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Abrasive waterjet turning of high performance materials

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Abstract

The cutting of high performance materials requires specific machine tools and cutting tools. The wear resistance of cutting tools is important for turning of hypereutectic aluminium silicon or titanium aluminide alloys. Abrasive waterjet turning has been shown to be a suitable cutting process for these challenging materials. The tool life time of at least 10 hours combined with a material removal rate of up to 0.8 cm^3/min and low process temperatures give this cutting technology a very high potential. Furthermore the material close to the cutting surface is less modified compared to conventional rough turning. The same effects are of particular interest with regard to the functional capability of waterjet turned γ-TiAl-alloys.

Keywords: Waterjet machining; Turning; Aluminium; Titanium aluminides; Cutting

1. Introduction

For the last decade it has been known, that substantial advancements could be made by using γ-titanium aluminide for applications in the aerospace industry. This material offers similar properties to nickel alloys with regard to its strength to density ratio. However, no material innovation is possible without an appropriate machining technology [1].

Development with regard to a higher energetic efficiency of work and power engines leads to the usage of lightweight but functionally capable materials. The high requirements of e. g. the design of turbines and power engine components are the minimum demands for improvements in industrial and production technology engineering [2].

The properties of these alloys make them on one hand very attractive for use in high performance applications but on the other hand render them to be extremely difficult to machine. Low thermal conductivity and high hardness for example lead to limitations regarding the applicable machining parameters, particularly continuous turning operations. Cracks and break-outs in the machined surface can result due to the low fracture toughness. A wide acceptance of these promising high performance materials by the industry can only be achieved if appropriate machining technologies can ensure reliable and economic machining [3-5].

This investigation presents waterjet turning as an alternative or as an additional preliminary rough turning technology to manufacture rotational parts out of high performance materials such as hypereutectic aluminium silicon or titanium aluminide alloys. Waterjet cutting with abrasive additives is a well-established two dimensional cutting tool in the metal and sheet metal industry. Furthermore, waterjet cutting has achieved a high acceptance as a universal and flexible production process especially with regard to the variety of machinable materials.

2. Motivation

The wear resistance of cutting tools is a significant issue for economic evaluations of turning hypereutectic aluminium silicon or titanium aluminide alloys. Side effects of turning aluminium alloys are for instance the abrasive wear caused by the hard silicon grains or the built-up edge resulting from the soft aluminium matrix. Cutting of a γ-TiAl-alloy is limited by the temperature stability of the titanium component [3-5].

Uhlmann et al. [6] and Herter [5-6] investigated the performance of machining titanium aluminium alloys by

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conventional turning with different cutting part inserts. Herter describes a material removal rate (MRR) up to 3 cm³/min at a tool life time of 18 min with round and chamfered cutting inserts [5]. For the investigations a near-gamma structured Ti44.5Al5Nb extruded alloy was used as workpiece material and cemented carbide was chosen as the tool material. A cutting speed of $v_c = 30$ m/min, a feed of $f = 0.1$ mm at a depth of cut of $a_p = 1$ mm as well as a cooling lubricant at a jet pressure of $p_A = 0.5$ MPa was used for the investigation of the tool life time. Another characteristic to qualify cutting tools is the volume of removed material during the tool life (tool life volume). Herter identified a maximum tool life volume of 55 cm³ [5-6].

In contrast to conventional cutting processes the tool life criteria of abrasive waterjet (AWJ) cutting, especially the tool wear, are dependent on the process time. Abrasive waterjet turning (AWJT) combines the advantages of waterjet cutting with the kinematics of a conventional turning process. The resulting influential factor on the material removal rate and the abrasive mechanisms are quite different to the plain waterjet cutting. However, the fundamental parameters for a combined process, e. g. pressure, rotational speed or depth of cut, have to be evaluated.

Hashish [7] investigated the AWJT parameters jet pressure, the abrasive flow rate, the abrasive particle size, the orifice size and the feed rate. Most of the experiments were performed with a standard aluminium workpiece material (AlMg1SiCu). It was noted that Hashish and Ansari [8] achieved a maximum MRR of 9 cm³/min for such ductile materials. An additional result of Hashish was that the maximised MRR correlates with coarse-grained surface conditions [7-8].

