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Paper

CASE STUDY ON POSSIBLE PRODUCTIVITY IMPROVEMENTS OF WATERJET TURNING OPERATIONS

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ABSTRACT

Cutting with high pressure abrasive waterjets offers the possibility to shape workpieces with the kinematics known from conventional turning. A previous investigation has shown that abrasive waterjet turning (AWJT) can be used for roughing to reduce the tool wear for challenging materials e.g. hypereutectic AlSi-alloys. However, so far the combined process takes longer than the conventional process chain. In this study, new strategies for AWJT are considered to reduce the process time.

Trepanning into a flat surface is possible for deep and small kerfs with AWJT. A whole piece can be extracted from a workpiece when the process is combined with a radial cutting operation. Hence, the volume removal rate increases to a higher value. In this study feasibility, process times and volume removal rates were calculated and evaluated for a number of possible strategies, following the procedure described above. The combination of waterjet turning operations offers an additional benefit for aluminum alloys. The study shows promising results for the combined processes, especially for difficult to machine materials.

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1. INTRODUCTION

The use of high-performance materials allows lightweight design and efficiency improvements especially for the automotive and aviation industry. The ongoing development of these high-performance materials signifies challenges for todays manufacturing methods due to the hardness, brittleness and low thermal conductivity of some materials. Aluminum silicon alloys such as G-AlSi17Cu4Mg (AlSi17) offer a high strength to density ratio and good wear resistance [1]. Therefore, the material is a favorable option for a number of applications. The good mechanical performances emerge from the hypereutectic silicon crystals in the material structure. Unfortunatly, the silicon crystals also lead to high abrasive and adhesive wear during the machining process [2]. High amounts of silicon particles and increasing particle size raise the abrasive tool wear even more [3]. Hard cutting tools like brazed polycrystalline diamond (PCD) tools are used for turning of AlSi17 [3, 4]. In order to enable complex shaft-type tools CVD-diamond coatings can be applied and allow cutting with a long tool life time and reaching high surface qualities [3]. However, tool failure due to sudden delamination of the diamond layer limits the cost-effective cutting of aluminum silicon alloys [5, 6].

Abrasive waterjet (AWJ) cutting has shown its suitability for manufacturing challenging materials [7]. The main advantage is its independence of the material to be processed. In addition, initial surface conditions and material inhomogeneity have no repercussions on the tool, the AWJ [8]. Hence, the wear of the focus nozzle and the waterjet orifice only depends on process inherent parameter settings. AWJ cutting is commonly used in industry for sheet metal cutting and has obtained a high acceptance as a universal and flexible production process. Intensive scientific research allows the application of the process, not only for cutting sheet metal but also for manufacturing more complex geometries like pockets and rods with milling and turning operations [7, 8, 9].

HASHISH [9] was the first to investigate abrasive waterjet turning (AWJT) as an approach to use the AWJ for more than 2-dimensional cutting and to broaden the application fields of the process. The investigation has shown that the process can be used for near-net-shaping of workpieces. Further investigations have shown that the turning operation can be applied to manufacture a variety of 3D workpieces [10]. Kerf slotting was investigated by HASHISH and ANSARI [11]. The investigation provides a model for kerf slotting which relates well with the measured kerf depth. The authors found the process to be suitable for slicing of wafers.

