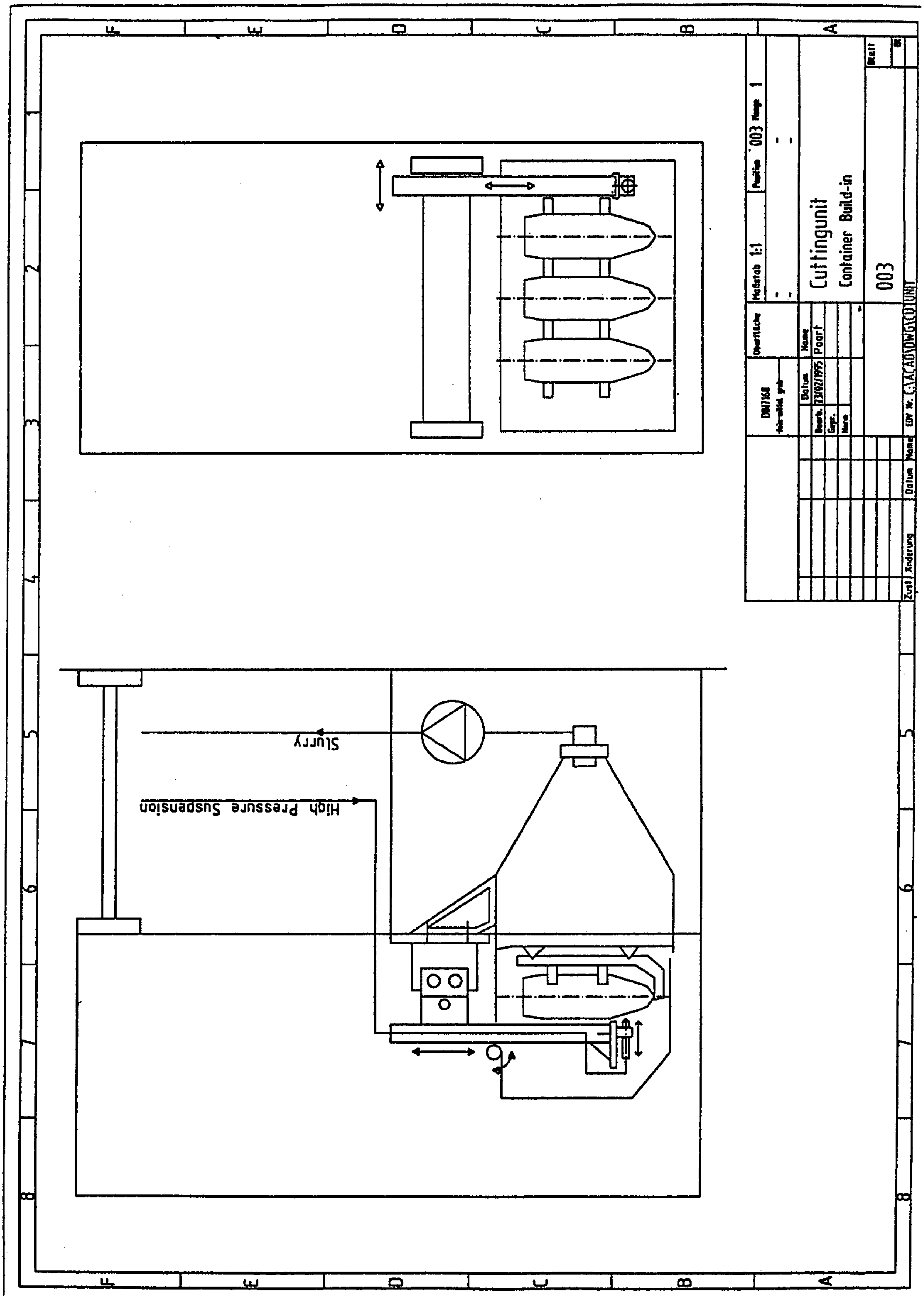
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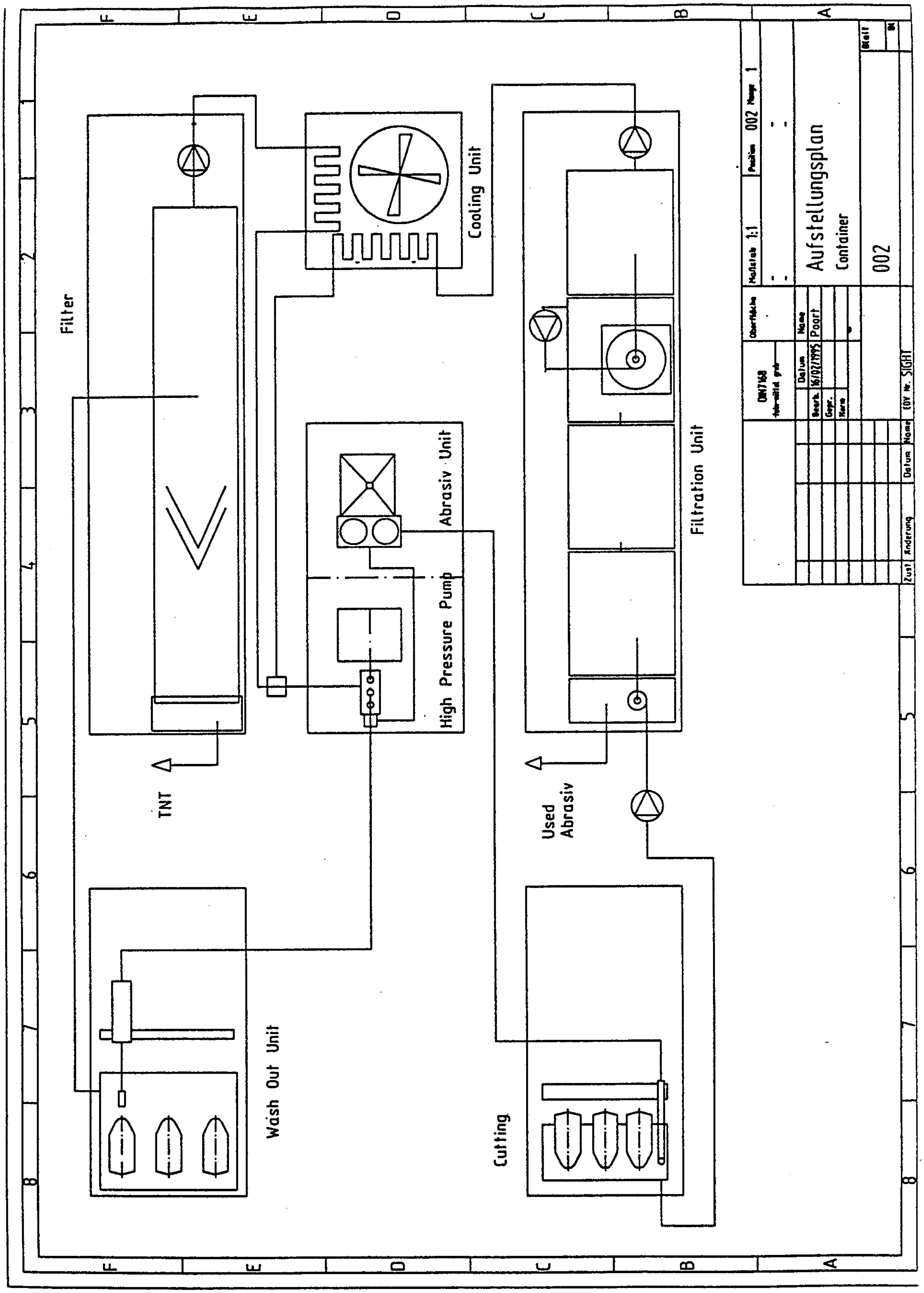
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Abrasiv Unit
High Pressure Pump
Filtration Unit
TNT
Used Abrasiv
Wash Out Unit
Cutting
Aufstellungsplan
Container
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ABRASIVE WATER JETS FOR DEMILITARIZATION OF EXPLOSIVE MATERIALS