The design of experiments was used to identify the influences of varied parameter settings on MRR as well as surface and geometrical characteristics. Firstly, the significance of main and multi-interaction effects on AlSi17Cu4Mg cylindrical workpieces was analysed.

The results are expected to allow the definition of parameter settings for excellent cutting results of titanium aluminium alloys, which combine high material removal rates with a defined surface quality. As a consequence, the roughness and altered surface layer properties were analysed. In contrast to conventional rough turning less surface hardening is expected.

3. Experimental method

The experimental investigation was conducted with a waterjet system based on a five axis robot manipulator. The robot combines a flexible path routing with the necessary precision, stability and stiffness. To rotate the workpiece material, an implemented spindle with maximum rotational speed of up to 2,000 rpm was used. The abrasive flow rate can be varied from 100 g/min to 600 g/min. The selection of the orifice size, focus length and focus diameter is based on previous experience and commonly used parts. The pressure source is a hydraulic intensifier with a maximum water volume flow rate of 2.5 l/min and a 45 kW electric motor. In combination with the cutting head and an orifice diameter of 0.25 mm, a water pressure of up to 600 MPa can be applied. The machine setting parameter variations are summarised in figure 1.

The investigation comprehends a full factorial experimental design of six factors with two settings of each parameter. The settings were chosen through preliminary tests. The design of experiments included a triple repetition of each setting combination and a randomisation to avoid coincidental interferences. For a time efficient test procedure, the generated experimental design was structured in eight blocks according to the standardised test plan of Scheffler [9]. Target values were the depth of cut, which deviated from initial to final workpiece diameter as well as the change of surface roughness Ra and the established effective roundness variation.

a_p	depth of cut
p_A	jet pressure
d_F	focus diameter
m_A	abrasive flow rate
D	outside diameter
θ	jet entry angle
d_E	shaft diameter
v_f	feed rate
α	jet impact angle
l_F	focus length
n	rotational speed

