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Dry cutting with high-pressure liquid CO_2 jets

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Abstract

The main advantages of cutting with liquid jets are the flexibility and consistently 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. A new test stand was put into operation and a feed line with abrasives was added. Technological investigations concerning the formation of kerfs with high-pressure liquid CO_2 and water jets were performed with and without abrasives as well as subsequently analyzed. The cutting tests were carried out on parts of various metals and technical plastics. The influence of the fluid on the attained cutting surfaces and kerfs produced by the jet was investigated. The experiments indicate that the performance of the CO_2 jet as well as of the waterjet depends mainly on pressure and nozzle diameter but show different separation behavior. Especially the impact of the working distance will be discussed. The investigations reveal that high-pressure liquid CO_2 jet cutting has a high potential in the field of dry and residue-free cutting of metals, technical plastics and CFRP. Furthermore, no temperature influence was observed and the potential for jet cutting in 3D-applications and for hollow profiles was proven. Copyright © 2019 VBRI Press.

Keywords: Liquid CO_2, dry cutting, water jetting.

Introduction

Water jet machining has developed to a multifunctional tool for processing various technical materials. The main advantages of the technology, like continuous transport of chips, high flexibility and the availability of a persistently sharp tool with low thermal and mechanical load on the workpieces, still open up new fields of applications. For some applications, water jetting will not be considered as first choice of machining technology due to its additional process steps such as the microfiltration before as well as the post-treatment with the disposal of water, cleaning and drying of the workpieces after machining [**1, 2**]. The germ load and humidification, unhelpful for example in medical or cleanroom applications, are limiting factors of the conventional jet process and motivate to search for alternative cutting methods.

Due to the complete sublimation of the jet medium, jet cutting with carbon dioxide (CO_2) is a dry and residue-free process. The used CO_2 is a waste product of industrial processes and can be considered as environmentally neutral [**3**]. Snow blasting with solid CO_2 was established in recent years for pre-treating and decoating [**4**] but the low hardness of the particles prevents the ability to be more than a cleaning process. Therefore, jetting with liquid CO_2 represents an alternative option.

High-pressure jet cutting with liquid CO_2 as a jet medium was first investigated in a feasibility study by DUNSKY and HASHISH [**5**]. They proved the realisability of the process under atmospheric conditions and showed 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 an evaluation of kerf geometries on plastic specimens were conducted to show the industrial potential of a high-pressure jet cutting process. Originating from a joint research project with the PTC, ENGELMEIER [**7**] carried on investigations in order to analyse pressures and temperatures in the process and their influence on jet deformation and decay.

In previous work [**8, 9**] a general suitability of the process for a dry and residue-free cutting of metal materials was proven. Investigations on jet velocity, jet impulse force, jet distance and kerf geometry on aluminium specimen of AlMg3 using jet pressures up to

300 MPa led to knowledge about the main differences between plain water jet cutting and jetting with liquid CO_2.

Continuing, in this paper the process of jetting with liquid CO_2 should be supplemented by the addition of particles to open new fields of application. By investigations on the depth of cut for metals and plastics, depending on various influencing factors, the ability of increasing jet power will be discussed. Not only for common process parameters like pressure and nozzle diameter, but also for the working distance.

Method and Machine system

By using a prototype system, functional correlations between significant setting parameters and results were experimentally investigated in order to analyse the cutting properties of the CO_2 jet. The significant values to qualify the kerf geometry will be described. Following, the test stand and the measuring principle to analyse these values are described.

CO_2 test stand

The innovative liquid CO_2 cutting jet system is divided into three functional modules: A climatic chamber, a high-pressure pump and a cutting chamber (**Fig. 1**). The liquid CO_2 is supplied by a riser pipe bottle inside the chamber via high-pressure hoses to the suction side of the high-pressure pump. Depending on the temperature inside the climatic chamber, the supply pressure is regulated up to p_V = 9 MPa at a temperature of T = 40 to 50 °C [**6**]. Within the pump, liquid CO_2 is gradually compressed up to 300 MPa and pumped to the pulsation damper to the closed cutting head in the cutting chamber. The high-pressure intensifier pump is a Streamline 1 of Ingersoll-Rand plc, 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, is attached to a gantry robot which realises the chosen direction at the selected feed speed. The machining with the high-pressure CO_2 jet takes place on a worktable with the fixed specimen. The removed material falls through a grating and can be collected and analysed afterwards.