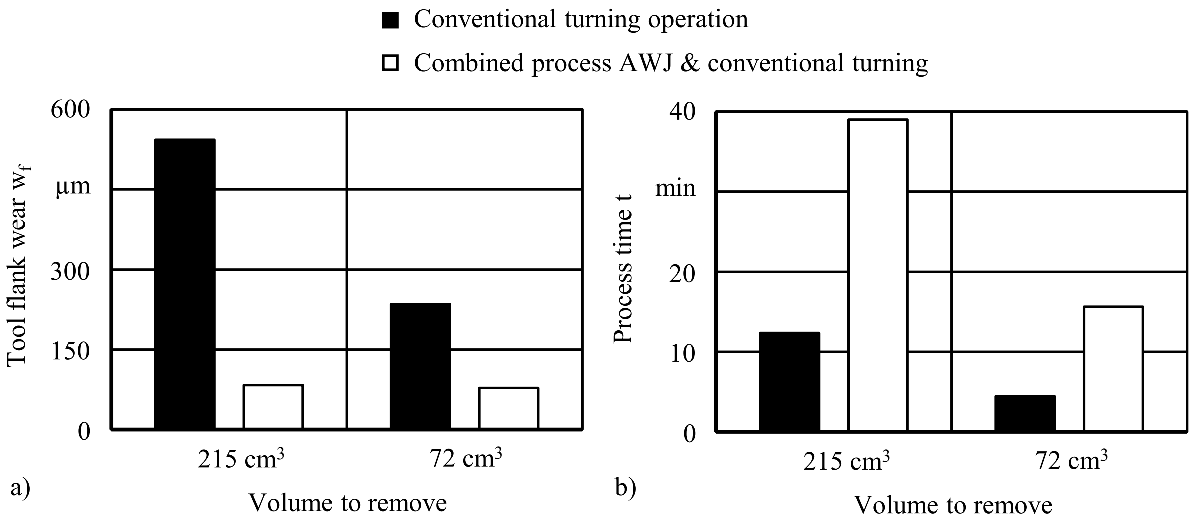
Most studies on turning focus on external turning and radial kerf cutting [9, 11]. LAURINAT [12] reveals the possibility to cut simple 3-dimensional workpieces by cutting into the material from more than one side. This idea requires a radial kerf cutting process as well as a trepanning operation into the end face of a rod. With this strategy, material can be extracted from the workpiece which leads to an increase of the material removal rate since the removed material is not entirely chipped. This procedure requires solid knowledge about the fundamental coherences of cutting with a specific kerf depth. LAURINAT [12] infers that increasing velocity of the waterjet leads to a more stable process behavior. Hence, repetitive high velocity treatment of the same kerf allows a deep and more smoother kerf ground than one slow crossing. AWJ operations are limited by the attainable surface roughness, which in many cases, is not sufficient as a functional surface. However, previous studies have shown that no negative effects considering hardness or surface roughness have to be taken into consideration when applying AWJT as roughing process [1].

Considering advantages and challenges of conventional and AWJ machining on high-performance materials, makes it relevant to investigate a combined process in this study.

2. POTENTIAL OF A COMBINED PROCESS OF AWJ AND CONVENTIONAL TURNING

The process combination was investigated in a previous work [1], which compared the feasibility of turning a simple rotational workpiece conventionally with a lathe and with AWJT. In the study, AWJT was introduced as an alternative preliminary roughing process for AlSi17. Hence, completely conventional machining was compared to AWJT followed by a conventional finishing operation, in order to maintain good surface qualities of the final part. In the study, tool kinematics of the conventional external turning were adopted for the AWJT. The waterjet proceeded with a feed rate along the rotating workpiece like a conventional cutting tool. Using this strategy, the feed rate was set to a value allowing the waterjet enough time to cut the rotating bar to the desired diameter.

Figure 1a shows the tool flank wear and Figure 1b the process time for the conventional turning operation and the process combination. The resulting tool flank wear of the process combination results from the final finishing operation. It can be derived that the possible tool flank wear reduction increases with the volume removal. Adding AWJT as a roughing process before conventional machining allows a reduction of the tool flank wear of up to 84 % for an examplary part with a volume of $V_r = 215\ cm^3$ to cut. However, the material removal rate for AWJT of $Q_{WAWJT} = 5.6\ cm^3/min$ is lower than the material removal rate for conventional turning of $Q_{WCONV} = 17.9\ cm^3/min$ resulting in higher process times for the combined process. The authors of the study summarize that the process combination can be a suitable approach to replace the conventional roughing process when seeking reductions of costs for inserts.



