6th CIRP International Conference on High Performance Cutting, HPC2014

Machining of hypereutectic Aluminum Silicon Alloys

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Abstract

In the work presented in this paper, combined machining of hypereutectic G-AlSi17Cu4Mg with abrasive water jet turning (AWJT) as a roughing process and conventional turning as a finishing process was studied. The duration of the single processing steps was estimated and compared to the length of a conventional machining process. The tool life of AWJT of at least 10 hours combined with a material removal rate of up to 13 cm³/min and low process temperatures give this cutting technology a very high potential. Furthermore the material close to the cutting surface is impacted less by the cutting process, in comparison to conventional rough turning. The results obtained showed that AWJT roughing combined with conventional finishing generates parts with high surface qualities and with further optimization may be a possible process substitution with high productivity.

1. Motivation

The economical cutting of high performance materials such as aluminum silicon alloys requires superhard cutting tools and specific machining strategies. The use of these alloys is continuously increasing in the automotive and aeronautical industries due to their high wear resistance and excellent strength to weight ratio. However due to the hypereutectic silicon crystals in the structure, which are between 2 and 8 μm in size, cutting tools are exposed to high abrasive and adhesive wear during the machining process [1]. Machining trials in turning of the hypereutectic aluminum alloy G-AlSi17Cu4Mg with diamond chemical vapor deposition (CVD) coated inserts have shown that a long tool life and a high surface quality are attainable. However, the occurrence of sudden tool failure, caused for example by delamination of the diamond layer, limits the automation of this machining process.

In recent years abrasive water jet turning (AWJT) has been shown to be a suitable cutting process for this challenging material [2,3]. Nevertheless the surface roughness following machining with AWJT is higher than in conventional turning processes. A combination of AWJT and conventional turning with diamond coated tungsten carbide tools could therefore be a suitable and time-saving solution for the machining of high performance materials when high removal rates and a low surface roughness are required [2]. The removal of the often irregular outer material of cast workpieces, which may cause sudden tool failure of conventional cutting tools, could be carried out through AWJT, followed by turning with CVD diamond coated inserts for obtaining the required low surface roughness [3,4]. The AWJT has to be qualified as a pre-machining process to substitute the conventional CNC operations.
2. Potential of a hybrid process

2.1. Conventional turning of hypereutectic aluminum silicon

To meet the demands for cutting difficult to machine materials such as hypereutectic aluminum silicon alloys it is necessary to combine the excellent properties of diamond with complex tool geometries. The CVD technology for depositing diamond layers on carbide tools enables this to be achieved, in contrast to CVD diamond thick films and poly crystalline diamond, which are limited to planar tool geometries [3,5,6]. During the cutting of difficult to machine materials such as fiber reinforced plastics, graphite and hypereutectic aluminum silicon alloys with CVD diamond coatings on carbide tools long tool life travel paths can be reached [7,8]. However the use of these layers in the industrial production process has thus far been limited by the low process stability due to sudden coating delamination which leads to early tool failure. Often the coating adhesion differs exceedingly even within one batch of tools and as such the entire manufacturing chain of CVD diamond coated tools must be optimized in order to reach their potential in an industrial environment [9-13].

During machining of hypereutectic aluminum silicon alloys the cutting edge alternately comes into contact with the soft aluminum phase and hard silicon particles. It has been previously shown that the abrasive tool wear rises with increasing silicon content and size of silicon particles [14]. The aluminum phase of the material leads to adhesive wear in the terms of built-up edges, which occurs more dominantly during the machining of hypoeutectic [8]. During the machining of hypereutectic alloys, the proportion of adhesive wear decreases and the abrasive wear and surface fatigue becomes dominant [8].

Uhlmann et al [8] carried out turning trials using carbide inserts with CVD diamond coating. The hypereutectic aluminum silicon alloy G-AlSi17Cu4Mg was dry machined with a range of cuttings speeds from \( v_c = 200 \) m/min to \( v_c = 1000 \) m/min and a constant feed rate \( f = 0.1 \) mm. The tool life time \( t_{LC} \) of the inserts are significantly affected by the main process parameters. From this study on the wear behavior of cutting with CVD diamond coated tools, the curves shown in Figure 1 for the tool life time \( t_{LC} \), the material removal rate \( Q_w \), and the tool life volume \( V_{Lc} \) can be determined.

