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Influence of Process Cooling on the Workpiece Quality in Face Milling of Aluminum Alloys

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Face milling is a frequently used machining operation for the production of functional faces on components. These faces often take over the task of seal faces for which high demands on surface integrity and burr formation exist. Especially the burr formation is of great importance. Burrs breaking away in the use of the part can lead to malfunction, for example in internal combustion engines. To avoid this effect and to ensure the required workpiece quality, today often additional processes for deburring are necessary. These additional processes incur some additional costs. Because of that, an essential aim in face milling of aluminum alloys is the avoidance of these processes by an adaption of the machining process to reach a burr reduction as well as the attainment of the required surface quality. In this research, a process cooling with carbon dioxide snow is used for an in-process enhancement of the workpiece quality. Here, the process cooling is applied to influence the workpiece properties during the cutting process. Furthermore, the kinetic energy of the carbon dioxide snow blast is used for an in-process deburring. Using a process cooling with carbon dioxide which is moved with the feed motion of the tool, a burr reduction and an improved workpiece quality is achieved. A further advantage of this approach is the applicability in machining complex-shaped workpieces.

Keywords: *Machining, Face Milling, Burr Formation, Temperature Compensation, Carbon Dioxide Snow*

1. Introduction

The compliance with the quality requirements of components is essential for the functionality of the whole product. With respect to parts with face milled faces, the surface quality and the shape of the workpiece edges are of great interest. Non-compliance with one of the quality requirements can lead to malfunction of a component in operation. In addition to its importance for functionality of part, an unsatisfactory edge shape complicates the manageability of the workpiece and can lead to injuries while handling the workpieces [1]. To ensure the edge shape as required, often deburring processes are necessary. These finishing operations are associated with considerable costs [2]. Another study on costs associated with burr minimization, deburring and part cleaning was carried out in the German automotive industry and machine tool industry. Burr related expenses are caused by an increase of about 15 % in man- and cycle-times [3]. Only in Germany, burr related costs are estimated as up to 500 million euro expense per year [4]. Because of that, both, from technical and economical point of view, the reduction of burr formation in face milling processes is of particular importance. Based on this situation many research studies on the identification of influencing variables on burr formation and burr reduction strategies in face milling operations have been carried out. One of the variables, which influences the burr formation, is the in-plane exit angle. Chern [5] found a strong interdependence of this angle and the burr geometry. When machining ductile materials, an increase in width of cut, that influences the in-plane exit angle, has a significant influence on burr formation. However, Avila and Dornfeld [6] have shown, that an adaption of different variables on burr formation can lead to low burr formation even at higher values for width of cut. Also the cross-section of undeformed chip influences the burr formation. Higher burrs were produced with increasing feed per tooth. The depth of cut also has an influence on burr formation. Chern [5] has found a critical depth of cut. When choosing higher values of depth of cut than the critical value, suitable burr forms can be achieved. This effect interferes with the influence of the

in-plane exit angle and the corner radius on burr formation [5]. Compared to the feed-per-tooth and the depth of cut, the influence of the cutting speed on burr formation is marginal. An increase in cutting speed leads to a slight reduction in burr formation [7].
The choice of suitable process conditions is often limited by boundary conditions. For example, in industrial applications, the parts have a complex contour, tools with large diameters and higher cutting parameters are used in order to reduce cutting time. These boundary conditions narrow the window for suitable process parameters for burr reduction. Therefore, in this research the dependence of material properties on the temperature and the kinetic energy of the cooling media would be taken into account. Burr formation depends on the material properties, especially on the material ductility. The impact of temperature on the properties of material can be used for burr reduction. By avoiding an increase in the formability of the material arising from the process temperatures, the more brittle material behavior can be utilized to reduce burr formation.

2. Experimental set-up

In this research, plates made of two different aluminum alloys were used as workpieces with dimensions of 300 mm x 250 mm x 30 mm. These materials are the wrought alloy EN AW-6082 (AlSi1MgMn) and the cast alloys EN AC-46000 (AlSi9Cu3(Fe)). Both materials are widely used in various industrial applications. The wrought alloy is applied in machinery construction, for example, as pump bodies, steering plates or other construction parts. In comparison to other aluminum alloys this one has a medium strength and a high formability. The main application area of the cast alloy is in the automotive industry, for example, for cylinder-heads or powertrain components. The main characteristic of the cast alloy is its temperature resistance. For workpiece temperature measurement, a clamping device with integrated thermocouples was designed. The thermocouples were fixed in a clamping device using holes and steel tubes in defined distances to the machined surface. Furthermore, a preparation of the workpieces was necessary. Blind holes with a depths according to the respective lengths of the steel tubes were produced at the defined temperature measurement positions. For clamping, the workpieces were centered to ensure that the steel tubes with the thermocouples were inserted into the holes. Additionally, workpiece surface temperature was measured in the machining processes by thermography. The experimental set-up is shown in Fig. 1.

