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Effects of abrasive waterjet cutting on surface properties of hardened steel

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Abstract

The importance of cutting hardened materials without influencing their structural properties makes abrasive waterjet machining a favorable choice in certain applications in comparison with other manufacturing technologies. Using this technology, faulty surface structures and errors caused by high thermal loads such as burrs, burns and cracks, can be avoided. In this paper, the results of applying the abrasive waterjet technology for cutting of hardened steel and its advantageous properties in comparison with cut-off grinding will be presented. The influence of process parameters on surface properties and burr formation has been determined by experimental analysis.

Keywords: Abrasive waterjet machining; Hardened steel; Cut-off grinding; Burr formation

1. Introduction

Separating bars with small diameters made of hardened steel is usually conducted by applying the cut-off grinding technology [1]. This approach results in high temperatures within the cutting process, which leads to thermally influenced structural and surface errors on the workpiece, such as grinding burns, burrs and residual stress within the material [2]. These negative effects can be lowered by optimizing the machining strategy and process parameters in addition to using a CBN grinding wheel, which exhibits a high thermal conductivity and reduces the temperature transferred in the workpiece [3]. However, such an approach increases tooling costs and the overall processing time per one workpiece, which makes the application of these strategies applicable only when these factors are not of high importance. In this paper, a different approach for separating bars made of hardened steel using the abrasive waterjet technology is investigated.

The abrasive waterjet technology exhibits a high application versatility, due to the fact that it can be used for machining almost any technical material [4]. Because of its low thermal and mechanical influence on the processed material, structural and surface errors caused by these negative effects can be neglected [5]. Due to these properties the use of this technology is suitable for cutting of hardened steel. However, in comparison to the cut-off grinding, the abrasive waterjet technology exhibits some disadvantages caused by the shape of

Nomenclature

D	Diameter of the cut sample [mm]
d	Stand-off distance [mm]
h	Cutting thickness [mm]
p	Water pressure [MPa]
$\dot{q}$	Abrasive supply rate [g/min]
r	Edge radius in the jet entry zone [mm]
t	Time [s]
u	Angular (taper) error [mm]
$\dot{V}_M$	Material removal rate [mm³/s]
v_f	Feed rate [mm/s]
v_{fx}	Feed rate component in x direction [mm/s]
v_{fz}	Feed rate component in z direction [mm/s]
w	Width of the cut at the bottom of the sample [mm]
x	Distance in the feed direction [mm]

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the waterjet, its increasing spread with the increase of the stand-off distance to the workpiece and its energy loss with increasing cutting depth. Some results of these effects are different surface properties at the top and bottom of the cut, a tapered kerf and different edge properties at the jet entrance and the jet exit zone [4,5,6]. The presented research aims to analyze these effects and to define general conditions for abrasive waterjet cutting of bars made of hardened steel.

2. Experimental analysis

The cutting tests were conducted on a 5-axis abrasive water injection jet test machine. In order to generate the high water pressure needed for the jet formation, a Böhler Dynatronic 404R high-pressure intensifier pump was used. All tests were run with a water pressure of $p = 300$ MPa. In an abrasive water injection jet cutting head, the pressurized water flows through a water orifice which generates a high-velocity pure waterjet. This jet streams through the mixing unit creating a vacuum, which sucks in the abrasive material supplied through a hose. The abrasive material used in this experiment was garnet with a Mesh #220 particle size distribution. All tests were run with a constant abrasive supply rate of $\dot{q} = 25$ g/min. The generated mixture of water and garnet as well as the air that is being sucked in incidentally enter the focusing tube, where abrasive particles are being carried and accelerated by the stream of water. The inner diameter of the focusing tube defines the diameter of the exiting abrasive waterjet and is generally three times larger than the inner diameter of the selected water orifice [6]. In all experiments, a focusing tube with an inner diameter of $d_f = 0.3$ mm was used. The samples used in this experimental analysis were round bars with a diameter of $D = 7$ mm made of hardened high-strength steel 1.7102 (54SiCr6). The experimental setup is presented in Fig. 1.