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ABSTRACT

Suspension abrasive water jets generated by DIAJET® equipment are an established technique for cutting open and cutting up munitions. The advantage of using DIAJET type suspension abrasive water jets in hazardous situations are discussed and details given of the wide range of explosives and propellants sectioned. The requirements from abrasive water jet cutting equipment are considered along with jet characteristics needed for "safe" cutting. Future developments to meet the needs of the demilitarization community are outlined, including collaborative work to establish "safe" operating envelopes for a wide range of propellants and explosives.

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1. INTRODUCTION

In the past five years many thousands of tonnes of munitions have been cut open and cut up using DIAJET® abrasive water jets. Cutting has ranged from the sectioning of fuses, through shells, bombs and mines to large rockets. As far as is known there have been no energetic incidents caused by abrasive water jets.

In Europe, abrasive water jet cutting has been more widely used for opening up and cutting up of munitions than in the US. For 10 years engineering contractors in Europe have been using DIAJET® (Direct Injection of Abrasive JETing) equipment for hazardous cutting in process plants, refineries, off-shore and sub-sea. It was a relatively simple step to begin using this equipment to cut open shells, bombs, mines and rockets. This has allowed organizations to experiment in cutting munitions without a large investment in equipment. A number of European companies have carried out major demilitarization contracts using DIAJET equipment to cut open and to cut munitions into small pieces for feeding into furnaces.