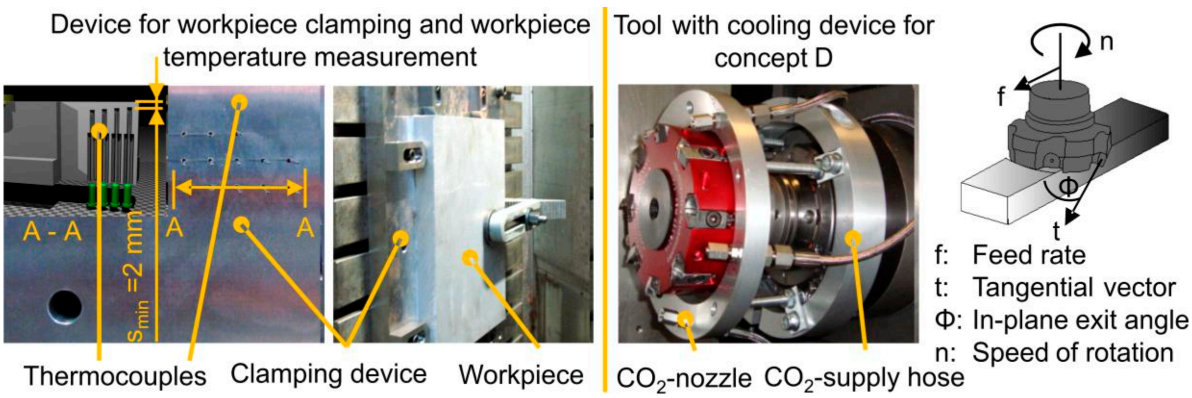


Fig. 1: Experimental set-up

To ensure the significance of the machining tests with industrial practice, a face milling cutter with PCD inserts was chosen. This tool had a diameter of d = 125 mm and number of teeth of z = 8. In the investigation done, the effects of different cooling concepts and cooling strategies on the workpiece quality were tested by face milling with constant process parameters. The cutting conditions include a cutting speed of v_c = 2,000 m/min, a feed rate of f = 0.8 mm/rev, a depth of cut of a_p = 2 mm and a width of cut of a_e = 62.5 mm, resulting in an in-plane exit angle of Φ = 90°, were used. In these experiments, up-milling was implemented as milling strategy. For the investigation on influences of different cooling concepts on workpiece quality – especially on burr formation and surface quality – different cooling media and cooling strategies were applied. As cooling media, compressed air and carbon dioxide snow (CO_2-snow) were used. Concerning cooling strategies, a stationary cooling of the exit edge of the workpiece and a process cooling using a cooling device which is moved with the feed motion of the tool was used. The cooling capacity was varied using nozzles with different diameters. To evaluate the influence of a process cooling on the workpiece quality, all results were compared to that of dry machining using the same process parameters. The cooling concepts realized are listed in Table 1.

Table 1: Cooling concepts

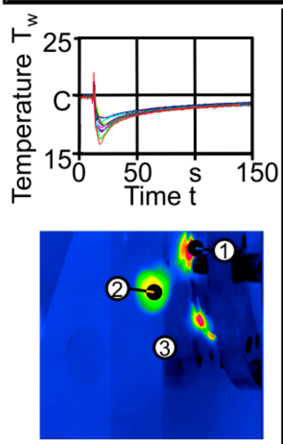
Cooling concept:	**Specifications:**
Concept A	Dry machining
Concept B	Compressed air, stationary cooling of the exit edge, volume flow V = 33 m³/h
Concept C	Carbon dioxide snow, stationary cooling of the exit edge, cooling capacity per nozzle P = 4.9 kW
Concept D	Carbon dioxide snow, stationary cooling of the exit edge, cooling capacity per nozzle P = 8.6 kW
Concept E	Carbon dioxide snow, cooling device moved with the feed motion, 5 nozzles, nozzle diameter d = 0.6 mm, cooling capacity per nozzle P = 2.96 kW

3. Results and Discussion

3.1 Influence of Process cooling on process temperatures

The surface temperatures near the cutting zone, the surface temperatures of the chips and of the workpiece were detected by thermography and the workpiece temperature at a distance of s = 2 mm to the machined surface was measured by thermocouples. As an example, the results of temperature measurements machining the cast alloy are presented in Fig. 2.