Process:
Turning
AWJT & Turning

Machine tool:
Boehringer, VDF 180 C-U
MaximatorJET, HRX 160 L

Workpiece:
Hypereutectic
aluminum silicon
(G-AlSi17Cu4Mg)
Machined bar
d = 78 mm

Tool:
SPUN 120408
Substrate type
EMT 100
Coating thickness:
s_D = 8.00 µm

Turning
parameter settings:
v_c = 200.00 m/min
f = 0.10 mm
a_p = 0.50 mm

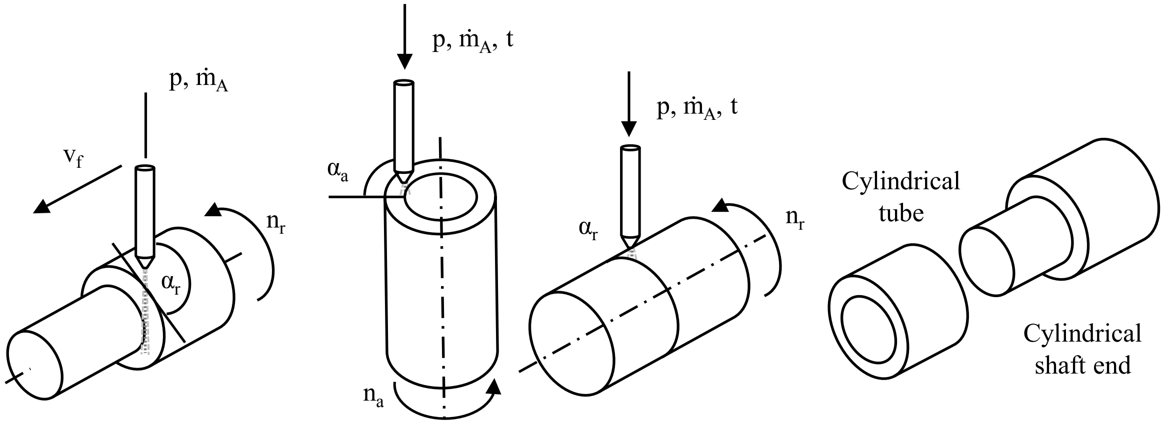
Abrasive:
Garnet (Bengal Bay)
Mesh 80

AWJT
parameter settings:
p = 420 MPa
v_f = 20 mm/min
n = 200 rpm
a_p = 1 mm
$\dot{m}_A$ = 350 g/min
d_d = 250 µm
d_f = 760 µm
l_f = 76 mm

Figure 1. Features of a combination process [1]; a) Tool flank wear; b) Process times

3. THEORETICAL MACHINING DESIGN

For the following considerations, only the roughening process is taken into account. The previous investigation [1] states that using AWJT allows a tool flank wear reduction, but leads to an increase of the process time. This referential procedure, using kinematics from conventional turning operations, is depicted in Figure 2a. However, analyzing the workpiece and the material to be cut from the given workpiece, a complete cut of all material seems to be an unnecessarily high effort. A more material-efficient way to remove the material is to cut into the workpiece twice by radial cutting into the rod and trepanning into the end face as illustrated in Figure 2b. By applying both operations, the separated part can be removed from the workpiece. This strategy can be further improved by performing the operations with angles α_a, $\alpha_r \neq 90$ ° in order to broaden the complexity of manufacturable parts.



a) b) 1. JetGroove axial mode 2. JetGroove radial mode 3.

Figure 2. Principals of AWJT operations; a) AWJ external cylindrical turning; b) Radial cutting, trepanning and material extraction

Three methods of generating a cylindrical part without cutting the whole material are presented in Figure 3. Figure 3a shows the dimensions of the part and Figure 3b gives the reference procedure. Method 1 and 2 in Figure 3c are strategies with radial kerf cutting and trepanning operations. In method 1 (M1) a first cut M1a with an adjusted angle into the cylindrical surface and then a cut into the end face M1b is applied. The combination of both steps allows the extraction of volume V_{rM1a}. In a third step M1c, an additional cut into the end face takes place. This operation leads to the removal of volume V_{rM1b}. The possibility to extract sleeves enables an actual reduction of the material to be cut by the waterjet from $V_r = 215$ cm^3 to $V_{M1} \approx 12.46$ cm^3. The volumes for a cut and the volumes to be extracted from the workpiece are given in Table 1 for all conducted methods.

In method 2 (M2) a similar strategy as in M1 is used, but the implemented kerf depth for the trepanning operation is reduced by changing the cutting order. In the first step of M2 a cut M2a into the end face of the rod is made and the volume V_{rM2a} is extracted. The following trepanning operation M2b is shortened and consequently the accuracy for the cut might be improved. Following cut M2c the volume V_{rM2b} can be removed and the final part is created. M2 enables a high reduction of cutting volume, like for M1, Table 1.