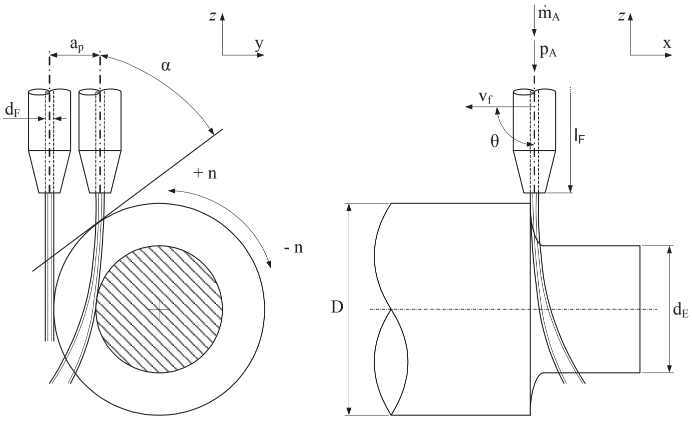

Fig. 1. Main settings of abrasive waterjet turning

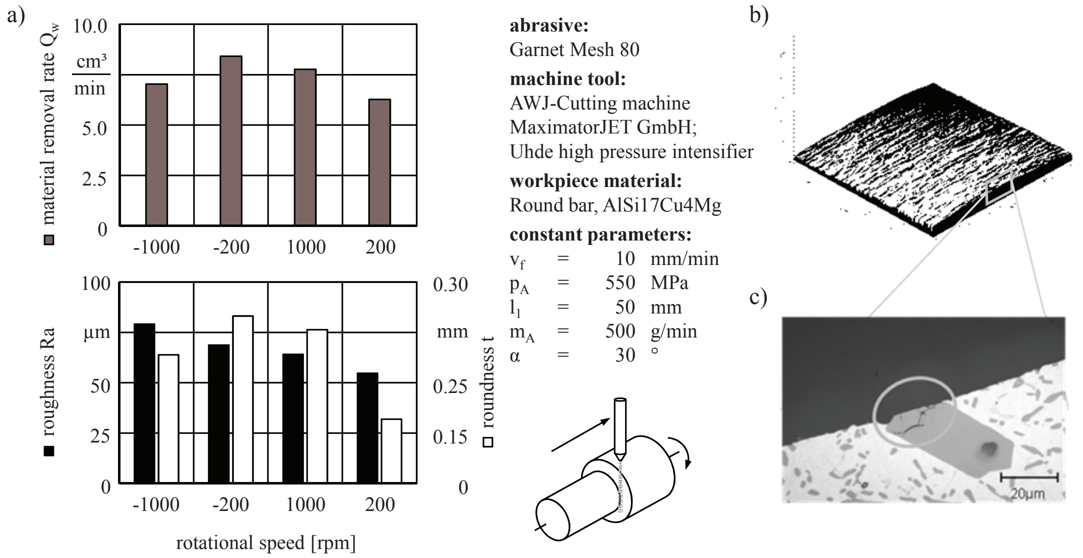

Fig. 2. a) Determined material removal rates for AWJ-turning with Ra up to 85 µm, b) surface topology of AWJ turned AlSi17Cu4Mg workpiece, c) low grade of grain damage in the workpiece boundary layer by AWJT recorded with SEM

4. Results and Discussion

The abrasive waterjet turning experiments on AlSi17Cu4Mg workpieces showed a significant relationship of the main influencing factors impact angle, water pressure and feed rate. Furthermore, the two factor interactions of feed rate combined with jet impact angle and jet pressure combined with jet impact angle have a significant influence with regard to the surface roughness Ra.

Figure 2 a) shows the highest material removal rates with an average surface roughness of Ra = [50..80] µm. All four presented test setups have a constant parameter setting for jet pressure, feed rate, jet impact angle and abrasive flow rate. The lower the rotational speed, the higher the measured MRR. The local maximum of 8.5 cm³/min was achieved at a rotational speed of 200 rpm in the opposite direction to the jet flow.

The investigations showed a high standard deviation of the surface roughness with respect to the determined MRR. Figure 2 b) shows an example of AlSi17Cu4Mg surfaces machined with AWJT, detected with the optical surface measuring system of Microprof-FRT. To measure the surface quality, the average surface finish was determined with a Taylor Hobson ultra precision tactile instrument type Form Talysurf 120 L. The produced surface roughness varies within a range of Ra = 5.5 µm up to Ra = 142.5 µm.

The initial and target roundness of the workpieces was measured with a portal measuring system Prismo Vast No. 7 HTG from Carl Zeiss IMT GmbH according to DIN EN ISO 1101. The roundness varied from t = 0.06 mm to t = 0.26 mm referenced to the related workpiece diameter of d_E = 74.9 mm.

Micro hardness profiles of abrasive waterjet turned cylinders showed a small difference between boundary and bulk hardness. This effect is particularly important with regard to the functional capability of machined high performance materials. To investigate the behaviour of AlSi17Cu4Mg with regard to general hardening effects of the boundary surface layers the effective hardening depth was analysed. In figure 3 the measured micro-hardness in dependence of the depth from surface is shown. The AWJT manufactured workpieces showed a small hardening effect along the penetration depth. The profile has an almost constant distribution with a minimal absolute difference of 6.8 HV 0.05. In contrast, the conventional turned cylinders show a decreasing distribution with an asymptotic behaviour against the bulk hardness of 100 HV 0.05. The maximum hardness of the surface layer of 155.8 HV 0.05 for conventional

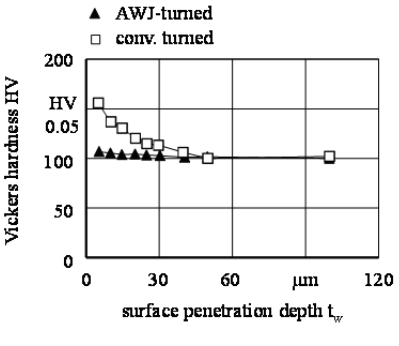

Fig. 3. Hardness profile on AlSi17Cu4Mg

turning was measured at a depth of 5 µm.

