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ABRASIVE SURFACE TREATMENT WITH LIQUID CO_2

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ABSTRACT

The main advantages of cutting with liquid jets are the flexibility and consistent sharpness of the tool, which allows the machining of a variety of materials and complex shapes. Unfortunately, the humidification of the components can be a problem for certain applications and inhibits the spread of jet technology. Besides, the dry and residue-free cutting of materials is an important topic of today's research in manufacturing engineering. Due to these advantages, high-pressure liquid CO_2 jet cutting has the potential to open new fields of applications in which water jet cutting is not suitable. The liquid CO_2 jet with a pressure of up to 300 MPa can be used to machine various materials and functional surfaces before it expands to gas and atmospheric pressure. However, the transition from liquid to gaseous phase implicates density differences, which change the cutting performance. As a result, the knowledge about waterjets cannot be adapted to CO_2 jets and further investigations are necessary.

At a prototypical test stand for high-pressure liquid CO_2 jets, a feed line with abrasives was added. Technological investigations concerning the surface properties with high-pressure liquid CO_2 and water jets were performed with and without different abrasives. The tests were carried out on parts of various metals and technical plastics. The influence of the fluid on jet properties as well as the attained workpiece surfaces and kerfs produced by the different jets were investigated.

The experiments indicate that the performance of the CO_2 jet as well as of the waterjet mainly depends on pressure, focus tube and nozzle diameter but show different behavior. Especially the impact of the working distance and the jet temperature will be discussed. The investigations reveal that high-pressure liquid CO_2 jets have a high potential in the field of dry and residue-free cutting and dry surface treatment, like peening, of metals, technical plastics and CFRP.

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1 INTRODUCTION

Jet machining has established itself for years as an efficient and progressive manufacturing process and has been enhanced continuously. The manufacturing process produces kinetic energy by means of a continuous jet of liquid, usually water, which can be used to implement various manufacturing options and new fields of applications. On the one hand, the well-known omnidirectional cutting effect can be used to process a wide range of materials, which are subjected to both low mechanical and low thermal loads during the low-wear manufacturing process. On the other hand, the resulting negative pressure in the abrasive tube and the special properties of water can also accelerate materials in powder form, so-called blasting abrasives. This can either increase the cutting performance, as in abrasive water jet cutting [1, 2], or the material properties of the surface can be changed, as in shot peening [3].
However, for some applications water will never be the first choice of jet medium or machining technology due to its additional needed machine periphery and process steps, such as the disposal of water or cleaning and drying of the workpieces after machining [2]. In contrast, comparable blasting technologies with air or blast wheels for surface treatment cannot accelerate the abrasive sufficiently or are not suitable for certain geometries [3, 4].
Debunking these limiting factors of conventional processes, while simultaneously using the advantages of jet machining, the liquid carbon dioxide (CO_2) jet is an alternative acceleration medium with high potential for new applications. Due to the complete sublimation of the jet, high-pressure jet cutting with liquid CO_2 is a dry and residue-free process. It was first investigated in a feasibility study by DUNSKY and HASHISH [5], proving the realisability of the process under atmospheric conditions and showing similarities to water jet cutting as a residue-free cutting process. Based on these results, BILZ [6] designed a prototype system at the Production Technology Centre Berlin (PTC) and continued with detailed analytical and experimental investigations. Force impulse measurements and the evaluation of kerf characteristics on plastic specimens were conducted to show the industrial potential of the high-pressure jet cutting process. Originating from a joint research project with the PTC, ENGELMEIER [7] carried on investigations in order to analyze pressures and temperatures in the process and their influence on jet deformation and decay. In previous work, a general suitability of the process for a dry and residue-free cutting of metal materials was proven [8]. Investigations on jet velocity, jet impulse force and kerf geometry on aluminum specimen ($AlMg_3$) using jet pressures up to 300 MPa led to knowledge about main differences between water jet cutting and jetting with liquid CO_2. Continuing, pressure, nozzle diameter, but also the working distance, secondary material damage and the potential of accelerating abrasives was examined [9, 10, 11]. This paper will investigate the depth of cut for aluminum AlMg3 depending on various influencing factors. Not only obvious process parameters like pressure and nozzle diameter, but also the working distance, the jet temperature and the adding of different abrasives will be examined.