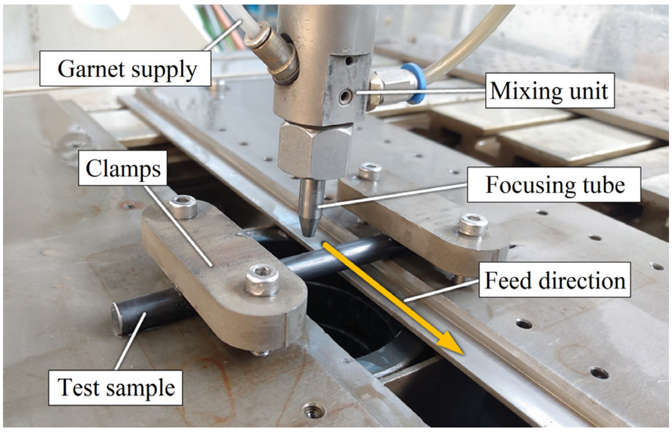

Fig. 1. Setup for the experimental analysis.

Due to the spread of the abrasive waterjet and its complex three-phase inner structure (water, garnet and air), the surface generated during the cutting process has a complex spatial shape with different features along the cutting depth. An increase of the surface roughness with the increase of the cutting depth can be observed [4,6]. In the jet entry zone, a wider jet affected zone caused by the spread of the waterjet results in an edge rounding towards the kerf. When machining hard materials, the entry zone is always wider than the jet exit zone [6]. This effect results in a kerf taper, which exact form is dependent on the selected process parameters. According to the recommendations of the Swiss-Norm SN 214001:2010, this taper is considered to be an angular error and is measured as a linear length value u, as shown in Fig. 2 [7,8]. On the jet exit side of a surface machined with the abrasive waterjet technology burr formation may occur. Its occurrence generally depends on the selected process parameters and the properties of the machined workpiece [9,10]. The size of the burr may generally be negligible, however, when machining very thin workpieces, a formation of relatively high burr can be observed [9]. The described surface properties are presented in Fig. 2 and they are investigated within this research work.

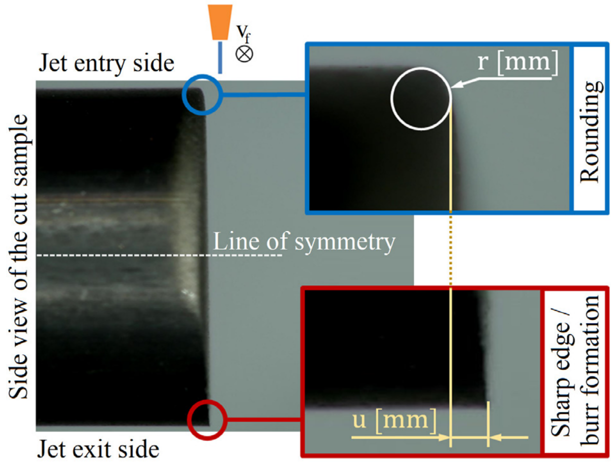

Fig. 2. Effects of the abrasive waterjet on the properties of a cut sample.

The value of the edge radii r in the jet entry zone was measured using the optical 3D surface measurement GFM MikroCAD microscope. Burr formation was observed using the Keyence VK-9700 laser scanning microscope. The observation of the surface properties was conducted using the Vision Makrolite digital microscope.

3. Results and discussion

In regard to the properties presented in Fig. 2, the influence of the process parameters on the properties of the cut were analyzed. Hereby, the achieved surface quality and the kerf width, radius of the edge in the jet entry zone and the shape of the edge in the jet exit zone were observed. The completed analysis of properties of the surface machined using the abrasive waterjet technology is used afterwards to provide a comparison with the cut-off grinding technology.

3.1. Linear feed motion

In order to analyze the surface quality of the cut in regard to the feed rate, two test cuts with a linear feed motion were conducted. The selection of a higher feed rate value results in a higher jetlag, which causes the appearance of grooves and an overall poor surface quality. An example of different surface qualities achieved using different feed rates is presented in Fig. 3. The measurement of surface roughness parameters was not conducted within this experimental analysis, as it was not of high interest by the application case.