In contrast, in the US, abrasive water jet cutting of munitions has been carried out using abrasive entrainment equipment developed for manufacturing industries. For reasons to be discussed, entrainment equipment requires a higher quality installation and operating environment than that needed for DIAJET equipment. As a result it has been much more expensive and taken longer for US organizations to experiment in cutting munitions and to build demilitarization facilities based on abrasive water jet cutting.

This paper explains the operation of entrainment and DIAJET abrasive water jet cutting systems. It sets out the advantages and disadvantages of the two methods of generating abrasive water jets. The requirements from abrasive jet cutting equipment are considered along with jet characteristics needed for "safe" cutting. The need for further studies to better exploit abrasive water jets are outlined, including collaborative studies to establish "safe" operating envelopes for a wide range of explosives and propellants.

2. ABRASIVE WATER JET CUTTING SYSTEMS

Abrasive water jets are known as power beams, which include lasers, plasma, and oxy-fuel. In common with other power beams, abrasive water jet involves no direct contact between the cutting head and the workpiece. This means that manipulator forces are low allowing a wide range of manipulation strategies to be used. The advantage abrasive water jets have over other power beams is that they are cold cutting tools that will cut any material and hence can be used to cut explosives with appropriate safety precautions. The disadvantages are low cutting speeds compared to lasers and plasma and the use of water and abrasive, which give rise to contamination and clean up problems. In munitions decommissioning, cutting speed will not usually be a controlling factor. A powerful DIAJET can cut open a 155 mm shell in 90 seconds (Fig. 1). Contamination of propellants and explosive fillers by abrasive can be avoided or minimized by appropriate cutting and manipulation strategies and optimization of cutting nozzle size and operating pressure. Water and abrasive re-cycling are important factors in minimizing clean up problems.

2.1 Abrasive Entrainment Systems

In the 1970's plain water jet cutting became established as a method of cutting soft materials, such as carpets, plastics, food etc. Typical jet diameters are 0.15 to 0.3 mm (0.006 to 0.012 inches). Jet driving pressures of 3000 to 4000 bar (45,000 to 60,000 psi) are provided by ultra high pressure intensifiers driven by hydraulic systems. Many thousands of plain water jet cutting systems are installed on production lines in automobile, food, furniture and other mass production industries.

Once ultra high pressure pumping equipment had been developed for plain water jetting it was a relatively low cost development to add an abrasive particle entrainment head, to the water nozzle, to produce an abrasive water jet cutting capability.

Fig. 2 shows a schematic arrangement of an entrainment cutting head. Typically an intensifier pumping system feeds 2 to 5 litres (0.5 to 1.3 US gals) of water per minute, at 3000 to 4000 bar (45,000 to 60,000 psi), to a cutting head assembly. The cutting head has a primary nozzle of 0.15 to 0.2mm diameter that creates a water jet moving at 700 to 900 m/s (2000 to 3000 ft/sec). This jet is focused into a mixing tube of 0.8 to 1.5 mm (0.03 to 0.06 inches) diameter. The water jet acts as an ejector (jet pump), sucking air into the cutting head. A metered flow of abrasive is carried into the cutting head by the air flow and is accelerated in the mixing tube to 300 to 400 m/s (1000 to 1300 ft/sec).

Over the past 10 years over 1000 entrainment systems have been fitted to X-Y cutting tables for the cutting of sheet materials - metals, glass, plastic, stone etc. About 80 percent of the entrainment cutting equipment used worldwide has been manufactured in the US.

2.2. DIAJET Abrasive Water Jet Cutting

Engineering contractors' requirements for a powerful cold cutting tool was the driving force behind the development of the DIAJET abrasive jet cutting system by BHR Group. The cutting tool had to be easy to deploy and manipulate, and to be safe with minimal environmental impact. Cutting capabilities required were over 500 mm (20 inches) of reinforced concrete and 300 mm (12 inches) of steel in a single pass. Such demanding cutting duties could only be met by an abrasive water jet formed by passing the abrasive slurry at pressure through the cutting nozzle. In a DIAJET, abrasive is mixed with water upstream of cutting nozzle to form a slurry (Fig 3). This slurry then flows through standard hydraulic hoses, for up to a 1000 m (3000 ft) to an easily manipulated cutting nozzle. Acceleration of the abrasive in the nozzles is such an efficient process that DIAJETs can operate with only 20 percent of the pressure needed by entrainment systems. This enabled contractors to drive DIAJETs with the pumps they used for water jet cleaning.

After 10 years of site experience and development, DIAJET is a dependable cutting tool that has been used on thousands of successful cutting jobs in process plants, refineries, on offshore platforms and sub-sea, on board ships, down mines and in many other difficult and often hazardous situations.