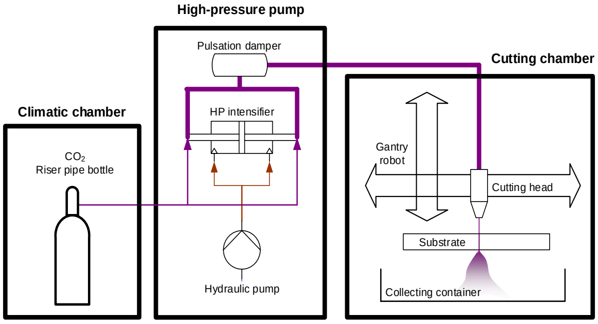

Fig. 1. Schematic sketch of the high-pressure liquid CO_2 jet cutting system.

CO_2 with abrasives

In order to increase the removal rate of the jet, additives 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 economical processed. The proof of concept and the industrial potential of liquid CO_2 cutting has already been demonstrated by Bilz [**6**] with a prototype out of many waterjet components. However, so far there were no additives added to the jet because of the phase transformation of the jet and its effects on the system periphery. Additives for liquid CO_2 cutting would have a big influence.

To investigate this, water abrasive injection jet cutting was chosen as an overall concept. It is established in the industry and there are technically mature 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 aim is to find out to what extent this technology is sufficient for jet cutting with liquid CO_2 or which modifications have to be carried out. 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. Different powders show different behavior and the dosing has to be tested. The additives have been Garnet sand with Mesh 80, 120 and 140 (d_G = 0.09 to 0.25 mm grain size) from BARTON International plc, Glen Falls, USA. Ceramic balls named microblast B120 from ARTEKA e.K., Backnang-Waldrems, Germany, with a grain size of d_G = 0.03 – 0.125 mm and plastic PA650 from Advanced Laser Materials, LLC, Temple, USA, with d_G = 0.03 – 0.1 mm. AlSi10Mg powder from SLM Solutions Group AG, Lübeck, Germany, with a grain size between d_G = 0.02 – 0.63 mm was the choice for metals.

However, different material density and powder size cause a different mass flow $\dot{m}$ of the additive behind the screw conveyor. However, this can be corrected by adjusting the rotational speed of the screw conveyor. First of all, the abrasive feed was calibrated for each powder. With a precision balance of the type PLS 1200-3A from KERN & Sohn GmbH, Balingen, Deutschland, the correct potentiometer settings were found.

Jet quality

To analyse 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 the 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 k_B was measured at half of the depth of cut. The kerf shape k_F is a qualitative value and compares the kerf profile along the abscissa axis by cutting vertically through the kerf (**Fig. 2**).

For the investigations metallic and plastic specimens were processed with different parameters. To show the cutting behavior on metals, specimen of rolled sheet with a thickness of 2 mm consisting of the aluminum alloy AlMg3 were processed. The material was chosen due to the characteristic properties of metal, but low hardness. The plastic specimens consist of Polyethylene (PE). They were supplied with the dimensions of 60 x 60 x 20 mm from CARL SPAETER GMBH, Berlin, Germany. The material were chosen due to their characteristic properties, e.g. shore hardness at room temperature, and a wide range of industrial applications (**Table 1**). Previous results regarding the jet impulse forces F_S [**8**] as well as preliminary tests led to the parameter field shown in **Table 2**. To provide statistically solid 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 digital microscope Dino-Lite Edge AM7915MZT from ANMO ELECTRONICS CORPORATION, New Taipei City, Taiwan. The second measurement system was the digital microscope VHX-5000 from KEYENCE DEUTSCHLAND GMBH, Neu-Isenburg, Germany. All following tests were repeated at least three times for statistical verification.