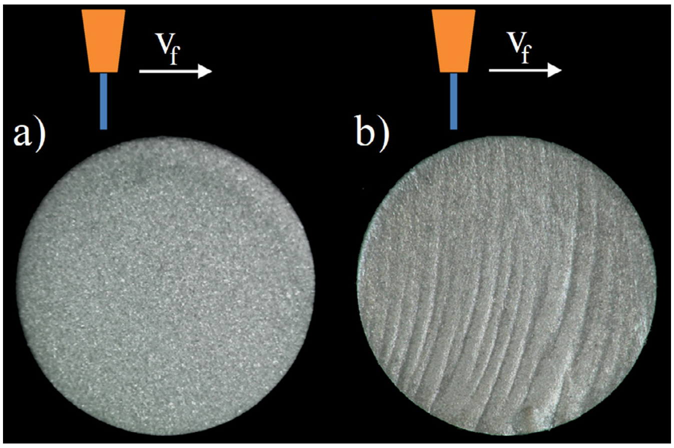

Fig. 3. Comparison of different surface qualities machined with different feed rates: (a) $v_f = 0.25$ mm/s (fine cut); (b) $v_f = 1.25$ mm/s (separation cut).

When cutting round bars using linear feed motion, a variable stand-off distance of the focussing tube in regard to the cut sample can be noticed. This change results in a larger jet influenced area at the top surface of the cut sample due to the radial expansion of the waterjet. This expansion not only results in an increase of this zone, but also influences the edge rounding in the jet entry zone, since the abrasive particles within the waterjet are being spread over a larger area. This dependence of the edge radius in the jet entry zone from the stand-off distance was measured for the sample presented in Fig. 3a. The results show that an increase of the stand-off distance generates an increase of the edge radius of the rounding in this zone. The results of this analysis are presented in Fig. 4.

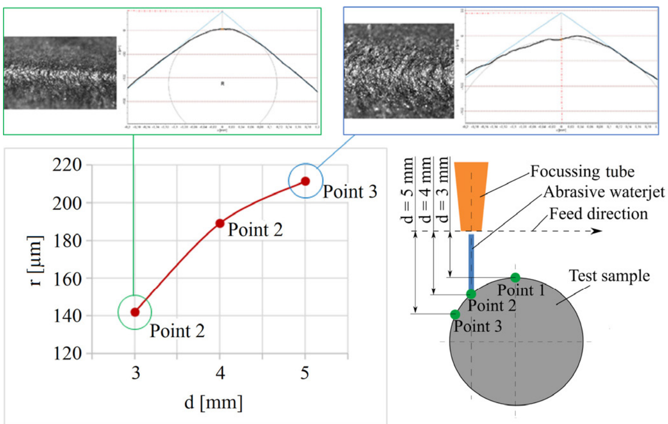

Fig. 4. Influence of the stand-off distance on the edge radius in the jet entry zone for the sample cut with $v_f = 0.25$ mm/s.

3.2. Adjustment of the feed motion

The increase of the stand-off distance furthermore results in an increase of the kerf width and the kerf taper angle. In order to eliminate these negative effects caused by the variable stand-off distance, a different cutting strategy with a motion that insures a constant stand-off distance can be applied. A comparison of these two strategies is presented in Fig. 5.

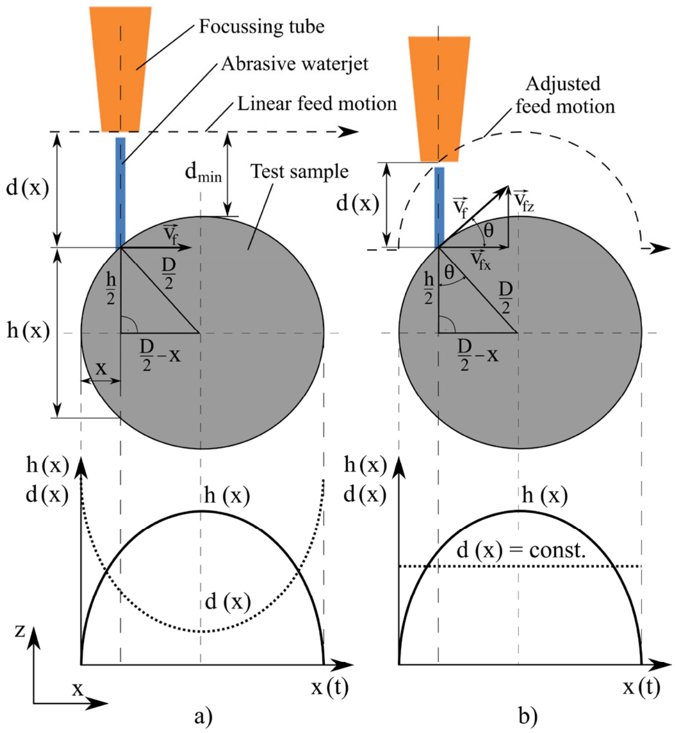

Fig. 5. Comparison of different feed motion strategies: (a) linear feed motion that results in a variable stand-off distance; (b) feed motion adjusted to the shape of the sample to ensure a constant stand-off distance.