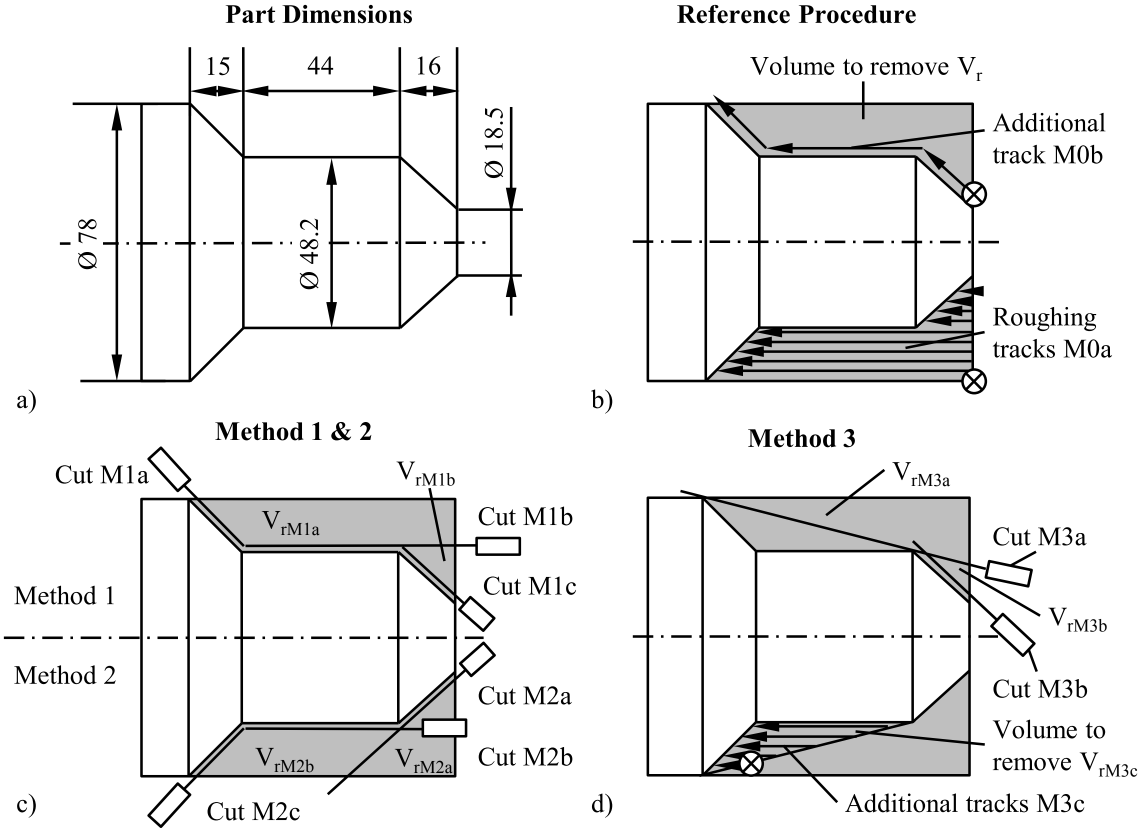


Figure 3. Strategies to manufacture a part by AWJT; a) Part dimensions; b) Reverence procedure; c) Method 1 and 2; d) Method 3

Both methods M1 and M2 assume that a precise kerf depth is possible for radial kerf cutting and trepanning operations. By this, the application of M1 or M2 requires knowledge about the kerf depth for process parameters over time. However, other strategies exist to reduce the process time which does not require knowledge about the precise kerf depth. One of the strategies is considered and shown in Figure 3d as method 3 (M3). M3 is constructed to use only complete cutting operations. First, a trepanning operation M3a is implemented which cuts into the end face of the workpiece until the cylindrical face. The volume V_{rM3a} is extracted by this operation. An additional cut M3b removes the volume V_{rm3b}. The remaining material is cut using AWJT like in the reference procedure (M3c). This method still enables a high reduction of the material to be cut compared to the reference procedure (Table 1). The values given in Table 1 are calculated assuming a constant kerf width of 0.8 mm and cut perfectly aligned besides the desired contour. In the next step, a feasibility test was carried out to test the three methods regarding there possibility of machining the accuracy of the contour and to find out the process times and material removal rates.