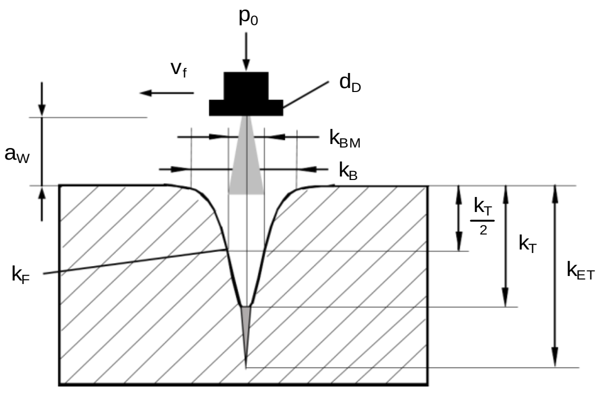

Fig. 2. Characteristic values to specify kerfs created with liquid CO_2 jets.

Table 1. Material properties of the specimens.

Material property	**Abb.**	**Dim.**	**Values for**	
Name	-	-	**AlMg3**	**PE**
Density	ρ	g/cm^3	2.66	0.95
E-module	E	MPa	70000	1300
Ball impression hardness	H_K	-	50 (HB)	57
Hardness Shore	H_S	-	-	D64
Melting temperature	T_M	°C	600	135
Brittle temperature	T_V	°C	-	-80

Table 2. Parameters to determine jet quality.

<table>
<tr><th>Expl. variable</th><th>Abb.</th><th>Dim.</th><th colspan="12">Input values</th></tr>
<tr><td>Jet fluid</td><td>-</td><td>-</td><td colspan="6">CO₂</td><td colspan="6">CO₂ + abrasive</td></tr>
<tr><td>Specimen material</td><td>-</td><td>-</td><td colspan="6">AlMg3</td><td colspan="6">PE</td></tr>
<tr><td>Abrasive</td><td>-</td><td>-</td><td colspan="3">Garnet</td><td colspan="3">Ceramic</td><td colspan="3">PA12</td><td colspan="3">CO₂</td></tr>
<tr><td>Jet pressure</td><td>p₀</td><td>MPa</td><td colspan="3">100</td><td colspan="3">200</td><td colspan="3">300</td><td colspan="3">-</td></tr>
<tr><td>Supply pressure</td><td>p_V</td><td>MPa</td><td colspan="3">9.00</td><td colspan="3">-</td><td colspan="3">-</td><td colspan="3">-</td></tr>
<tr><td>Nozzle diameter</td><td>d_D</td><td>mm</td><td colspan="2">0.10</td><td colspan="2">0.12</td><td colspan="2">0.15</td><td colspan="2">0.17</td><td colspan="2">0.20</td><td colspan="2">0.25</td></tr>
<tr><td>Working distance</td><td>a_W</td><td>mm</td><td colspan="4">5</td><td colspan="4">10</td><td colspan="4">15</td></tr>
<tr><td>Mass flow</td><td>ṁ</td><td>g/min</td><td colspan="4">250</td><td colspan="4">300</td><td colspan="4">350</td></tr>
<tr><td>Jet feed speed</td><td>v_f</td><td>mm/min</td><td colspan="3">0</td><td colspan="3">30</td><td colspan="3">60</td><td colspan="3">120</td></tr>
</table>

Results and discussion

Negative pressure

The usual ratio of nozzle diameter d_D to focus tube diameter d_F for waterjet cutting is $d_D/d_F = 1/3$, so that abrasive can be optimally brought into the jet. However, this ratio could not be confirmed for liquid CO_2 cutting in order to produce the necessary negative pressure. It turned out that for the present machine system the focus tube diameter has the greatest influence. In the course of this examination it was determined that a focus tube diameter of at least $d_F = 2.0$ mm must be present. With a diameter of $d_F = 3.2$ mm, a negative pressure was generated for all nozzles and pressures, therefore this was selected for the further tests. This identified a ratio $d_D/d_F = 1/32$, probably due to the immediate phase transformation from liquid to gas behind the sapphire nozzle. The gas flows abruptly in all directions and counteracts the negative pressure in the abrasive hose, the result of the actual volume flow direction.