When applying the adjusted feed motion presented in Fig. 5b, a uniform rounding of the sample edge in the jet entry zone can be achieved. However, due to the changing cutting thickness, keeping a constant feed rate results in variation of the kerf width along the cut. This can be explained considering the fact that the change in material thickness causes a change in the material removal rate.

According to Fig. 5b and based on [6], the material removal rate for the abrasive waterjet technology can be approximated as:

$$\dot{V}_M = h \cdot d_f \cdot v_{fx} \quad (1)$$

This approximation is geometrically simplified, due to the fact that it neglects the tapered shape of the kerf. According to Fig. 5a, the cutting thickness *h* at a defined distance cut in the direction of the feed motion *x* can be calculated using the following equation:

$$h = 2 \cdot \sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{D}{2} - x\right)^2} \quad (2)$$

Substituting the Eq. (2) into Eq. (1), the material removal rate can be calculated as:

$$\dot{V}_M = 2 \cdot \sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{D}{2} - x\right)^2} \cdot d_f \cdot v_{fx} \quad (3)$$

The Eq. (3) shows the relation of the material removal rate to the assumed waterjet diameter and the selected feed rate. The parameter *x* describes the location at which the material removal rate is calculated. Considering Eq. (3) it is certain that the material removal rate at a certain cutting location can be presented as a function of the feed rate. Keeping a constant material removal rate implies the application of a higher feed rate value at the start of the cut where the cutting thickness is at its lowest value and lowering it towards the middle of the distance in the feed rate direction, where the cutting thickness is at the highest value and equals the diameter of the test sample. Towards the exit of the cut, the feed rate has to be accelerated to compensate the decrease of the cutting thickness.

In order to achieve a constant material removal rate along the whole cut, the feed rate in the x-direction has to be adjusted during the cutting process using a rearranged Eq. (3), as follows:

$$v_{fx} = \frac{\dot{V}_M}{2 \cdot \sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{D}{2} - x\right)^2} \cdot d_f} \quad (4)$$

Based of Fig. 5b and Eq. (2), the general feed rate of the focusing tube in the direction tangential to the feed motion can be calculated as:

$$v_f = \frac{v_{fx}}{\cos\theta} = \frac{D}{h} \cdot v_{fx} = \frac{D}{2 \cdot \sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{D}{2} - x\right)^2}} \cdot v_{fx} \quad (5)$$

Substituting Eq. (4) into Eq. (5), the feed rate necessary to ensure a constant material removal rate can be defined as:

$$v_f = \frac{D}{4 \cdot \left(\left(\frac{D}{2}\right)^2 - \left(\frac{D}{2} - x\right)^2\right) \cdot d_f} \cdot \dot{V}_M \quad (6)$$

In order to analyze the influence of the feed motion with a constant material removal rate and to provide a comparison of this approach with the one that utilizes a constant feed rate, an experimental analysis was conducted. In both approaches the adjusted tool path, that ensures a constant stand-off distance during the whole cutting process, was applied. A comparison of the feed rate and the material removal rate for these two strategies is presented in Fig. 6.

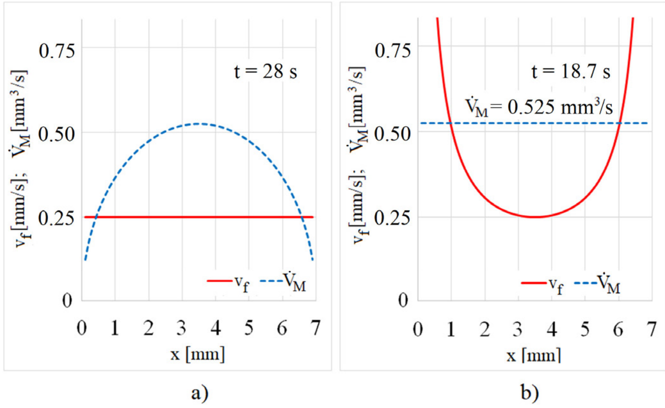

Fig. 6. Comparison of different cutting strategies: (a) Cutting with a constant feed rate v_f; (b) Cutting with a constant material removal rate $\dot{V}_M$