While the material removal rate proportionally increases as the cutting speed increases, the tool lifetime decreases with an exponential trend and achieved a tool life time of 2.5 min at a cutting speed of \( v_c = 1000 \) m/min. Because the tool life volume \( V_{Lc} \) is determined as the product of life time and material removal rate, the distribution follows the course of the tool life time.

2.2. AWJ-Turning of hypereutectic aluminum silicon

This investigation presents waterjet turning as an alternative or as an additional preliminary rough turning technology to manufacture rotational parts from high performance materials such as hypereutectic aluminum silicon alloys. Waterjet cutting with abrasive additives is a well-established two dimensional cutting process 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.

The AWJT process combines the kinematics of conventional turning methods with process-specific advantages of the abrasive waterjet machining. The main advantages are the high variety of machinable materials, the long life time of the focus nozzles of at least 200 minutes and its independence of the material to be processed. Blickwedel [16] recognised an earlier negative wear influence with regard to the cutting quality after an operating time of 4.5 hours. This is nevertheless an improvement on the typical tool life time in conventional cutting processes. Furthermore, material inhomogeneity or the initial geometrical contour of the workpiece does not contribute to tool failures. Figure 2 illustrates the continuous cutting of the AWJT process. The tool movement is known from conventional external turning. The waterjet cuts the workpiece in the contact area with an effective cutting radius depending on the vertical distance of the focus nozzle to the workpiece surface as well as the machined workpiece hardness.

![Fig. 2. AWJ principle of operation.](image)

In contrast to conventional cutting processes the tool life criteria of abrasive water jet (AWJ) cutting, especially the tool wear, are dependent on the process time and on the process inherent parameter settings; pressure and the choice...
of performance determining component geometries for the water orifice and focus nozzle. Process forces are significantly lower than the cutting forces of conventional processes. The resulting influencing factors on the material removal rate and the abrasive mechanisms are quite different to 2-D waterjet cutting. However the fundamental parameters for a combined process, e.g. pressure, rotational speed or depth of cut for the AWJT have already been evaluated.

The experimental result of AWJT of the hypereutectic aluminum silicon alloy G-AlSi17Mg4Cu shows that linear main effects as well as interaction effects are higher than the calculated level of significance for the implemented depth of cut. Therefore the effects of the adjusted depth of cut \( a_p \), the feed velocity \( v_f \), the abrasive particle size \( d_p \), the rotational speed \( n \) and the mass flow rate \( \dot{m}_w \) would be investigated. The main effects of \( a_p, v_f, d_p \) and the interaction effects of \( v_f a_p \) and \( d_p a_p \) are identified as important influences on the determined depth of cut \( d_c \). The rotational speed \( n \), the rotating direction and the mass flow rate \( \dot{m}_w \) of the abrasive as well as all other interaction effects are classified as not significant in the investigated range.

3. Experimental Procedure

For the comparison of the roughing processes of AWJT and CNC turning, a reference geometry was implemented in this study. Two different initial geometries and as such two different material removal percentages were studied, see Table 1. Cast hypereutectic aluminum silicon AlSi17Cu4Mg was used as the workpiece material for all investigations.

3.1. Conventional CNC turning

The reference geometry is shown in Figure 3. The geometry was adapted to the implementation of the two tool life volumes in the radial dimensions, the dimensions in the axial direction remained constant.

![Fig. 3. Reference geometry and path planning.](image)

The depth of cut and the cutting speed for the roughing and finishing cycles were kept constant. This inevitably leads to different process times for roughing, but remain comparable for finishing and roughing cycles with respect to the tool load. The finishing cycle has a tolerance of 0.5 mm. For better comparability with the previous research results, cooling lubricant was not used. Research results of Brinksmeier et al. have shown that the use of cooling lubricant does not have a significant impact on the wear behavior of CVD diamond tools [17].