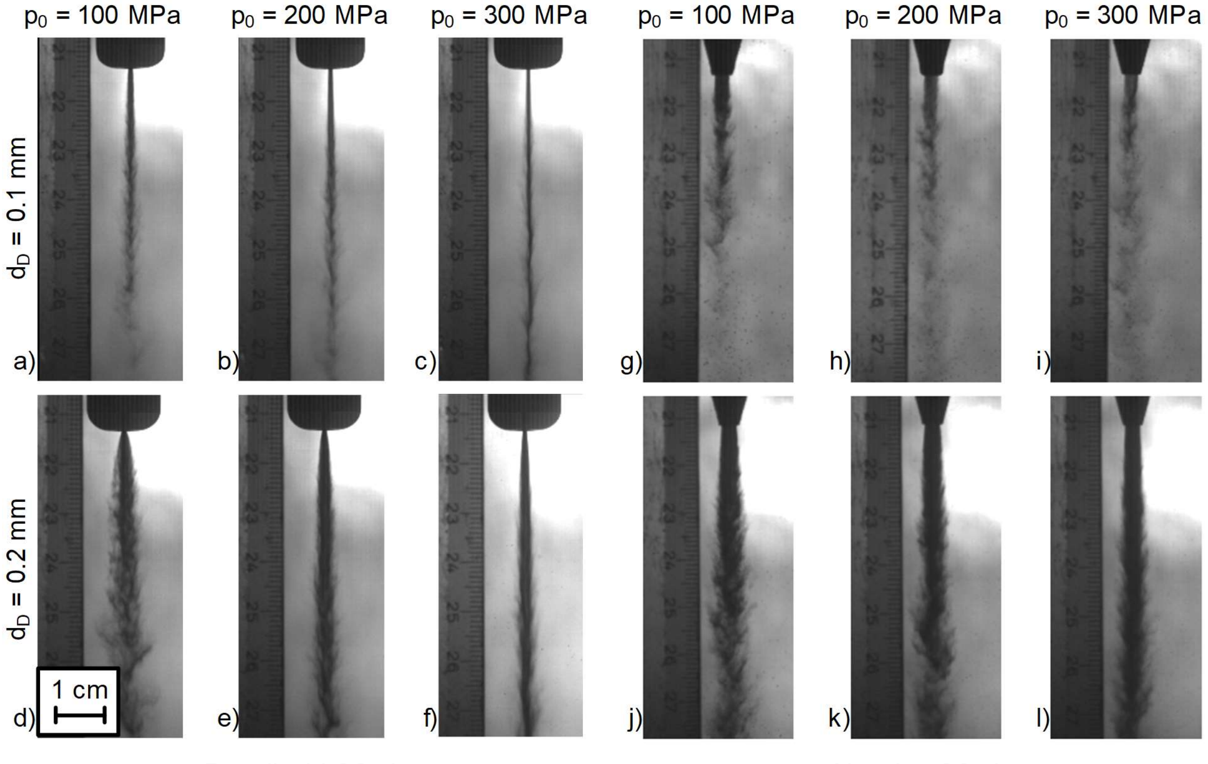
2 TEST STAND AND MEASUREMENT SETUP

2.1 Test stand for liquid CO_2 jets

By using the prototype system [6], functional correlations between significant setting parameters and results were developed analytically and experimentally in order to analyze the cutting properties of the CO_2 jet. Following, the test stand and the measuring principle to analyze these quantities are described.

The empirical investigations on the plain water jet cutting technology were performed with the system Jet Max HRX 160L from Maximator Jet GmbH, Schweinfurt, Germany, with a high-pressure pump HPS 6045 which realizes jet pressures up to $p_0 = 600$ MPa.

The liquid CO_2 cutting jet system is divided into three functional modules: Climatic chamber, high-pressure pump and cutting chamber. The liquid CO_2 is supplied from a riser pipe bottle inside the chamber via high-pressure hoses to the suction side of the high-pressure pump. According to the temperature inside the climatic chamber, the supply pressure is regulated up to $p_V = 9$ MPa at $T = 45$ to 50 °C. Within the pump, liquid carbon dioxide is gradually compressed up to 300 MPa and pumped to the pulsation damper and subsequently to the closed cutting head in the cutting chamber. The high-pressure pump is a Steamline1 of Ingersoll-Rand, Swords, Ireland, with a maximum pressure of $p_0 = 345$ MPa and a maximum flow rate of $Q = 3.8$ l/min. The cutting head is pneumatically actuated and opened, allowing the high-pressure fluid to exit the nozzle. The cutting head, Active Autoline II from KMT GmbH, Bad Nauheim, Germany, attached to a gantry robot is moved according to the chosen direction and at the selected feed speed. This experimental setup allows the machining of parts with high-pressure CO_2 jets of different length and power, depending on the influencing variables (Figure 1a-1f).



Pure liquid CO_2 jet

Abrasive CO_2 jet
with d_F = 3.2 mm and $\dot{m}$ = 250 g/min garnet sand

Figure 1. High-pressure liquid CO_2 jets [11].

In order to increase the removal rate of the jet, abrasives such as garnet sand, quartz sand or corundum are used in abrasive waterjet cutting. Thus, hard materials such as steel, stone or glass can also be processed economically. The proof of concept and the industrial potential of abrasives added to the liquid CO_2 jet for cutting has already been demonstrated with a prototype out containing many waterjet components [10]. To investigate this, water abrasive injection jet cutting was chosen as an overall concept. It is established in the industry and their sophisticated components for which spare parts and technical service are already available. This offers the simultaneous advantage that existing systems do not have to be modified at all or only slightly. Thus, for the dosing of the abrasive a commercial abrasive dosing unit and feed as well as further required parts with already existing technology were selected. The experimental investigations were amended by the FEEDLINE V and by the focusing tubes HYPERTUBE 54x947x50-21-A1, both of the KMT GMBH, Bad Nauheim, Germany. The abrasive feed system is able to realize a mass flow up to $\dot{m} = 1000$ g/min.

The major challenge hereby is to realize a vacuum in the abrasive hose and getting the abrasive into the mixing chamber or afterwards into the jet. Therefore, various parameters like the jet pressure p_0, the nozzle diameter d_D and the focusing tube inner diameter d_F have to be verified. The different focusing tube inner diameters d_F were adjusted within the investigations through eroding.

In order not to lose the process advantage of a residue-free process, various additives were tried out. In this paper, Garnet sand with Mesh 140, grain size $d_G = 0.14$ mm, from BARTON INTERNATIONAL PLC, Glen Falls, USA, was the choice for machining metals. In addition, to maintain the advantage of residue free machining, CO_2 crystals have been added to the jet instead of garnet sand. The CO_2 crystals had to be smaller than $d_G = 0.6$ mm in order not to block the focus tube and the mixing chamber. Therefore, two different possibilities were carried out. In a first feasibility test, conventional CO_2 pellets, from PRAXAIR DEUTSCHLAND GMBH, Düsseldorf, Germany, have been chopped and sieved by hand. In the second approach, a supplementary machine system, i^3 MicroClean DX from COLD JET GMBH, Weinsheim, Germany, was used for shredding a CO_2-cube and accelerating the particles into the cutting head.

However, different material densities and powder sizes cause a different mass flow. Therefore, the abrasive feed was calibrated for each powder. With a precision balance of the type PLS 1200-3A from KERN & SOHN GMBH, Balingen, Germany, the correct potentiometer settings were found. Finally, the experimental setup allowed the machining of parts with high-pressure abrasive CO_2 jets of different length and power, depending on the influencing variables (Figure 1g-1l).