Mass flow $\dot{m}$

Regarding the calibration of the mass flow $\dot{m}$ it turned out that the particle size and shape of the tested material plays a decisive role in the dosability. For very small grains, it is very difficult to dose the powder, as there is no longer a uniform flow from the storage container into the dosing chamber. Shaft formation took place in the storage container itself, so that the tested materials only continued to flow by vibrating the dosing unit.

This was observed with the PA powder and the ceramic abrasive, both have a very round grain shape. The aluminium powder has the smallest grain size and also showed the most irregular behaviour in dosing (**Fig. 3**). The garnet sands showed the best behaviour. The smallest dispersion of results was repeatedly achieved there.

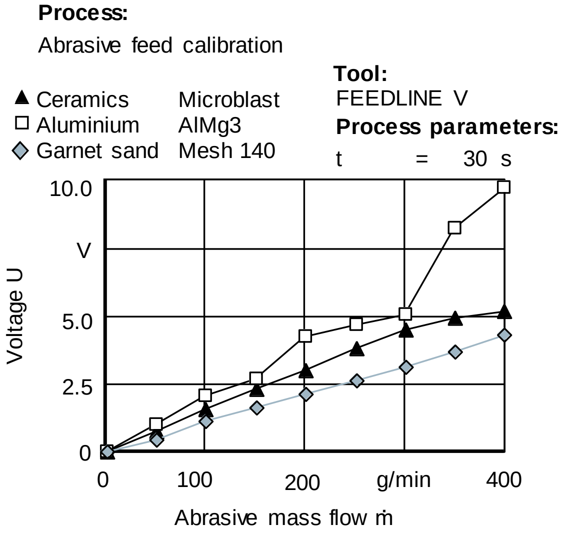

Fig. 3. Abrasive feed calibration for differentz materials.

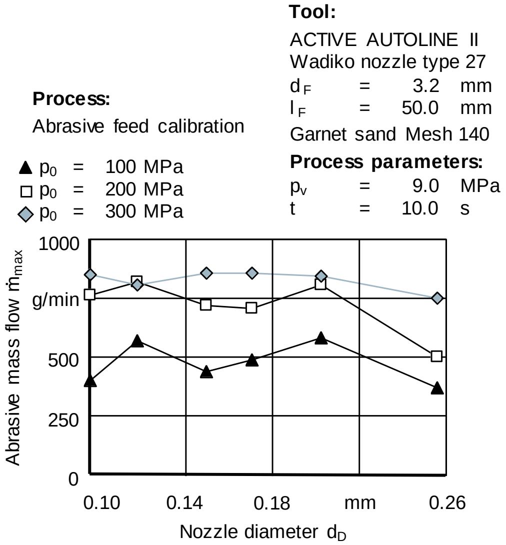

Fig. 4. Maximum abrasive mass flow for different pressures p_0.

Maximum mass flow $\dot{m}_{max}$

Subsequently, it was examined whether the negative pressure was sufficient to realize industrially targeted abrasive mass flows $\dot{m}$. All investigations were carried out with the $d_F = 3.2$ mm widened focus tube and garnet sand with Mesh 140. The maximum possible abrasive mass flow $\dot{m}_{max}$ depends on pressure and nozzle diameter. This showed that the abrasive medium is best sucked in at a nozzle diameter of $d_D = 0.15$ mm and $p_0 = 300$ MPa (**Fig. 4**). Thus, an abrasive mass flow of $\dot{m}_{max} = 862$ g/min could be realized. Furthermore, with a nozzle diameter of $d_D = 0.25$ mm and a jet pressure of $p_0 = 100$ MPa, the worst suction behaviour was determined. Here the achievable abrasive mass flow was $\dot{m}_{max} = 370$ g/min. It can clearly be seen that with $p_0 = 100$ MPa too little negative pressure is generated and that at $d_D = 0.25$ mm the volume flow generated by the prototype machine system is no longer sufficient to supply the large nozzle. Therefore, the following investigations were carried out not exceeding $\dot{m} = 350$g/min.

Creating kerfs

The investigations were divided into pure jet tests and abrasive jet tests 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 jet pressure p_0, nozzle diameter d_D, jet distance a_w and abrasive mass flow $\dot{m}$ were varied.