Fig. 4 shows the schematic arrangement of a DIAJET system for cutting and explosive washout. A pumping system typically feeds 2 to 60 litres (0.4 to 16 US gals)of water per minute at 700 bar (10,000 psi), to a slurry generation module (Fig 5). In the slurry module 10 to 20 percent of the water is diverted through a vessel containing abrasive particles. The water flow into the vessel causes a flow of abrasive slurry from the vessel into the main water flow on its way to the cutting head. Depending on the flow rate and operating pressure, jet diameters ranges from 0.4 mm to 3 mm (0.016 to 0.12 inches). Slurry modules are available for continuous and discontinuous operation. Man portable systems are being developed.

3. COMPARISON OF ENTRAINMENT AND DIAJET SYSTEMS FOR MUNITIONS CUTTING

From the beginning of the development of high pressure abrasive water jet cutting it was understood that the best way of generating an abrasive water jet was to pass the abrasive slurry through the cutting nozzle, but the technologies needed to reliably generate abrasive slurries at high pressure had first to be developed and proven.

Abrasive jet cutting systems for munitions have several requirements which are not important in other cutting situations. Each of these requirements leads to the conclusion that a DIAJET type system should be selected in preference to an entrainment systems when decommissioning munitions. These requirements include:

1. The need for a coherent jet to contain abrasive particles within the jet. An entrainment jet is a highly turbulent mixture of air/water/abrasive. A percentage of particles have a significant radial velocity component as they leave the mixing tube. These particles strike the item being cut, away from the area being cooled by the main water flow. This gives rise to sparking when cutting metals. Sparking can be suppressed by operating the cutting head submerged, but this causes problems in feeding abrasive to the cutting head of entrainment systems.
2. Being able to use robust pumping equipment that can operate on contaminated water. Reliable, relatively low cost triplex and swash plate pumps can be used to power DIAJET slurry generation units. Entrainment systems need ultra high pressure intensifier pumps operating at 3000 to 4000 bar.
3. Feeding abrasives and water to cutting heads 100's of metres from the pumping and abrasive feed systems. DIAJET cutting heads can operate more than a 1000 m from the slurry generation module. In the case of entrainment systems the abrasive feed systems has to be located close to the cutting head and hence in the danger zone.
4. The ability to operate under harsh environmental condition. In particular abrasive for entrainment systems has to be protected from moisture in order for the abrasive feed system to operate.

5. Efficient energy transfer to the abrasive particles in the cutting head. The 3 to 5 times higher effectiveness of DIAJET type systems allows finer abrasive to be used which reduces particle inertia and hence energy available to initiate an incident.
6. Minimizing capital costs. Capital costs of DIAJET systems can be considerably lower than those of entrainment systems, particularly when both cutting and washout are carried out using the same pumping unit.

4. CUTTING PERFORMANCE DATA

Standardized procedures for gathering cutting performance data have been developed by an EU supported Brite-Euram collaborative project that is managed by BHR Group. Cutting performance data banks are being produced for both entrainment and DIAJET systems. Supporting software will allow optimization of cutting, taking into account operating pressure, nozzle size, material being cut, cut shape, abrasive material, particle size, cut edge quality required, etc.

Fig 6 illustrates the performance data available for DIAJET type systems. Cutting performance predictions can be made for a wide range of materials at pressures from 250 to 2500 bar, nozzle diameters of 0.2 to 3.0 mm and a number of abrasives.

5. ABRASIVE WATER JET EQUIPMENT REQUIREMENT FOR MUNITIONS CUTTING

An abrasive water jet cutting module is a means of providing a cutting tool. This tool must be built into a total cutting system to meet a munitions cutting objective. If the objective is to cut open munitions to establish their contents and state, the abrasive jet cutting module may represent a substantial part of the total system. In situations where cutting is part of a munitions re-cycling or destruction capability, the cutting module may represent a few percent of the total capital and operating costs.

The success of an abrasive water jet installation will depend on how well the requirements specification is prepared. In drawing up the requirements specification, factors to be considered include:

i) What is the cutting duty? A jet diameter of over 1mm (0.040 inches) will be necessary, if metals thicker than 25mm (1 inch) have to be cut as fast as possible, or the jet is required to section a bomb in a single pass or cut metal structures inside a large rocket from the outside of the rocket, or cutting has to be carried out with the nozzle standing off from the munition.
ii) Is the system in a production cutting situation or an intermittent duty? For an intermittent duty a simpler system can be used.
iii) How important is dependability (reliability, serviceability, operability)? This has to be engineered in at the design stage.
iv) What are the restrictions on water and abrasive disposal? Is re-cycling required?

v) If re-cycling is to be used, will the water be corrosive? If so will a stainless steel system address the problem?
vi) Is explosive or propellant washout required and if so is the pump to carry out both washout and cutting?
vii) Is the cutting module to be used in a fixed installation or is it to be portable?
viii) Does the munition have internals, such as a copper cone? If it does trials may be necessary to establish the behavior of the jet inside the munition.