2.2 Measurement of kerf characteristics

To analyze the jet quality, the potential of creating kerfs is a valid method [6]. Therefore, the depth of cut k_T, kerf width k_B, middle kerf width k_{BM} and kerf shape k_F were investigated. As a result of the special cutting behaviour of plastics, the depth of the kerfs is divided into the parameters depth of cut k_T and penetration depth k_{ET}. The penetration depth k_{ET} is defined as the maximum depth at which an influence of the jet is still visible, whereas the depth of cut k_T only includes the area in which the material was visibly separated. The middle kerf width was measured at half of the depth of cut k_T. The kerf shape k_F is a qualitative value and compares the kerf profile along the abscissa axis by cutting vertically through the kerf (Figure 2). For these investigations the specimen of rolled sheet with a thickness of 5 mm consisting of the aluminum alloy $AlMg_3$ were processed with different parameters. The material was chosen due to the characteristic properties of metal, but with low hardness. Previous results of the jet impulse forces F_S [8] as well as preliminary tests [10, 11] led to the parameter field shown in Table 1. To provide statistically firm results, kerfs with a length of $k_L = 10$ mm were processed for each parameter variation and measured at three different locations. The measurements on the specimen were realized by using the chromatic white light interferometer FRT MicroProf and the chromatic sensor FRT CWL from FRIES RESEARCH & TECHNOLOGY GMBH, Bergisch Gladbach, Germany. To evaluate the data the software FRT Mark III from the same company was used. The second measurement system was the digital microscope VHX-5000 from KEYENCE DEUTSCHLAND GMBH, Neu-Isenburg, Germany.

Table 1. Parameters to determine the jet quality.

Explanatory variable	Abb.	Input Values	Dimension
Jet fluid	-	CO_2 / CO_2 + abrasive	-
Cutting head	-	Pure Jet / Abrasive jet	-
Jet pressure	p_0	100 / 200 / 300	MPa
Supply pressure	p_V	9	MPa
Nozzle diameter	d_D	0.10 / 0.15/ 0.20 / 0.25	mm
Working distance	a_W	5 / 10 / 15 / 20 / 25 / 30	mm
Jet feed speed	v_f	0 / 30 / 60 / 120	mm/min
Abrasive mass flow	$\dot{m}$	200 / 300 / 400 / 588	g/min
Abrasive material	-	Garnet / CO_2-microcrystals	-

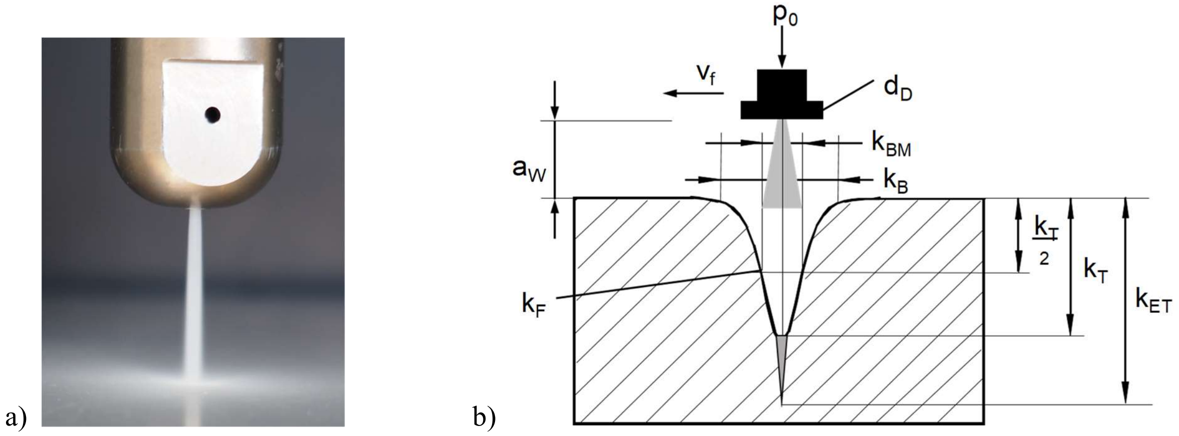


Figure 2. Characteristic liquid CO_2 jet; a) optical; b) values to quantify.

2.2 Measurement of jet temperature characteristics

Considering the thermodynamic properties of CO_2 it is obvious, that the temperature is an important factor for the cutting properties of a CO_2 jet. The jet temperature T_S is an indicator of the phase transition of the CO_2 as well as its density. To analyze the sequence of the phase transition of the CO_2, the working distance is the most important parameter to be varied. Another aspect is the temperature development during the cutting process on the specimen. An example is thermoplastics, which have, compared to other materials, a low melting temperature and tend to become brittle at very low temperatures. In order to investigate the temperature development during the cutting process, the temperature curve during a jet time t_S has to be recorded. The tests are carried out without a specimen by jetting directly onto a thermocouple on a grid table. The first measuring point is located directly at the nozzle, the others along the jet to simulate certain working distances a_W. The parameters are shown in Table 2.

Table 2. Parameters to determine jet temperature.

Explanatory variable	**Abbr.**	**Input values**	**Dimension**
Jet fluid	-	CO_2	-
Cutting head	-	Pure Jet / Abrasive jet	-
Jet pressure	p_0	100 / 200 / 300	MPa
Supply pressure	p_V	9	MPa
Nozzle diameter	d_D	0.10 / 0.15 / 0.20	mm
Working distance	a_W	0 / 5 / 10 / 15	mm
Jetting time	t_S	5	s

The temperature is measured by a thermocouple type T from TC DIRECT, Moenchengladbach, Germany, which has a measuring range from $T_S = -75$ to 250 °C. It consists of two conductive wires of different materials. Type T thermocouples are made of copper and copper-nickel. Due to the thermoelectric effect, temperature changes generate a voltage in the microvolt range. This voltage is automatically converted into an absolute temperature by the connected measuring device and can be read directly. The thermometer TM-914C from LUTRON ELECTRONIC ENTERPRISE CO., Taipei, Taiwan, serves as the measuring instrument.