No measurable results were obtained for pure jetting with the abrasive cutting head. Only a cleaning of the surface was detected. That indicates that the distance to the work piece 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.

With pure jet cutting, the old cutting head without mixing chamber, a kerf could be determined for a jet pressure of 300 MPa for all measured nozzle sizes. The maximum depth of cut with $k_t = 449$ µm was achieved at 300 MPa, sapphire nozzle $d_D = 0.12$ mm and a jet distance of $a_w = 10$ mm (**Fig. 5**). 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 determined. The increase of the nozzle diameter from $d_D = 0.10$ mm to 0.12 mm causes an increase in depth of cut k_T by a factor of 1.92. 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 process described. If the nozzle diameters are $d_D = 0.10$, 0.12 mm and 0.15 mm, the volume flows seem to be sufficiently large for optimum removal with a necessary and good density of the liquid phase. Furthermore, it could be determined that the depth of cut as well as the kerf diameter increases with increasing distance to the specimen. The increase in depth of cut is explained by the fact that the CO_2 partially passes downstream into the gaseous phase and thus accelerates the CO_2 present in liquid form.

All abrasive jet cutting tests were carried out with the focus tube expanded to $d_F = 3.2$ mm. The tests with abrasives showed a significant increase in depth of cut 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 greatest 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 $d_D = 0.10$ mm to 0.15 mm causes an increase in depth of cut by twice to three times. Contrary to all expectations, the variation of the abrasive mass flow hardly seems to have any influence on the depth of cut. However, it is determined that each nozzle diameter tested has a certain abrasive medium mass flow optimally accelerated. For example, the deepest kerfs were measured for all pressure stages at an abrasive mass flow of $\dot{m}$ = 300 g/min and a nozzle diameter of d_D = 0.12 mm. With a nozzle diameter of d_D = 0.15 mm, the deepest kerfs were measured at an abrasive mass flow of $\dot{m}$ = 350 g/min. The jet distance a_W has no influence on the depth of cut k_T. However, it strongly influences the maximum kerf diameter k_D. For example, an increase of around 30 % was observed when the jet distance changed from a_W = 5 mm to 15 mm. Furthermore, it was determined that the kerf diameter is influenced together with the abrasive mass flow and jet pressure. For high abrasive mass flow $\dot{m}$, the kerf diameter k_B increases with increasing pressure p_0. If, on the other hand, it is low, the kerf diameter k_B decreases with increasing pressure p_0.

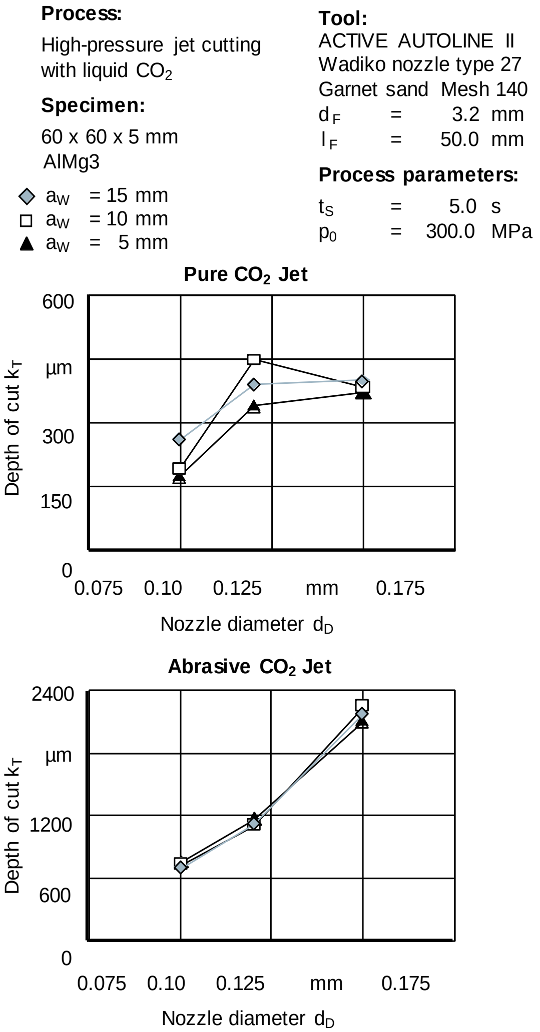

Fig. 5. Depth of cut k_T at AlMg3 for pure and abrasive jetting with CO_2.