Another aspect to analyse the workpiece surfaces with respect to the manufacturing process was the grain damage. The cut silicon grains were counted and classified as shown in figure 2 c). In figure 4 the relative grain damage of AWJT and conventional turned surfaces is shown. The corresponding parameters and settings are listed in table 1.

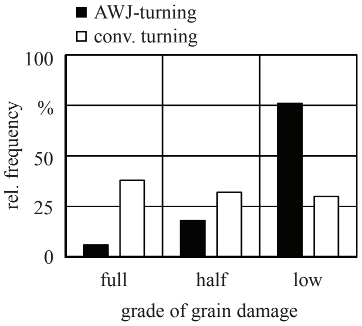

Fig. 4. Level of grain damage for conventional turning vs. AWJ-turning on AlSi17Cu4Mg

The total numbers of grains in the workpieces manufactured by both processes is 155. Figure 4 shows a balanced distribution for the conventional turning regarding the three damage classes in comparison to the abrasive water jet turning. AWJ turned cylinders show a higher proportion of only partially broken silicon grains in the boundary layer. The higher number of micro-cracks in the boundary layer is shown for example in figure 2 c). The silicon grains are not damaged in such a way as in conventional turning. In addition, the resulting cracks are not filled with melted material due the missing heat affected zone. Figure 5 shows the grain damage caused by conventional turning. The grain is entirely broken and the fragments are embedded in a matrix of melted aluminium. These broken fragments were detected to a depth of up to 70 µm.

Based on the results of the identification of the main factors in abrasive waterjet turning of AlSi17Cu4Mg, the machining of Ti44.5Al5Nb (TNBV5) shall be further investigated. The same parameter settings were used as described for the test setup in figure 2 a). The results of the tests on the two different materials are therefore comparable. Because of the smaller dimensions of the test specimen, a smaller depth of cut is required. The result of an impact angle of α = 30° by an initial diameter of 12.2 mm results in a depth of cut of 1.3 mm. The test sequence was repeated twice and designed analogues to the investigation on AlSi17Cu4Mg.

In this regard, a MRR of $Q_W = 0.3$ cm³/min was determined at an average surface roughness of Ra = 5 µm. An additional preliminary experiment with a depth of cut of 3.3 mm and a final diameter of $d_E = 4.98$ mm was conducted and led to a MRR of $Q_W = 0.8$ cm³/min at the same surface quality as shown in figure 6. To investigate the manufacturing accuracy of the AWJ turned cylindrical bodies with diameters of 3.9 mm, the roundness and the geometrical tolerance were measured. Roundness and the geometrical tolerance have the same value of t = 0.043 mm according to DIN EN ISO 2768-2. The roundness tolerance class for the manufactured cylinder is "H". The acquirable surface quality with a mean roughness of Ra = 5 µm and Rz = 24 µm can be placed in the tolerance class "fine", according to DIN EN ISO 8503-1.

The maximum MRR of AWJ turned AlSi17Cu4Mg workpieces of $Q_W = 13$ cm³/min applies to be insignificant in comparison to a theoretical MRR of up to 70 cm³/min of conventional turning. This is likely a consequence of the ductile material behaviour of the aluminium proportion. Additionally, the higher strength and fracture toughness counteracts the abrasive removal mechanism. Regarding the MRR, the conventional turning is favourable. Taking the tool life of more than 10 hours and the tool life volume into account the AWJT is an economic alternative. Blickwedel [10] recognised an earlier negative wear influence with regard to the cutting quality after an operating time of 4.5 hours, which is nevertheless an improvement on typical tool life in conventional cutting processes. AWJT has the same or a higher MRR than conventional cutting tools with respect to the turning of γ-titanium aluminide. The detailed relations between wear and machinability are for example influenced by the cutting time, the rotational speed, the feed rate and the depth of cut. In fact the last parameters are negligible with regard to the tool life time