The CNC machining was performed on a lathe by Traub. There the width of flank wear was measured at the tool edge after each of the roughing and finishing cycles using optical microscopy. For each cycle, a new cutting edge was used. Initially, the workpieces were entirely machined using conventional turning without the assistance of AWJT. In order to investigate the potential of a hybrid process, the workpieces were then rough machined using AWJT and finished using conventional turning. Finishing in the hybrid process was undertaken with the identical process parameters as in the complete conventional CNC machining process. After the finishing operation the width of flank wear was determined and compared with the complete CNC processing. Furthermore, the generated surface qualities and process times of the two process variations, i.e. complete conventional turning and hybrid turning were compared. The implemented process parameters are summarized in Table 1.

| Process parameter | Volume \( V_1 \) | Volume \( V_2 \) | Unit |
|-------------------|----------------|----------------|------|
| **CNC:**          |                |                |      |
| cutting speed     | \( v_c \)      | 200            | 200  | m/min |
| feed              | \( f \)        | 0.10           | 0.10 | mm/min |
| depth of cut      | \( a_p \)      | 0.50           | 0.50 | mm    |
| **AWJT:**         |                |                |      |
| pressure          | \( p_a \)      | 420            | 420  | MPa   |
| feed speed (roughing) | \( v_f \)   | 20             | 20   | mm/min |
| feed speed (finishing) | \( v_{fr} \) | 40             | 40   | mm/min |
| rotational speed  | \( n \)        | 200            | 200  | rpm   |
| nozzle diameter   | \( d_i \)      | 0.25           | 0.25 | mm    |
| focus diameter    | \( d_f \)      | 0.76           | 0.76 | mm    |
| depth of cut      | \( a_p \)      | 1              | 1    | mm    |
| **cutting volume/workpiece:** |          |                |      |
| initial diameter  | \( D_i \)      | 78.0           | 42.0 | mm    |
| target diameter   | \( d_i \)      | 48.2           | 26.0 | mm    |
| volume ratio      |                | 37.4           | 34.2 | %     |
| volume to remove  |                | 270.1          | 83.8 | cm³   |

3.2. Abrasive water jet turning

For the AWJT a CNC equivalent track planning for roughing was applied. The depth of cut was \( a_p = 1 \) mm with an allowance of 0.5 mm in the path programming. The AWJT roughing includes two process steps. First a roughing track planning with parallel paths to the rotational axis with a velocity of \( v_f = 20 \) mm/min. In the second step an AWJT finishing path is programmed. To reduce the aliasing effects at the conical geometry and to smooth the surface on the lateral surface these additional path was...
conducted. The feed velocity in this final path increased from \(v_{fR} = 20\) mm/min to \(v_{fF} = 40\) mm/min at the conical part of the path and otherwise moved at the maximum speed of \(v_{fF} = 40\) mm/min. After processing, the contours were measured and the roughness and waviness was determined with a tactile measurement system. It should be noted that an experimental setup was used for the AWJT, which was designed solely for feasibility studies.

4. Experimental Results and Discussion

Figure 4 shows the hardness profiles of the workpiece surfaces following AWJT compared with conventional CNC turning. The decreasing course of the graph resulting from the conventional CNC turning trials reaches a maximum hardness of approx. 75 % of the bulk material hardness in comparison to the AWJT. In a machining process including several steps, an increasing hardness of the surface layer during the machining process can lead to increasing abrasive wear on cutting tools. The images of the topography show that the AWJT, in comparison to the conventional CNC turning process, leads to a significantly rougher surface.

However neglecting the corresponding tool life time as depicted in Figure 1, the results of the machining trials are summarized in Figure 5. Figure 5 a) shows the achievable value ranges of surface roughness and material removal rates for both processes. As can be seen, there is some overlap between the attainable surface roughness range of AWJT and conventional turning, in the value range of \(R_a = 5\) \(\mu m\) to \(R_a = 3.5\) \(\mu m\). The material removal rates of both processes also overlap within the range of \(Q_w = 8.7\) cm\(^3\)/min to \(Q_w = 13.2\) cm\(^3\)/min. When comparing the reachable material removal rate in AWJT processes to the conventional CNC turning, the ratio \(q_{aw} = 0.08\) shows the benefit of conventional CNC turning, see Figure 5 b).

However when including the values of the tool life time and the average tool life volumes, the AWJT reaches a value 11 times higher than that of conventional CNC turning. Hence the application of AWJT for rough machining of workpieces with a high removal volume (more than 30 % of the blank and a minimal removal of 41 cm\(^3\)) could reduce the required amount of cutting tools and/or tool wear.