The direct comparison between pure and abrasive jetting shows that in the abrasive jetting process radiate significantly deeper kerfs can be produced. These are 5.5 to 5.8 times more than the pure jet. The kerf diameter is also larger in abrasive jet cutting and exceeds the kerf diameter of the pure jet by up to 4.3 times. The ratio of k_B/k_{BM} is 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. A comparison between the different jet shapes is shown in **Fig. 8**, where the different length, quality and strength of the jet can be assumed.

In additional investigations also plastics have been processed with different jet feed speeds v_F. For a feed speed of v_F = 120 mm/min (**Fig. 6**) the depth of cut for Polypropylene (PP) increased up to k_T = 11.2 mm which is a tremendous rise of the jet performance. The combination of hard abrasive with the cold jet and high velocities has a big effect on the depth of cut for plastics which are softer than metals.

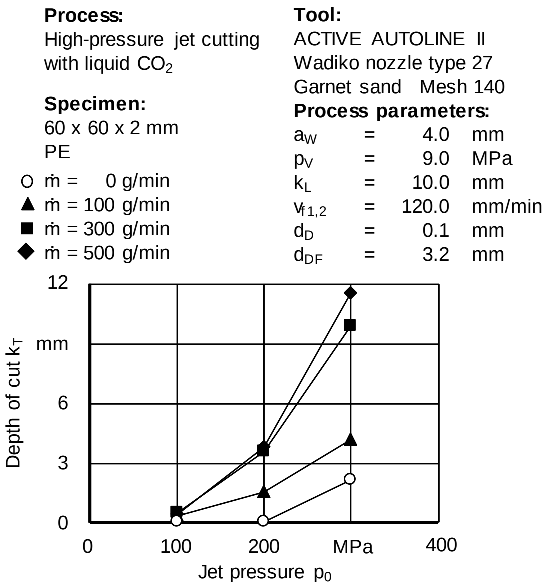

Fig. 6. Depth of cut k_T for pure and abrasive jetting of plastics.

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 600 µm in order not to block the focus tube and the mixing chamber. Therefore, CO_2 pellets from PRAXAIR DEUTSCHLAND GMBH, Düsseldorf, Germany, have been chopped and sieved. The surface of the AlMg3 specimens showed unusual undirected craters (**Fig. 7**). This small preliminary study had just little depth of cut but indicates a great potential for surface preparation before coating processes.

Fig. 7. Cutting surface at AlMg3 for liquid CO_2 with CO_2-microcrystals as abrasive.