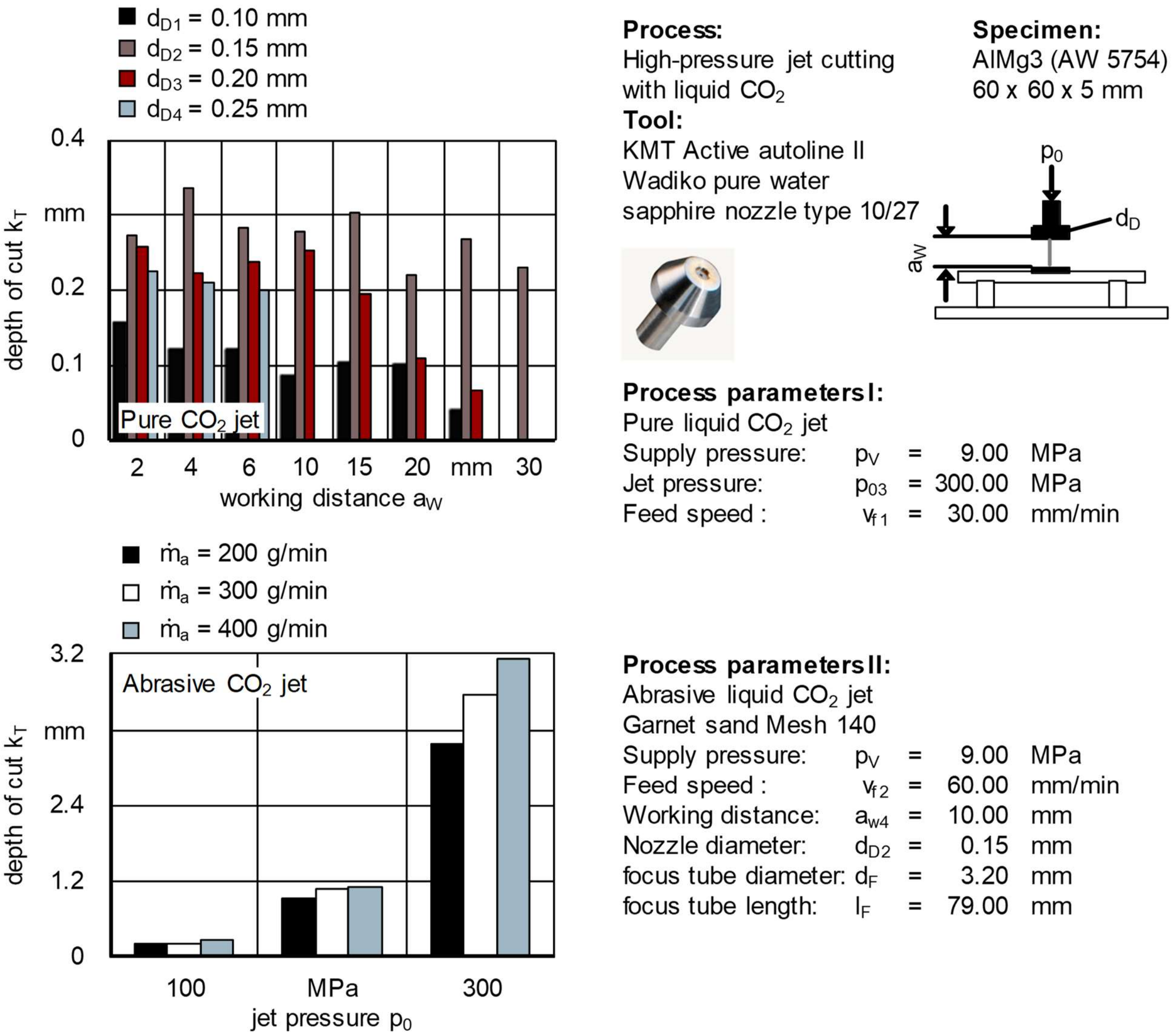
3 RESULTS AND DISCUSSION

3.1 Kerf characteristics for metals

The investigations were divided into jet tests with and without abrasives in order to compare them with each other. The pure jet tests were then again divided into normal jet tests and jet tests with the new abrasive jet head.

The pure jetting with the abrasive cutting head obtained no measurable results, but a cleaning of the surface was detected. This indicates that the distance to the workpiece is too high and the mixing chamber supports the phase transition, so that the density of the fluid is not sufficient to cut aluminium AlMg3.

For liquid jet cutting without abrasive cutting head, a jet pressure of $p_0 = 300$ MPa resulted in the deepest kerfs, which could be determined for all nozzle sizes. The maximum depth of cut with $k_t = 335$ µm was achieved at jet pressure $p_0 = 300$ MPa, nozzle diameter $d_D = 0.15$ mm and a jet distance of $a_w = 4$ mm (Fig. 3). The resulting kerf shape can be described as V-shaped. There is no flat kerf base. A dependence of the depth of cut on the nozzle diameter was also determined. The increase of the nozzle diameter from $d_D = 0.10$ to 0.15 mm causes an increase in the depth of cut k_T by a factor of 3.29. With a nozzle diameter of $d_D = 0.10$ mm, the volume flow is not yet sufficiently large to be able to achieve optimum removal through the described process. If the nozzle diameters are higher than $d_D = 0.15$ mm, the necessary volume flow seems to be too large for the machining system and the optimum was exceeded. Furthermore, it could be determined that the depth of cut increases to a certain optimum for every nozzle and afterwards decreases again with an increasing distance to the specimen. The kerf width k_B, not illustrated, increases with increasing distance to the specimen until no more kerf is cut. By increasing the distance from $a_w = 2$ to 30 mm, a widening of the kerf by factor 1.8 is possible. The increase is explained by the fact that the CO_2 partially passes downstream into the gaseous phase and loses depth impact but has a stronger jet decay.



Process:
High-pressure jet cutting
with liquid CO_2

Tool:
KMT Active autoline II
Wadiko pure water
sapphire nozzle type 10/27

Specimen:
AlMg3 (AW 5754)
60 x 60 x 5 mm

Process parameters I:
Pure liquid CO_2 jet
Supply pressure: p_V = 9.00 MPa
Jet pressure: p_{03} = 300.00 MPa
Feed speed : v_{f1} = 30.00 mm/min

Process parameters II:
Abrasive liquid CO_2 jet
Garnet sand Mesh 140
Supply pressure: p_V = 9.00 MPa
Feed speed : v_{f2} = 60.00 mm/min
Working distance: a_{w4} = 10.00 mm
Nozzle diameter: d_{D2} = 0.15 mm
focus tube diameter: d_F = 3.20 mm
focus tube length: l_F = 79.00 mm

Figure 3. Depth of cut k_T for pure and abrasive CO_2 jetting of AlMg3.