Table 1. Volumes to cut and volumes to remove

Cut	Volume to cut			Volume to remove		
			cm^3			cm^3
Method M1						
M1a	V_{M1a}	=	3.2			
M1b	V_{M1b}	=	7.4	V_{rM1a}	=	190.8
M1c	V_{M1c}	=	1.7	V_{rM1b}	=	12.0
Total	V_{M1}	=	12.4	V_{rM1}	=	202.9
Method M2						
M2a	V_{M2a}	=	5.2	V_{rM2a}	=	80.6
M2b	V_{M2b}	=	5.3			
M2c	V_{M2c}	=	3.2	V_{rM2b}	=	120.8
Total	V_{M2}	=	13.8	V_{rM2}	=	201.5
Method M3						
M3a	V_{M3a}	=	11.3	V_{rM3a}	=	134.9
M3b	V_{M3b}	=	1.7	V_{rM3b}	=	7.5
M3c	V_{M3c}	=	59.8			
Total	V_{M3}	=	72.9	V_{rM3}	=	142.4

4. FEASIBILITY TEST

The test was carried out on the waterjet system MAXIMATOR JET HRX 160 L, shown in Figure 4a. Two spindle systems and a six-axis robot manipulator were used to facilitate the desired cutting operations. One in the machine implemented spindle, shown in Figure 4b, enables a maximum rotational speed of up to $n_{1max} = 2{,}000$ rpm. This system is especially suitable for AWJT of the reference procedure. For the trepanning and the radial kerf cutting operations an additional spindle system is used, Figure 4c, which allows a maximum rotational speed of up to $n_{2max} = 140$ rpm and an angle of impact from $\alpha = 0$ - 180 °. The used parameter settings for the rotational speed and the pressure are given in Table 2. In the experiments an abrasive flow rate of $\dot{m}_A = 350$ g/min with Bengal Bay garnet mesh 80 were applied. A hydraulic intensifier with a power of 45 kW generates a water volume flow rate of up to 2.8 l/min and a maximum water pressure p of up to p = 600 MPa. The orifice diameter of $d_d = 0.25$ mm, focus diameter $d_f = 0.76$, focus length $l_f = 76$ mm and the standoff distance $l_s = 2$ mm were selected following industrial standards.