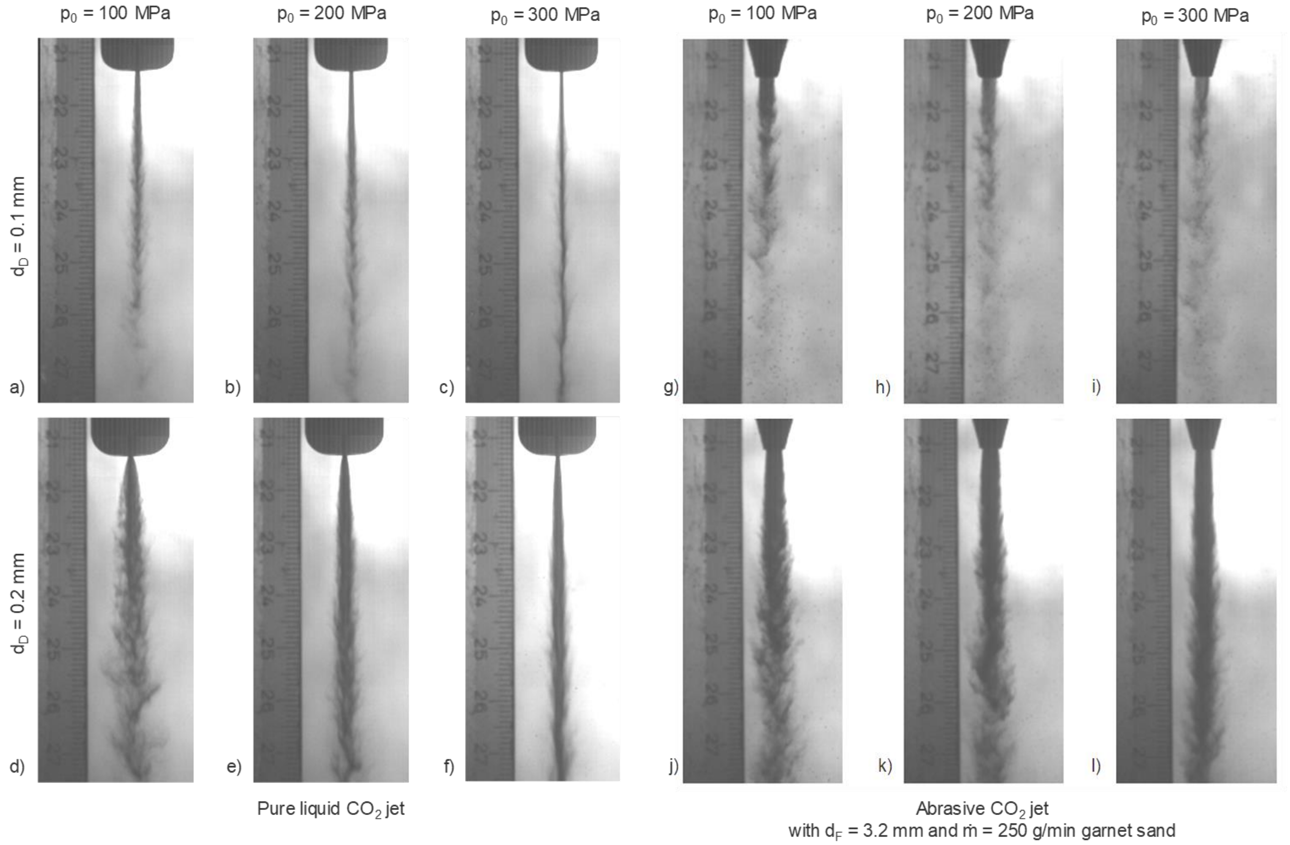

Fig. 8. Jet shape depending on varied d_D, and p_0 for liquid CO_2 with and without abrasive.

Conclusion and future perspectives

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 liquid CO_2 jet shows a similar behaviour to the plain water jet but with slightly lower kerf formation.

The particle addition into the liquid CO_2 jet was shown and thus proof of the suitability for increasing the performance of the jet but also for opening up new applications, e.g. dry high-pressure shot peening.

The experiments with specimens of AlMg3 and PE have shown a general suitability of the process for a dry abrasive cutting process for various materials.

By raising the nozzle diameter d_D and the jet pressure p_0 it was possible to increase the kerf formation significantly for both fluids.

The raising of the distance between the nozzle and the workpieces a_W as well as the jet pressure p_0 influences the depth of cut and kerf witdh. The effective liquid CO_2 jet length is especially depending on jet pressure and nozzle diameter and therefore qualified for robotic and hollow-chamber applications.

However, for a process that could be used in industry, further research is required. Other materials that can be used as abrasives must be tested. Another aspect that needs to be investigated is the effect of the temperature of the carbon dioxide in front of the nozzle. This significantly influences the jet shape and the time of the phase transition. The transition is strongly delayed at temperatures of -14 °C, as ENGELMEIER *et al.* [**7**] could show. This makes it possible to keep the diameter of the focus tube very small, so that even filigree structures can be processed. In the tests carried out in this work, the influence of the abrasive mass flow was classified as low. This may be due to the short jetting time of five seconds and the fact that the individual stages of the abrasive mass flow have been selected too narrowly. Another examination that needs to be done is jet cutting with different feed speeds. It is completely unknown how the kerf geometry changes when the jet moves over the work piece. The speed of the abrasive after leaving the focusing tube must also be investigated in order to gain a better understanding of the entire process.

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Supporting information

Authors have no competing financial interests.

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