6. ESTABLISHING SAFE CUTTING ENVELOPES

Numerous rockets, bombs, mines, shells and other munitions have been cut with DIAJET systems (Table 1). As far as is known there has been no explosive incidents. Although this knowledge is comforting, it does not provide the basis for developing responsible safety cases. In order to establish abrasive jet cutting as the preferred method of opening up munitions, a combination of cutting trials, supported by simulation of abrasive jet/explosive interactions, are required.

Strategies also need to be developed for cutting munitions. For instance, if it is required:

- not to contaminate explosive or other fillers with abrasive
- to maintain the containment of explosives up until the point where munitions are fed into furnaces:

the strategy could be to cut a slot to a specified depth in the casing in order to leave a thin wall section that can be easily broken. By this means explosive is not cut or contaminated with abrasive and the containment can be maintained until the munition is subsequently broken open.

For economic reasons, and to minimize pollution by contaminated abrasive and water, it is desirable to operate at as high a nozzle pressure as possible, within the constraints of pumping equipment reliability. Higher pressures allow smaller nozzles and abrasive particles to be used. The various relationships between cutting efficiency, operating pressure and particle inertia, can result in decreasing individual particle inertias with operating pressure. Safety may, therefore, be improved by operating with fine abrasive (<100 microns) at higher operating pressures than existing 700 bar (10,000 psi) DIAJET systems.

A collaborative project is being set up by BHR Group to provide experimental pressures up to 5000 bar (70,000 psi) and to develop simulations of the interaction between abrasive water jets and explosives. The aim is to generate "acceptably safe" operating envelopes for the abrasive water jet cutting of munitions. Of particular concern will be the likely factors of safety. Since abrasive water jets have been used to cut very sensitive materials, such as fuses, safety margins may be found to be considerable, reinforcing the confidence already established in the use of abrasive jet cutting systems.

7. CONCLUSION

Abrasive water jets are powerful, cold cutting tools that have wide application in munitions demilitarization. A major need is for information on abrasive water jet cutting to be provided in a form that the demilitarization community can better exploit the technology.

8. REFERENCES

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2. H.H. Alba & J. Wilhelm, "Safe Water Abrasive Cutting of Ammunition," Proc., Demilitarization Symposium, May, 23-25, 1994, Arlington, USA.

3. Communication with DERA Fort Halstead Explosives System Cente, Sevenoaks, Kent TW14 7BP, UK.

Table 1 - Examples of Munition Cut by DIAJET

a)	RMCS (Ref 1)	Munitions Sectioned	20mm High explosive (incendiary) fuzed cannon shell 35mm High Explosive (incendiary) fuzed cannon shell 84mm High explosive fuzed mortar bomb 4.5in Naval Shell plain detonator L1A1 (lengthwise section).
		Explosive Composition	Hexal W 30 (66.5% RDX, 30% aluminium, 3.5% wax) main charge HMX (pure, pressed booster charge) RDX/wax 95:5 (pressed booster charge) RDX/TNT 60:40 (main charge) Tetryl (detonator base charge) Azide/styphnate/Aluminium (detonator filling) Double base propellant (20 and 35mm fixed ammunition)
b)	Alba Industrie (Ref 2)	Munitions Sectioned	No. 8 detonating cap Propelling Charge Igniter 100 mm armor-piercing shell H.E. shell 100 mm Armor hand grenade RKG-3M Anti-tank guided missile warhead H.E. shell M 21
		Explosive Composition	Nitropenta and fulminate of mercury Black Powder and fulminate of mercury A-IX-2 hexogen with aluminum powder TNT Trinitrotoloul-hexogen mixture A-IX-1 hexogen TGAG 5 trinitrotoloul-hexogen-aluminium powder TD-50 trinitrotoloul-dinitronaphthalene
c)	DERA (Ref 3)	Munitions Sectioned	Warhead JP233 Primary Warhead JP233 Secondary Mine anti-tank MK7 Rapier Rocket Motor Booster pellet Detonator Demolition Electric L2A1 Tow warhead LX14
		Explosive Composition	EDC1A RDX/TNT/HMX TDX/WAX/AL TNT NC/NG TETRYL (CE) PETN & ASA HMX

FIG. 1 155 mm Shell Cut by a 700 bar DIAJET - Circumferential Cut made in 90 Seconds.