In order to compare the cut properties for these two cutting strategies, the width of the cut at the jet exit side (bottom of the cut) was measured. In this analysis, the cutting was conducted up until the abrasive waterjet passes the half of the sample, as shown in Fig. 7. It was observed that cutting with a constant material removal rate results in a lower difference of the cutting width on the bottom of the sample along the whole cut. The strategy of cutting the test samples with a constant material removal rate not only results in a better uniformity and quality of the cut surface, but also in an increase of productivity due to the fact that higher feed rates are applied for cutting lower material thicknesses.

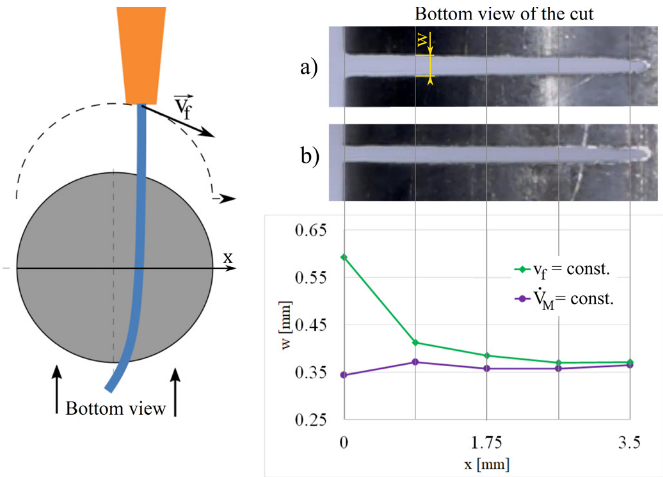

Fig. 7. Comparison of the width of the cut at the jet exit side: (a) Cutting with a constant feed rate v_f; (b) Cutting with a constant material removal rate $\dot{V}_M$.

3.3. Burr formation in the jet exit zone

An exemplary edge in the waterjet exit zone of a cut sample is presented in Fig. 8. Observing this zone, burr formation can be expected. However, in the experimental analysis of cutting the test samples, none or negligible burr formation was observed. Although a dependence of the edge shape to the surface quality of the waterjet cut surface can be noticed, a significant influence of the process parameters and the resulting surface quality to the formation of a burr at the bottom surface could not be observed in any of other tests conducted with different parameter combinations.

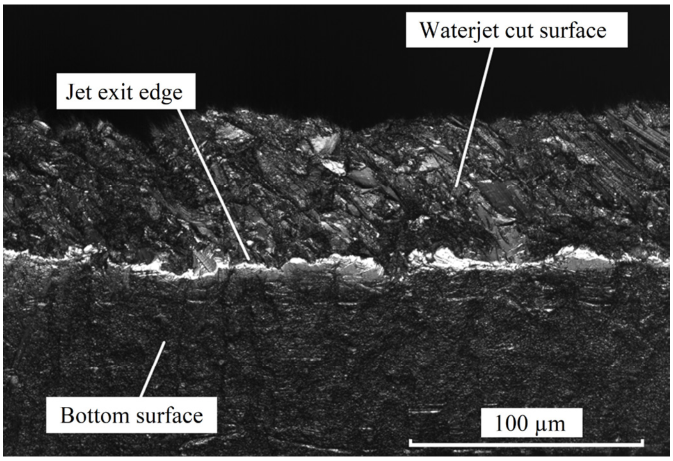

Fig. 8. Edge shape in the jet exit zone.

This non-occurrence of a burr on the bottom surface could be a result of good mechanical properties of the machined material and the relatively high thickness of the samples, as well as the negligible thermal and mechanical load of the abrasive waterjet on the processed material. The measurement conducted for the separation cut with a low quality surface (sample shown in Fig. 3b) is presented in Fig. 9.