The tests with garnet sand showed a significant increase in the depth of cut k_T compared to the pure jetting tests. The kerf also has a U-shaped cross-section with steep kerf flanks and a flat kerf base. The jet pressure p_0 and the nozzle diameter d_D have by far the largest influence on the maximum depth of cut k_T. Changing the pressure from $p_0 = 100$ to 300 MPa causes a 10-fold increase of the depth of cut k_T. Changing the nozzle diameter from $d_D = 0.10$ to 0.15 mm causes an increase in depth of cut by twice to three times. Contrary to expectations, the variation of the abrasive mass flow seems to have just small influence on the depth of cut k_T. However, it is determined that the increasing nozzle diameter and the mass flow results in an increased depth of cut. For example, the deepest kerfs were measured for all nozzle diameters at an abrasive mass flow of $\dot{m} = 400$ g/min and a pressure of $p_0 = 300$ MPa. With a nozzle diameter of $d_D = 0.15$ mm, the deepest kerfs were measured at $k_T = 3.19$ mm. In the investigated area, the jet distance a_W has no strong influence on the depth of cut k_T. However, it strongly influences the kerf width k_B. For example, an increase of around 30 % was observed when the jet distance changed from $a_W = 5$ to 15 mm. Furthermore, it was determined that the kerf width is influenced together with the abrasive mass flow and jet pressure. A higher pressure straightens the jet and cuts about 10 % more narrow kerfs.

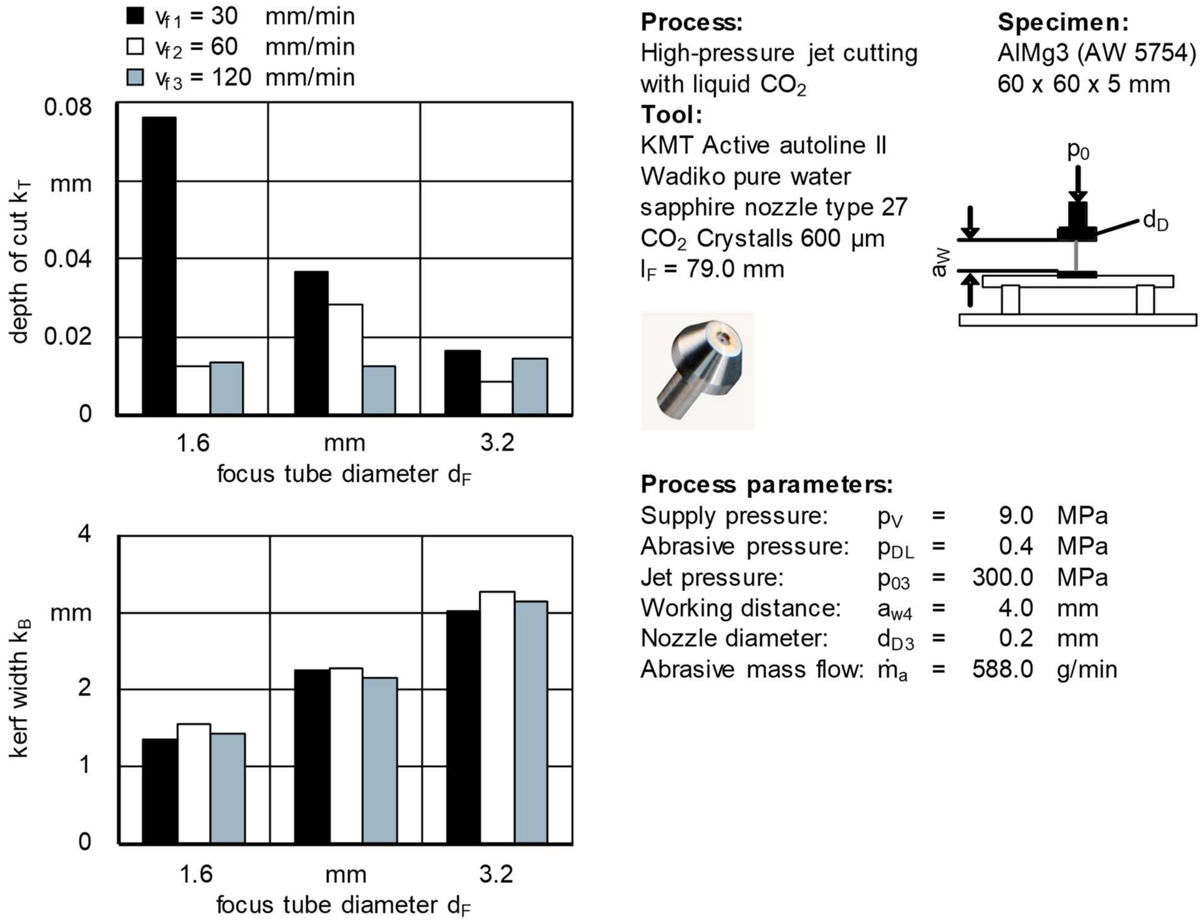
This assumption is also illustrated in Figure 1. It can be seen, that the jet is fraying at the edge and wave formation occurs. Only at increasing jet pressure, the inside of the jet can be identified as homogeneous liquid CO_2. By increasing the jet pressure from $p_0 = 100$ to 300 MPa the jet characteristics regarding cutting performance, homogeneity and jet expansion directly after the nozzle outlet could be influenced positively. As shown in Figure 1, the jet expands after the nozzle outlet and widens with an increasing distance. The pure jet diameter after the nozzle outlet is $d_{S1} = 1.08$ mm for the nozzle diameter $d_D = 0.1$ mm. This equates to an expansion by a factor of 10. The cutting performance at the workpiece only achieved a middle kerf width of $k_{BM} < 0.2$ mm, which corresponds approximately to the homogeneous liquid jet center. The expansion of the CO_2 is caused by the extreme pressure drop at atmospheric conditions and a concurrent temperature change directly after the nozzle outlet. Thus, the jet fluid CO_2 changes from liquid state to gaseous state at the outer edge of the jet.

The direct comparison between pure and abrasive jetting shows that by using the abrasive jetting process up to ten times deeper kerfs can be produced. The kerf width is also larger in abrasive jet cutting and exceeds the kerf width of the pure jet by up to 4.3 times. The ratio of k_B/k_{BM} is a reference for the kerf shape and consistently higher in pure jet cutting than in abrasive jet cutting. It amounts to pure jets up to 3.46 and in abrasive jets not more than 1.7. This explains the two different kerf shapes.