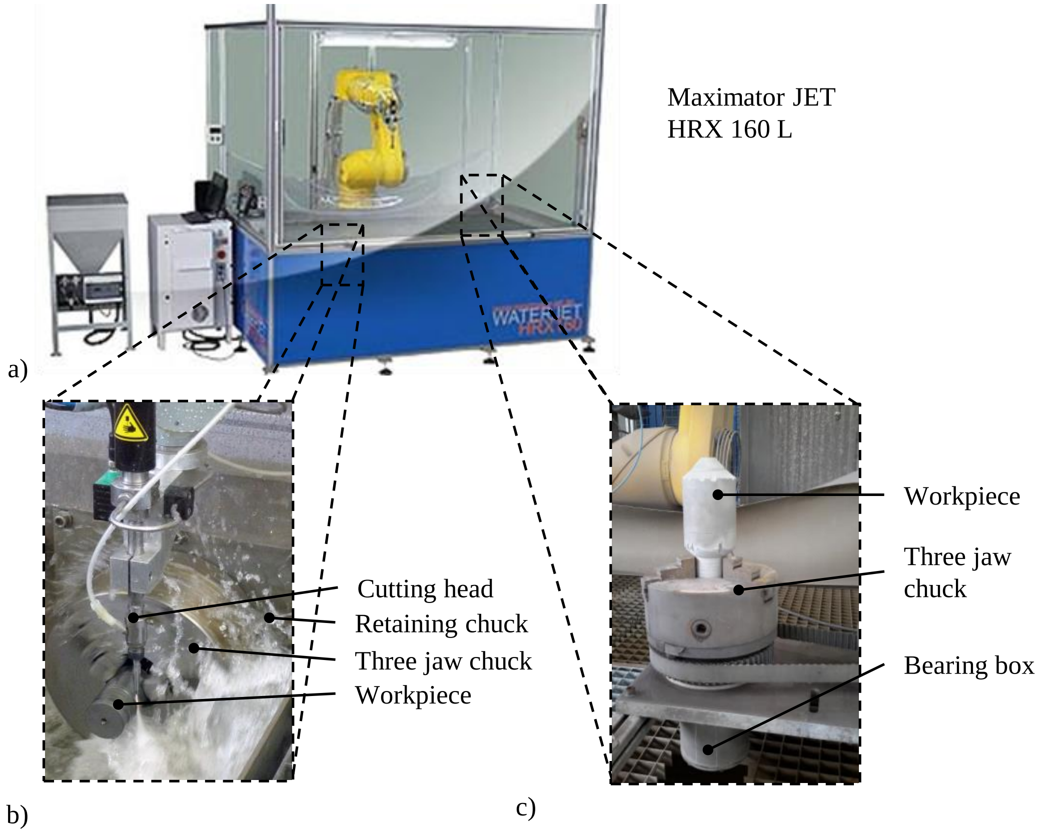


Figure 4. Test setup for the AWJ turning and trepanning operation; a) Maximator JET; b) horizontal spindle 1; c) Flexible spindle 2

Table 2. Process parameters for AWJT

Process Parameters		**Reference**	**M1**	**M2**	**M3**	
Pressure	p	420	250	250	420	MPa
Rotational speed	$n_{a/r}$	200	140	50	50	rpm
Cut		M3c	M1a, M1b, M1c	M2a, M2b, M2c	M3a, M3b	

5. EXPERIMENTAL RESULTS AND DISCUSSION

The first row of Figure 5 shows the specimen after the first two manufacturing steps, and the second row illustrates the end of the roughing operation. The pictures in Figure 5 prove that all three methods are qualified to produce the desired part. However, the pictures and the augments point out surface defects from the AWJT operations. Method 1 and 2 show an imperfection at the point where both turning operations intersect, leading to a partly deeper cut than anticipated. By this the original geometry was weakened at a critical point of the contour where a small diameter scales up. The defect can be described by the kerf ground waviness. The chosen process parameters for the cutting operation of method 1 caused a radial kerf ground waviness of approximately $w_{rg1} = 1.5$ mm and an axial kerf ground waviness of $w_{ag1} = 3.2$ mm. For method 2 a radial kerf ground waviness of $w_{rg2} = 4.5$ mm and an axial kerf ground waviness of $w_{ag2} = 15$ mm were measured. Method 3 was set up to avoid these kinds of defects by the implementation of cuts which allow the waterjet to proceed completely through the material. The pictures in Figure 5 show that the critical defects can be avoided. However, the applied parameter setting caused a high surface waviness of approximately $w_{s3a} = 3$ mm when reaching the outer cylindrical surface. Consequently, the geometrical integrity of the part was affected where the shaft shoulder blends into the cylindrical surface.