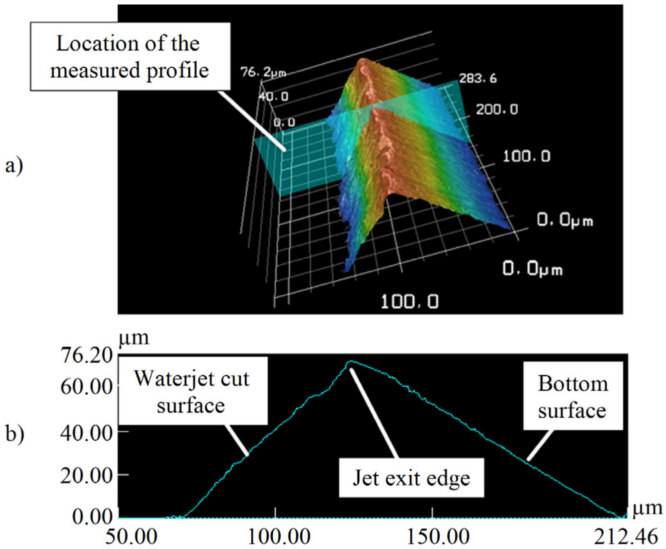

Fig. 9. Profile of the edge in the jet exit zone for a separation cut with a low quality surface: (a) 3D-View of the cut edge and the cross-area where the profile was measured; (b) Profile of the edge without burr formation on the bottom surface of the sample.

3.4. Comparison with cut-off grinding

Since the thermal influence of the abrasive waterjet technology on the machined workpiece can be almost neglected [4], it exhibits certain advantages over the conventionally used cut-off grinding process. Using the cut-off grinding process, the high thermal load on the workpiece caused by the relatively large contact-zone between the workpiece and the grinding tool results in a softening of the hardened material. Instead of being separated with a clean cut, this effect causes the material to be plastically deformed in the feed direction of the grinding wheel, which results in burr formation [11]. Furthermore, this high thermal load causes change in the material structure and other processing errors such as grind burns and residual stresses [2,12]. Aiming to reduce this thermal influence on the workpiece, coolant fluids can be used in order to remove a part of the generated heat in the cutting zone. The application of coolant strategies can reduce these mentioned processing errors. However, a complete prevention of their formation cannot be completely ensured [2]. By comparison, the application of the abrasive waterjet technology does not generate any heat affected zone in the workpiece. The conducted experimental analysis showed no burr formation on the bottom surface of the cut samples.

However, a disadvantage of the abrasive waterjet technology in comparison with cut-off grinding may be the tapered kerf shape for some applications where a straight cut has to be ensured. Even though this effect cannot be completely avoided, the experimental analysis showed that a reduction of the taper angle and an improvement of the surface can be achieved by selecting a lower feed rate, keeping a constant stand-off distance and by adjusting the cutting strategy. In addition to that, keeping a constant material removal rate during the whole cutting process ensures a better uniformity of the surface properties and the shape of the kerf along the whole cut.

4. Conclusion

In this research work, the influence of common abrasive waterjet process parameters and different cutting strategies on the surface quality and kerf properties were presented. Based on the study of the results gathered within the conducted experimental analysis of the abrasive waterjet cutting of the hardened high-strength steel 1.7102, following statements can be concluded:

- The increase in feed rate results in an increase of the angular (taper) error of the kerf due to the formation of a higher jetlag, which endorses the appearance of grooves and results in a lower cutting quality.
- Due to the round shape of the samples, a straight feed motion results in the change of the stand-off distance along the cut. The increase of the stand-off distance results in a radial expansion of the abrasive waterjet which results in an increase of the kerf width, angular (taper) error and the edge radius in the jet entry zone. A feed motion which follows the outer contour of the sample and ensures a constant stand-off distance results in uniform properties of the jet entry zone.
- The change of the cutting thickness in the feed direction results in an irregular shape of the surface of the cut. Keeping a constant material removal rate results in an improvement of the surface shape and increases the overall

productivity of the cutting process. Furthermore, a higher uniformity of the kerf width along the cut on the bottom side of the sample was observed when keeping a constant material removal rate in comparison with keeping a constant feed rate.

- No burr formation at the edge in the jet exit zone was noticed. The explanation for the non-occurrence of burr at the bottom edge can be the relatively high material thickness and the good mechanical properties in regard to tensile strength and material hardness, as well as the low thermal and mechanical load on the material.
- Compared to cut-off grinding, the abrasive waterjet technology exhibits advantageous properties regarding thermal and mechanical loads. However, the kerf taper and the lower productivity of the abrasive waterjet technology have to be considered when choosing the proper technology for a certain cutting application.

Acknowledgements

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