The proof that at low pressures and with the sharp-edged sand a low removal is possible, but nevertheless an acceleration of the particles is adjustable, qualifies the procedure for further blasting applications. An application of dry and highly accelerated shot peening is therefore conceivable, in which both small and large particles up to $d_G = 0.8$ mm with up to $v = 900$ m/s could solidify a metallic surface, comparable to previous work [3].

In additional investigations CO_2-microcrystals have been added to the jet and were processed with different jet feed speeds v_F and focus tube diameters d_F. As expected, increasing v_F and d_F results in decreasing depth of cut k_T (Figure 4). The feed speed has just marginal influence on the kerf width k_B. The main influence was proven for the focus tube diameter d_F, which naturally confines jet decay and centres the impact zone. The depth of cut is not competitive in comparison to the pure jet or the abrasive garnet, but the feasibility of a dry and residue-free abrasive jetting process was proven. Furthermore, the surface of the AlMg3 specimens showed unusual undirected craters (Figure 5c). Using the CO_2-microcrystals show just little depth of cut but give a hint to a potential for surface preparation, for example before coating processes. The reason are the different, jagged structures and undercuts in harmony with great roughness, as they are required for subsequent coating.

A comparison of the kerfs cut by the different jet fluids is shown in Figure 5, where the different length, quality and strength of the jets can be assumed. The investigation of the cutting surface shows a characteristic outcome for the pure waterjet: the depth k_T significantly increased and a rather U-shaped kerf profile was identified (Figure 5a). Quite different is the cutting result after jetting with liquid CO_2. The cutting surface shows a rather pore-like characteristic and the kerf root is wavy and rough. These results indicate a significant difference at the behavior of the backwater between liquid CO_2 and water. The density difference and gaseous phase seem to manifest here. That indicates a multiphase state of the CO_2 jet, which means that the density and therefore the cutting performance are higher inside the jet (Figure 5b).



Process:
High-pressure jet cutting
with liquid CO_2

Tool:
KMT Active autoline II
Wadiko pure water
sapphire nozzle type 27
CO_2 Crystalls 600 µm
l_F = 79.0 mm

Specimen:
AlMg3 (AW 5754)
60 x 60 x 5 mm

Process parameters:

Supply pressure:	p_V	=	9.0	MPa
Abrasive pressure:	p_{DL}	=	0.4	MPa
Jet pressure:	p_{03}	=	300.0	MPa
Working distance:	a_{w4}	=	4.0	mm
Nozzle diameter:	d_{D3}	=	0.2	mm
Abrasive mass flow:	$\dot{m}_a$	=	588.0	g/min

Figure 4. Depth of cut k_T and kerf width k_B for abrasive CO_2 jetting of AlMg3 with CO_2-microcrystals as abrasive.

The expansion of the CO_2 is caused by the extreme pressure drop at atmospheric conditions and a simultaneous temperature change directly after the nozzle outlet. Thus, the CO_2 changes from liquid state to gaseous state at the outer edge of the jet, which causes a density change of the CO_2. Alongside the jet from nozzle to workpiece, two different characteristics are influencing the decreasing cutting depth: On the one hand, there is a phase transformation from liquid to gas which causes a decrease in density of the fluid. On the other hand, the conical expansion of the jet enlarges the jet cross-sectional area and therefore decreases the effective area force. This distinct difference between water and liquid CO_2 jetting as well as pure and abrasive jetting enables a new technology for complex shapes and 3D-operations without jet catcher, for example necessary when machining using industrial robots.

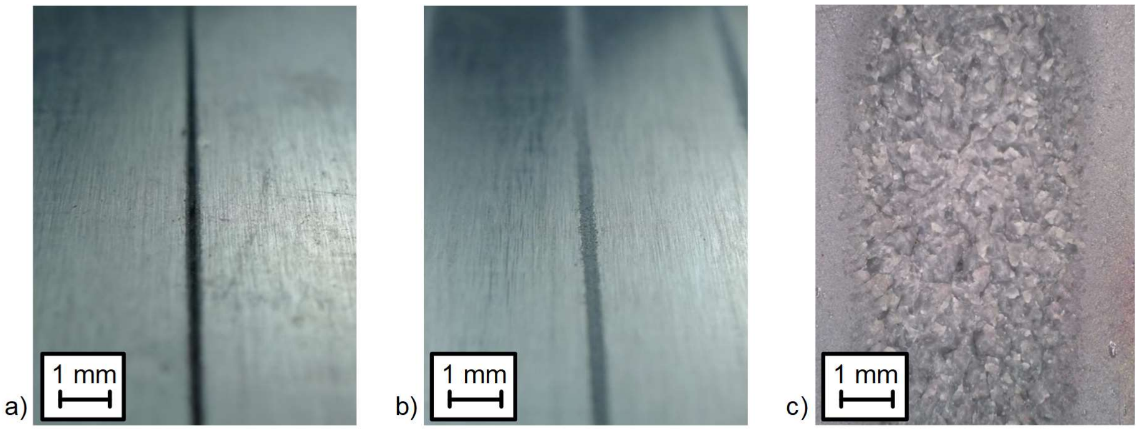


Figure 5. Cutting surface of AlMg3; a) pure water; b) pure liquid CO_2; c) liquid CO_2 with CO_2-microcrystals as abrasives.

3.2 The jet temperature

The temperature investigations were divided into pure jet tests and abrasive jet tests. In order to compare them with each other but not destroy the thermocouple, no abrasive was added, but the abrasive jet head was used. The jet pressure p_0, nozzle diameter d_D and jet distance a_w were varied. The analysis of the jet temperature T_S depending on the working distance a_W made it possible to trace the phase transition of the CO_2 jet. The temperature of the CO_2 jet depends significantly on the process parameters. To ensure that the CO_2 jet hits the workpiece in its liquid state, a temperature between $T_S = 31$ and -56.6 °C is required at jet pressures between $p_0 = 100$ and 300 MPa. As shown in Figure 6, the temperature is decreasing with higher distance a_W and lower jet pressure p_0 from $T_S = -14.7$ to -53.7 °C for the pure jet. Only at the abrasive jet and for the largest nozzle diameter, lowest pressure and highest distance to the workpiece, a temperature of $T_S = -58.3$ °C was measured. The abrasive jet expands to the gaseous phase, but is still able to accelerate abrasives as shown before.