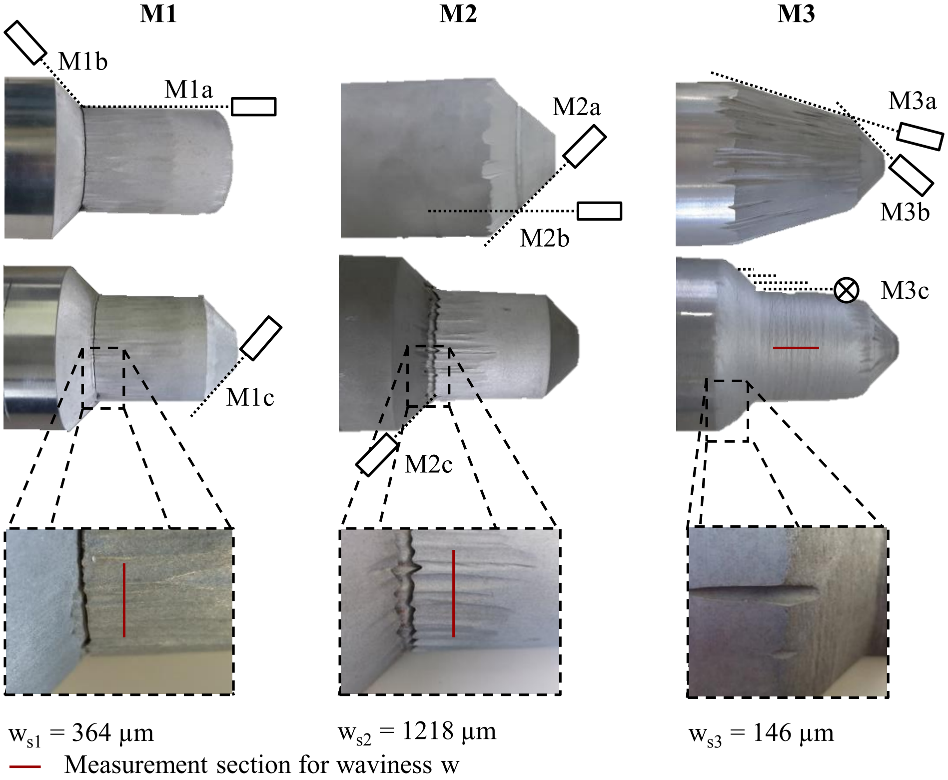
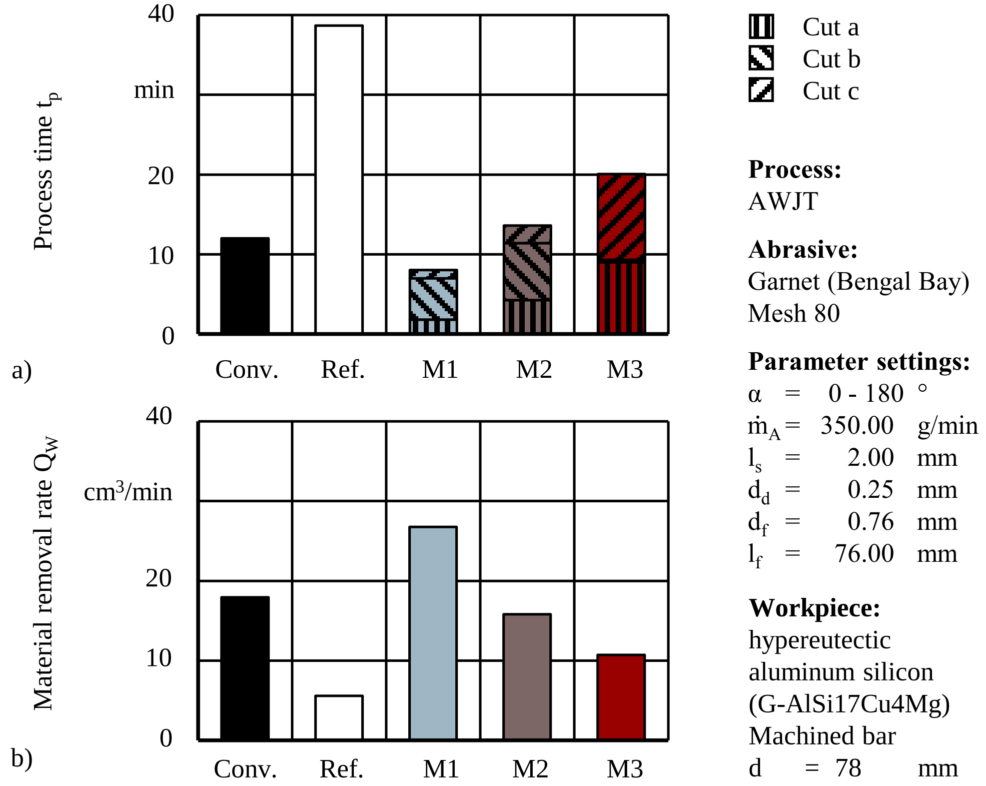


Figure 5. Results of the AWJ roughing process

Additionally, Figure 5 states the surface waviness of the final contour. The surface waviness determines the following steps of production and by this is the quality of the strategy can be evaluated. The maximum surface waviness occurs at the deepest point of the kerf and is $w_{s1} = 364$ µm for method 1 and $w_{s2} = 1.2$ mm for method 2. The large difference between both waviness values for M1 and M2 shows that the process parameters especially the rotational speed have a significant impact on the kerf surface and kerf ground waviness.