The following describes the resulting tool wear, surface qualities and process times of AWJT and conventional CNC turning as roughing processes followed by conventional CNC finishing. The machining result on the workpiece with the volume to remove \(V_1\) is shown in Figure 6.

The tool wear, workpiece surface qualities and process times were analysed and compared. In a machining process consisting of several path cycles, the increase in the hardness of the workpiece surface during the machining process may promote abrasive wear. Figure 7 presents a summary of the relevant results as to the determined flank wear of the complete CNC machining, the hybrid machining, the required processing time and the achieved surface characteristics in terms of the arithmetic mean roughness and waviness.

4.1. Flank wear following complete CNC turning

The flank wear after the roughing and finishing with conventional CNC turning shows the expected high wear for the higher machining volume \(V_1\). The cutting tools
following the machining process are shown in Figure 7, showing significant adhesion of the workpiece material, thus making the implementation of a new cutting edge necessary for subsequent machining operations.

4.2. Flank wear following conventional CNC finishing

The flank wear, see Figure 7 a) following the implementation of conventional turning as a finishing operation ranges from 20 μm to 55 μm. Finishing after AWJT roughing results in higher flank wear compared to finishing after a conventional roughing process. Delamination of the CVD diamond coating at the cutting edge complicated the determination of the flank wear, mainly in the case of the tools that were in use for the removal of the cutting volume \( V_1 \). This significant difference is presumably due to the still inadequate control of the AWJT process. The desired tolerance of 0.5 mm of the radius was exceeded considerably, especially at the conical transitions. Also, there are considerable variations in the adhesion strength of the CVD diamond coatings between two production batches of the cutting inserts.

4.3. Surface qualities and roughing process times of AWJT

The AWJT process exhibited relatively high process times, of 14 minutes to a maximum of 38 minutes, Figure 7 b). These process times lead to a material removal rate of at least \( Q_a = 6 \, \text{cm}^3/\text{min} \), which is further increased by adjusted track programming or optimized AWJT parameter. The implemented AWJT system is capable of producing a technical pre-contour for a subsequent finishing process with the desired final shape and required surface quality. When the AWJT experiments were conducted, significant wear of the focus nozzle was not detected.

The surface quality achieved after roughing with conventional turning was higher than with AWJT, as shown in Figure 7 c). The hybrid process resulted in the achieved arithmetic mean roughness \( R_a \) on the surface of the workpiece \( R_a = 1.5 \, \mu m \) to \( R_a = 2.8 \, \mu m \). This can be considered as low for this cutting conditions and it is three times lower than the arithmetic mean roughness \( R_a \) after AWJT.

5 Conclusions and Outlook

In conclusion, it can be considered to replace conventional roughing in the manufacturing process with AWJT roughing. The comparison of the roughing processes of conventional CNC turning and AWJT demonstrate that the generated surface quality following AWJT roughing is lower than that of conventional CNC roughing, however has no negative impact on the surface integrity after the finishing process,

1) a multipath roughing process can be realized with AWJT,
2) the cutting edge is subjected to increased wear during the finishing process following AWJT roughing in comparison to the wear following conventional CNC turning, however this does not negatively impact the surface integrity of the finished part,
3) the process times of AWJT are longer than those of the CNC roughing cycles.

These results indicate that higher productivity can be attained by using AWJT as a roughing process prior to conventional CNC finishing. The maximum allowable tool wear of the cutting tools was reached after each CNC roughing cycle and every tool change delays the production process. As such, despite the considerably longer processing times of AWJT in direct comparison, it must be considered that no change of the cutting tool is required. Accordingly, up to 10 parts in the case of the chip volume $V_1$ and up to 25 parts with $V_2$ are rough machined by AWJT in the tool lifetime of at least 350 minutes of a focus tube. The tool costs for the tools used in this study will break even in 25 to 30 parts to be produced. The cost of abrasive and water are not considered here. The increase in productivity can however only be expected in the machining of components where a high amount of material removal is necessary. Possible applications of the hybrid manufacturing process are thus large series technical components. With further research work the process times and workpiece surface roughness following AWJT will be further reduced, thus strengthening the potential of such hybrid processes further.

Acknowledgements

The authors wish to thank the German Research Foundation (DFG UH 100 119-1, DFG UH 100 88-1) for the funding of the work presented in this paper.

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