The temperature T_S is beyond the brittle temperature T_V of certain plastics like Polypropylene (PP) and Polyvinylchloride (PVC). That could have an influence on cutting behaviour in certain applications and for some materials. For aluminium there should be no significant influence and at least no thermal damage. In most machining operations high temperatures insult the workpiece, the opposite behaviour is now proven for jetting with liquid CO_2.

By raising the nozzle diameter d_D the influence of a_W and p_0 is increasing. That could be an indicator, that the machine system has an influence. Higher volume flow rates require more pump strokes, which heats up the machine and the fluid. The heating of the system as a result of the high-pressure pump will overlap the effect of the phase transition. That could be another reason, why high jet pressures p_0 produce more stable CO_2 jets (Figure 1).

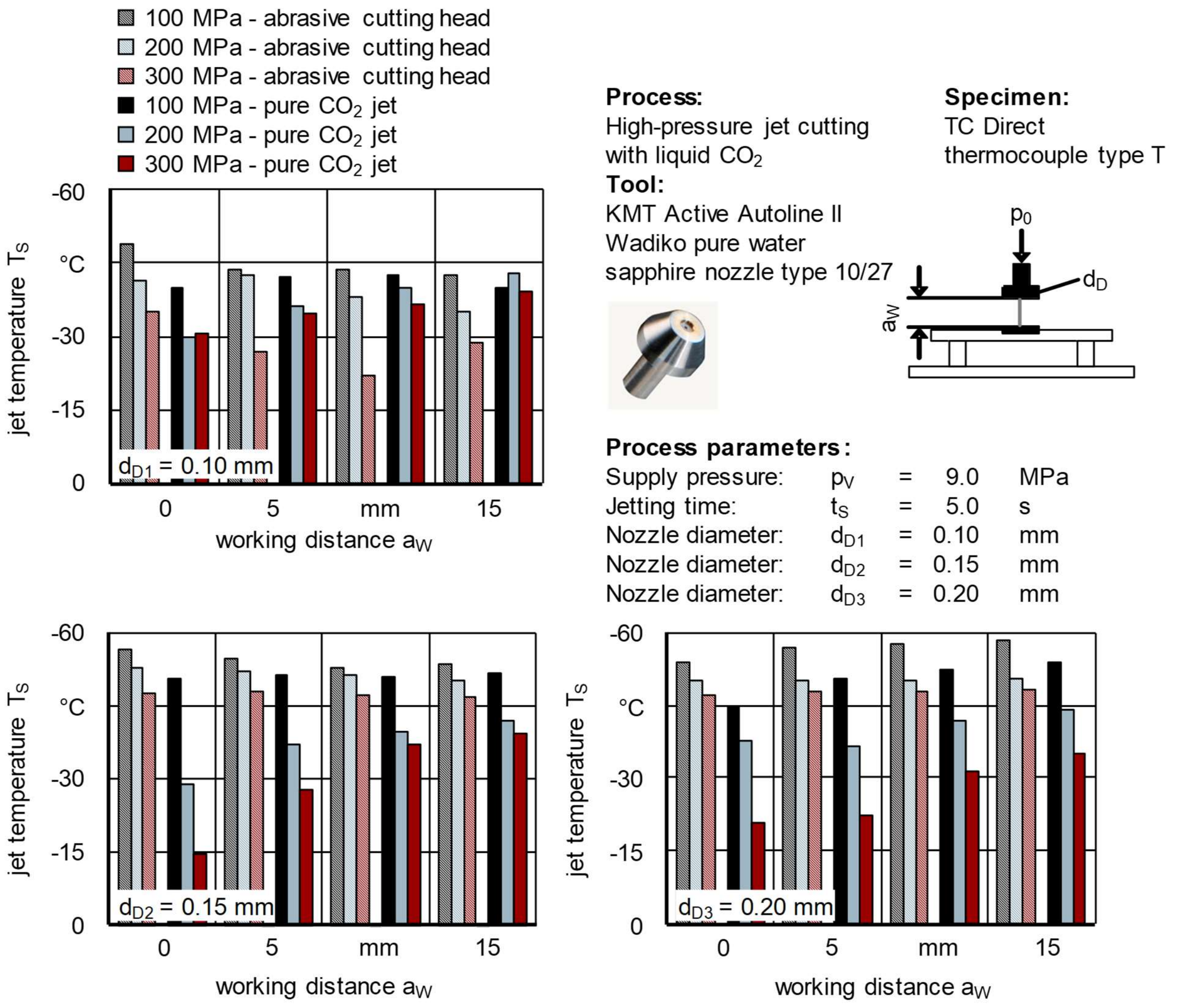
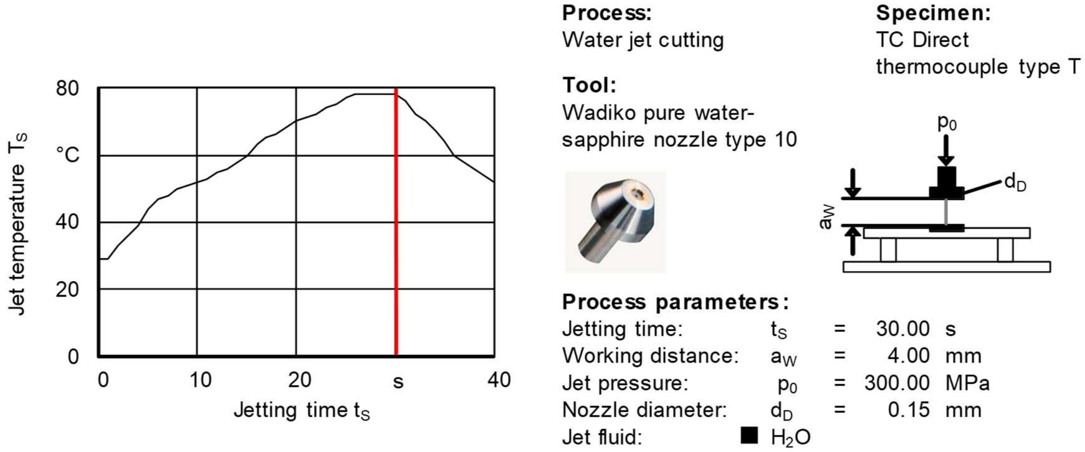


Figure 6. Jet temperature T_S of pure and abrasive liquid CO_2 jets.