Figure 6 presents the process times and material removal rates for the given part for conventional machining, the reference procedure and the three tested methods. The process times for all three methods could be decreased compared to the reference procedure. Method 3 takes about half of the time of the reference procedure. The reductions of the process time is made possible through the first two cuts allowing the removal of large amounts of material and by this increasing the material removal rate in the anticipated way to $Q_{WM3} = 10.7$ cm^3/min. Since material remains to be cut with external AWJT the expected increase in the material removal rate is attenuated. In addition, the strategy reveals that the material removal rate for a trepanning operation with $Q_{WM3a} = 1.2$ cm^3/min is lower than for external AWJT, if the removal of material is not considered. Method 2 allows the construction of the part without external AWJT. By this, an increase in the material removal rate compared to the reference procedure and the method 3 is achieved. Method 1 follows a similar strategy as method 2 but with slightly adjusted process parameters causing a further reduction of the process time. The parameter settings used for method 1 allow an overall material removal rate of $Q_{WM1} = 26.7$ cm^3/min which is in fact higher than material removal rate of conventional machining. The strategies show that the sequences of manufacturing and process parameters have a strong impact on the quality of the cut and on the process times.



▥ Cut a
▧ Cut b
▨ Cut c

Process:
AWJT

Abrasive:
Garnet (Bengal Bay)
Mesh 80

Parameter settings:
α = 0 - 180 °
$\dot{m}_A$ = 350.00 g/min
l_s = 2.00 mm
d_d = 0.25 mm
d_f = 0.76 mm
l_f = 76.00 mm

Workpiece:
hypereutectic
aluminum silicon
(G-AlSi17Cu4Mg)
Machined bar
d = 78 mm

Figure 6. Experimental results; a) Process times; b) Material removal rate

6. CONCLUSIONS

In conclusion the experimental results show a high potential to increase the material removal rate by applying two AWJT operations on a workpiece. The general transfer of the presented strategies to other applications are limited by the given geometry and volume to remove. However, given the described boundary conditions the strategies are a promising alternative for difficult to machine materials. The methods allow a reduction of the process time in addition to the established reduction of wear. The core findings of the study can be summarized with:

1. Using combinations of AWJT operations to extract material causes an increase in the material removal rate.
2. The conducted methods enable process times within a range of - 30 % to + 70 % compared to the conventional machining procedure.
3. The geometrical integrity can be negatively affected by the AWJT operation.

The cost-efficient implementation of the presented strategies highly depends on the tool life time, the geometry and the material. Given the applied angles and the rotational speed the investigated strategies require advanced machines or additional manipulation options for the workpiece. Within the manufacturing process, parts needs to be extracted, this requires an extra handling operation. The additional effort must be compared to possible cost reduction when considering the use of the operation presented in this paper.

It is to be expected from the results that the ideal process parameters might not yet be met. Especially, the trepanning operation requires further investigation. Additionally, cutting kerfs with precise depths with different angles would allow to broaden the scope of manufacturing. Further research questions are the directions of cutting and the interactions of kerf ground intersections.

7. ACKNOWLEDGMENTS

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9. NOMENCLATURE

Symbol	Unit	Definition
α	°	Angle of cut
a_p	mm	Depth of cut
AlSi17		Hypereutectic aluminum silicon alloys G-AlSi17Cu4Mg
AWJ		Abrasive waterjet
AWJT		Abrasive waterjet turning
d	mm	Diameter
d_d	mm	Orifice diameter
d_f	mm	Focus nozzle diameter
DFG		German Research Foundation
f	mm	Feed rate
l	mm	Length
l_f	mm	Focus nozzle length
M1		Method 1
M2		Method 2
M3		Method 3
$\dot{m}_A$	g/min	Abrasive flow rate
n	rpm	Rotational speed
p	MPa	Pressure
PCD		Polycrystalline diamond
Q_W	cm^3/min	Material removal rate
s_D	µm	Coating thickness
t	s	Time
t_p	s	Process time
V	cm^3	Volume
v_c	m/min	Cutting speed
v_f	mm/min	Feed speed
w_f	µm	Tool flank wear
w_g	µm	Kerf ground waviness
w_s	µm	Surface waviness