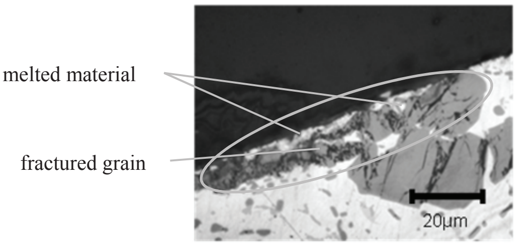

Fig. 5. SEM picture of grain damage in the boundary layer grade: full

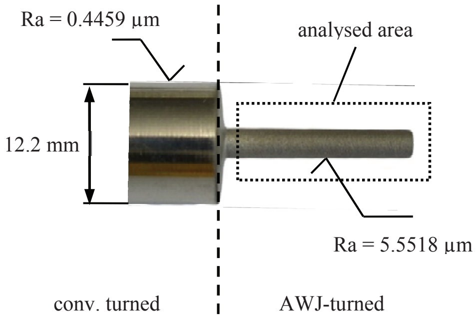

Fig. 6. Determined cylinder of TNBV5

of abrasive waterjet turning.

Due to the long tool life the AWJT has an estimated life time volume of 178 cm³ when machining TNBV5. For this calculation a life time of 200 min and a MRR of 0.89 cm³/min are assumed. As expected, a less hardening in the surface layer was occurred during the investigations on workpieces of AlSi17Cu4Mg.

The hardened profile of AWJ turned TNBV5 specimen in the surface boundary layer is shown in figure 7. The values for the micro-hardness due to conventional turning of TNBV5 are a result of Herter's investigations [5]. Except for the first measured value at 5 µm, the distribution of the AWJT-hardness is almost constant at the level of the bulk material in comparison to the conventional turned workpieces of Herter. The hardness penetration depth of conventional turning is also higher than for AWJT manufactured cylinders. The hardness of the surface skin layer is considerably lower for AWJT than in results of Herter. Even with regard to the hardness affected zone, AWJT generates a minimal hardening in the boundary surface layers.

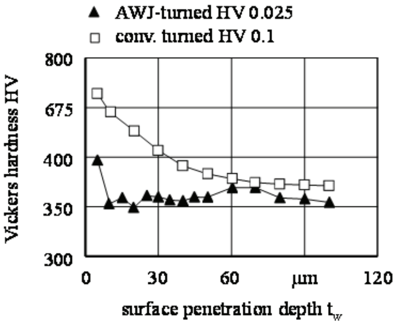

Fig. 7. Level of grain damage from conventional turning to AWJ-turning on AlSi17Cu4Mg

5. Conclusions

Abrasive waterjet turning of γ-TiAl-alloys results in a small mechanical effected zone within the same range of material removal rate in comparison to conventional turning. The determined numbers of micro-cracks in the boundary surface layer may lead to a reduced fatigue resistance. The results can be summarised as follows:

1) AWJT reaches a tool life time volume of 178 cm³ when turning of TNBV5 for a specified life time of 200 min.
2) The AWJT achieves a maximum MRR of 13 cm³/min when turning AlSi17Cu4Mg and 0.8 cm³/min when turning TNBV5.
3) The mean surface roughness Ra for AWJ turned TNBV5 workpieces ranges from 5 to 20 µm.
4) AWJT results in a lower hardness penetration depth in comparison to conventional turning.

6. Outlook

The influences of the AWJT on manufactured cylindrical geometries has to be investigated further with respect to the mechanical properties, e. g. the fatigue resistance. These Investigations show that AWJT is an economic production process for the machining of innovative and difficult to machine materials.

Table 1. Setting parameters of the grain damage research on AlSi17Cu4Mg workpieces

setting parameters		AWJT		conv. turning	
feed rate	v_f	10	mm/min	100	mm/min
rotational speed	n	200	rpm	500	rpm
jet pressure	p_A	550	MPa	-	-
jet impact angle	α	30	°	-	-
abrasive flow rate	m_A	500	g/min	-	-
lubrication cooling		-	-	none	l/min
depth of cut	a_p	1.5	mm	0.25	mm

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