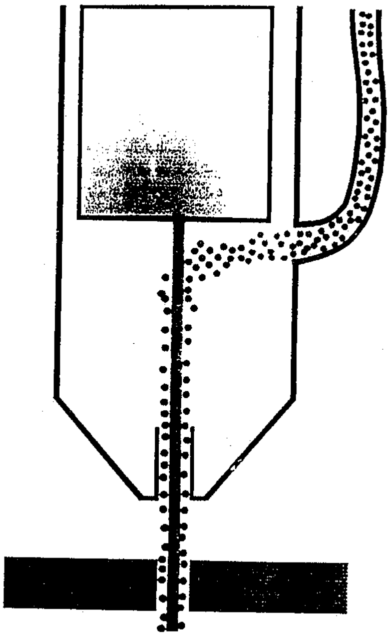

FIG. 2 SCHEMATIC OF A ENTRAINMENT WATER JET CUTTING HEAD

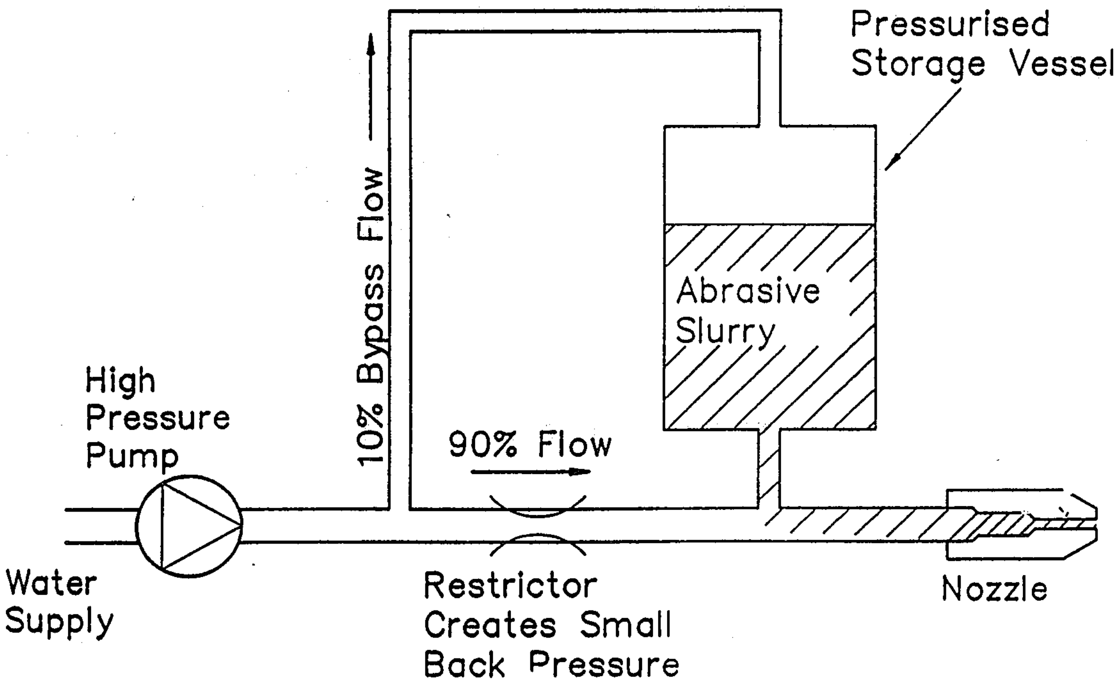

FIG. 3 SIMPLIFIED DIAJET CIRCUIT

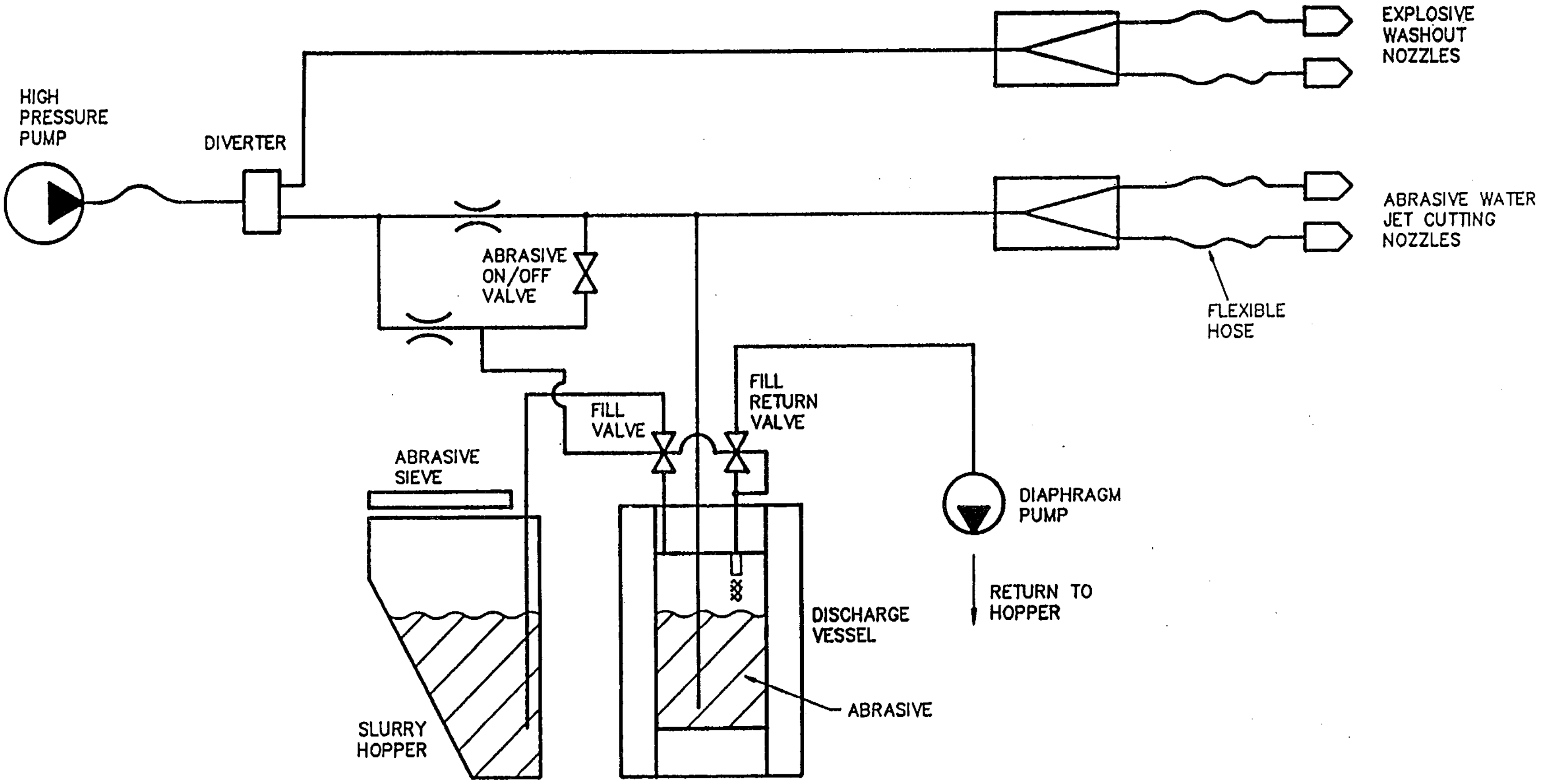