In order to classify these findings, a temperature measurement at a conventional water jet machine system with a pure water jet was done. After a jetting time of $t_S = 30$ s, marked with a red line in Figure 7, jet temperatures of about $T_S = 78$ °C were observed. These temperatures could cause damage inside the workpieces, e.g. with technical plastics like Polypropylene (PP) with a melting point of $T_M = 80$ °C. The difference between liquid CO_2 and pure water jets is significant. Potential for CO_2 jet cutting arises in particular in applications where gentle, precise dry and cold machining is required, such as in precision engineering or electrical engineering. The processing of fibre composite materials, which are increasingly used in industrial applications, also offers great potential.



Process:
Water jet cutting

Tool:
Wadiko pure water-sapphire nozzle type 10

Specimen:
TC Direct thermocouple type T

Process parameters:
Jetting time: t_S = 30.00 s
Working distance: a_W = 4.00 mm
Jet pressure: p_0 = 300.00 MPa
Nozzle diameter: d_D = 0.15 mm
Jet fluid: ■ H_2O

Figure 7: Jet temperature T_S of water jet cutting.

4 CONCLUSIONS

The described experimental and measurement setup provides a coherent and liquid high-pressure jet of CO_2 with and without abrasives which is comprehensible and reproducible. The experiments with specimens of AlMg3 have shown a general suitability of the process for a dry abrasive cutting process for various materials. The liquid CO_2 jet shows a similar behaviour to the water jet but with slightly lower kerf formation as a result of the different fluid density and machine system. The addition of abrasives into the liquid CO_2 jet and thus proof of the suitability for increasing the performance of the jet was shown. Solid CO_2 as an abrasive could not increase the cutting depth, but could produce unusual, undirected surface structures. Therefore, the acceleration of particles enables new potentials for opening up new applications, e.g. dry high-pressure shot peening or pretreatment prior to coating.

It could be shown, that the jet is fraying at the edge and a wave formation occurs, but with increasing jet pressure the jet is getting narrower and longer as well as the inside can be identified as homogeneous liquid CO_2. By increasing the jet pressure from $p_0 = 100$ to 300 MPa the jet characteristics regarding cutting performance, homogeneity and jet expansion directly after the nozzle outlet could be influenced positively.

The process can be optimized for a wide range of applications due to the possibility of influencing the jet properties by means of the process parameters. The phase conversion of the CO_2 jet can be used to machine workpieces within a certain temperature field.

However, another aspect that needs to be investigated is the effects on the workpiece surface depending on pressure and abrasive in order to widen the field of application. The targeted application of changing roughness and surface layer hardening would be a benefit.

5 ACKNOWLEDGMENTS

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6 REFERENCES

[1] Momber, W. A.; Schulz, R.-R.: Handbuch der Oberflächenbearbeitung Beton – Bearbeitung-Eigenschaften-Prüfung. Basel, Birkhäuser, 2006.

[2] Kolb, M.: Wasserstrahlschneiden – Materialbearbeitung mit einem Hochdruckwasserstrahl. In: Bibliothek der Technik Band 295. München, Moderne Industrie, 2006.

[3] Uhlmann, E.; Faltin, F.: Feasibility Study of Waterjet Fine Particle Peening. MFN Science Update, March issue 2018, pp 56 - 58.

[4] Uhlmann, E. (Ed.); Bilz, M.: Marktstudie Kohlendioxidstrahlen 2010. Fraunhofer-Institut für Produktionsanlagen und Konstruktionstechnik, Berlin, 2010.

[5] Dunsky, C.; Hashish, M.: Cutting with high pressure CO_2 jets. Allen, A. G. (Hrsg.). Washington: QUEST Integrated, 1994.

[6] Bilz, M.: Möglichkeiten und Grenzen des Strahlspanens mittels CO_2-Hochdruckstrahlen. Berichte aus dem Produktionstechnischen Zentrum Berlin. Hrsg.: Uhlmann, E. Dissertation, Technische Universität Berlin. Stuttgart: Fraunhofer IRB, 2014.

[7] Engelmeier, L.: Flüssige, kohärente Kohlendioxidstrahlen zum Schneiden von Materialien in atmosphärischer Umgebung. Berichte aus der Verfahrenstechnik. Dissertation, Ruhr-Universität Bochum. Herzogenrath: Shaker, 2017.

[8] Uhlmann, E.; John, P.: High-pressure jet cutting with liquid CO_2. In: Proceedings of the 23rd international conference on Water Jetting in Seattle, USA. Ed.: BHR Group, 2016, pp 315 - 326.

[9] Uhlmann, E.; Sammler, F.; Richarz, S.; Heitmüller, F.; Bilz, M.: Machining of Carbon Fibre Reinforced Plastics. Procedia CIRP, Volume 24, 2014, S. 19 - 24.

[10] Uhlmann, E.; John, P.: Advancements of the manufacturing technology with high-pressure liquid CO_2 jets. In: Proceedings of the 2017 WJTA-IMCA Conference and Expo in New Orleans, USA. Ed.: WJTA®-IMCA®, 2017.

[11] Uhlmann, E.; John, P.: Dry cutting with high-pressure liquid CO_2 jets. Advanced materials letters, Volume 10, Issue 1, pp 02-08, 2019. DOI: 10.5185/amlett.2019.2231.

7 NOMENCLATURE

a_W	Working distance
a_{WS}	Workpiece edge lenght
d_D	Nozzle diameter
d_{WS}	Workpiece thickness
k_B	Kerf width
k_{BM}	Middle kerf width
k_L	Kerf length
k_T	Depth of cut
p_0	Jet pressure
p_V	Supply pressure
p_{DL}	Abrasive supply pressure
t_S	Jetting time
T_S	Jet temperature
v_f	Jet feed speed