FIG. 4 SCHEMATIC ARRANGEMENT OF A DIAJET FOR CUTTING AND EXPLOSIVE WASHOUT

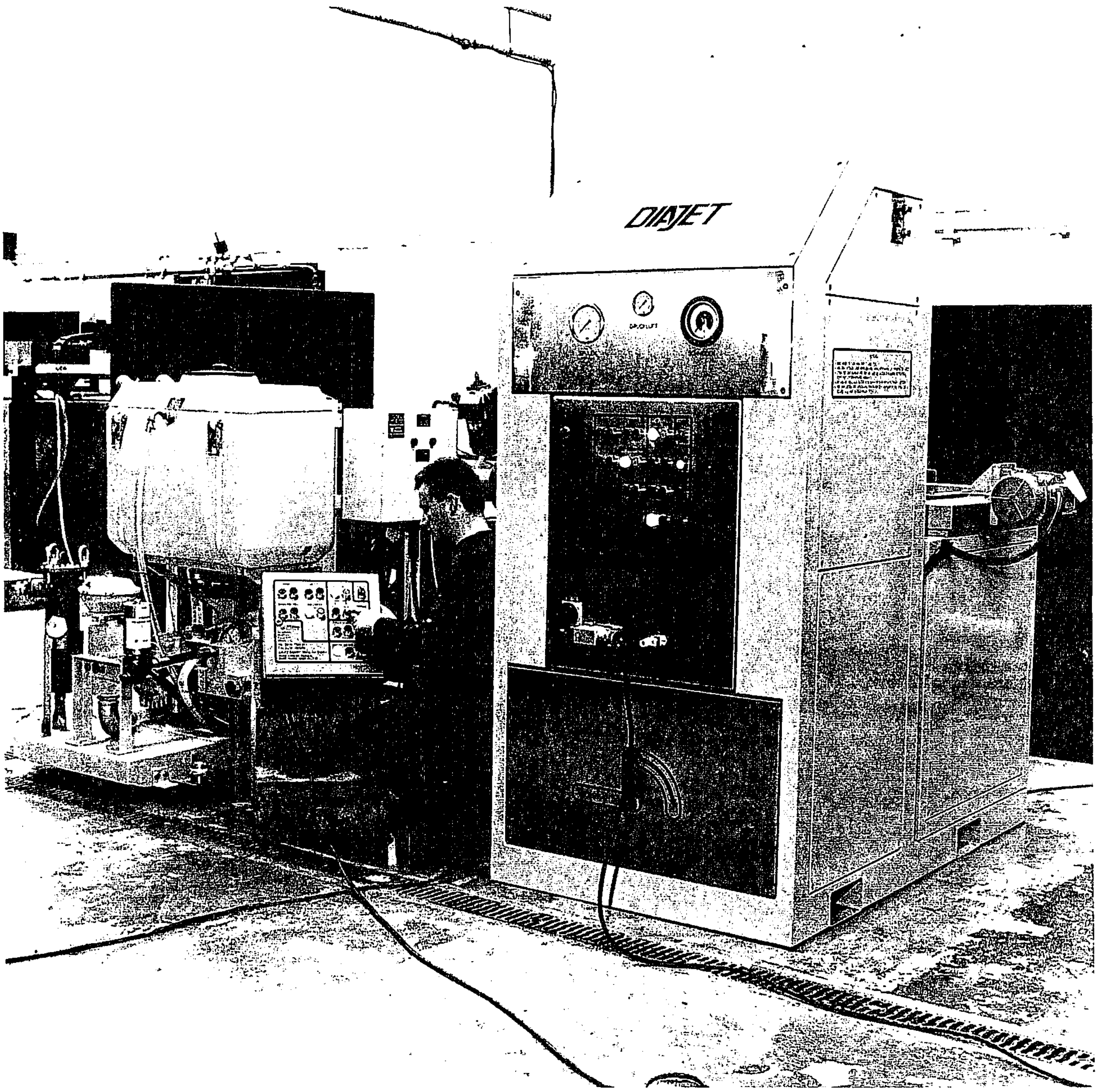

FIG.5 DIAJET Cutting and Explosive Washout Module

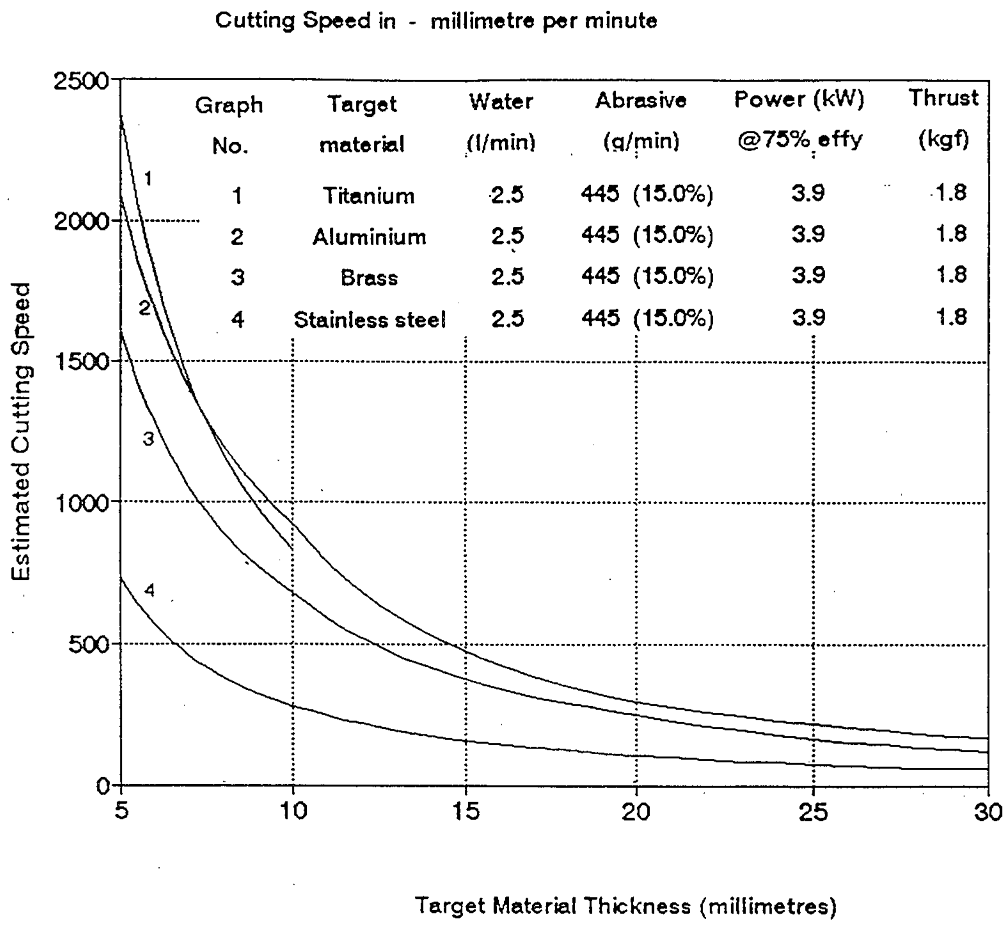

FIG. 6 Estimated Cutting performance for Parting Cuts (0.40 mm nozzle at 690 bar with Olivine abrasive at 15.0% by weight)

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