Tool:	Face milling cutter, d = 125 mm	Material:	EN AC-46000
Cutting speed:	v_c = 2,000 m/min	Cutting material:	PKD
Feed per tooth:	f_z = 0.1 mm	Cooling concept:	Varied
Depth of cut:	a_p = 2 mm	Milling strategy:	Up-milling
Width of cut:	a_e = 62.5 mm		



	Cooling concept				
	A	B	C	D	E
Difference in workpiece temperature T_w:	4.5°C	4°C	33°C	1.5°C	1.5°C
Cutting Zone temperature T_{cz} (1):	112°C	128°C	111°C	117°C	104°C
Chip temperature T_{ch} (2):	180°C	175°C	178°C	173°C	179°C
Surface temperature of the workpiece T_{ws} (3):	25°C	14°C	10°C	-15°C	-17°C

Fig. 2: Influence of the cooling concept on surface quality

The process cooling influences the resulting temperatures, in particular the surface temperatures of the workpiece. Due to the cooling of the workpiece, the increase in workpiece temperature can be minimized and the resulting temperatures are significantly lower than those when applying dry machining. However, the cutting zone and chip temperatures are not influenced by the process cooling used. The same results were observed during machining the wrought alloy.

3.2 Influence of the process cooling on surface quality

For the evaluation of the influence of process cooling on surface quality, face milling experiments were done using the conditions given in section 2. To ensure repeatability, the experiments were repeated three times. The characterization of the surface quality of the machined surface was done by measuring the roughness depth Rz and the arithmetic average roughness Ra. The results of the influence of the cooling concept on the surface quality are shown in Fig. 3.

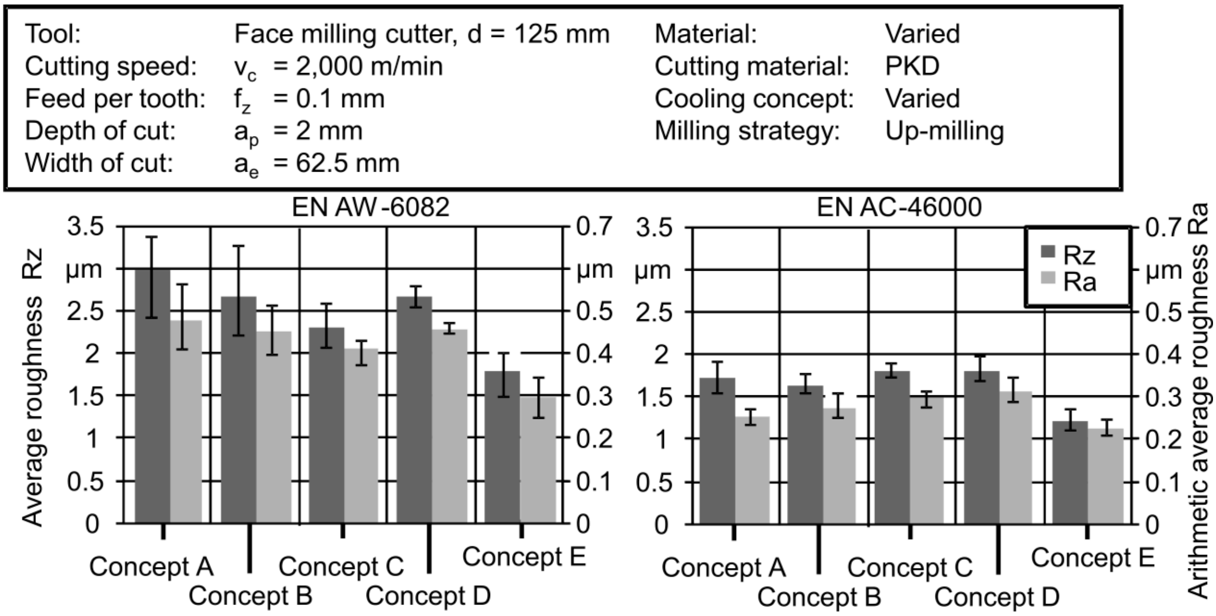


Fig. 3: Influence of the cooling concept on surface quality

When machining the wrought alloy, an influence of the process cooling on the surface quality is obvious. In comparison to concept A, independent of the cooling media used the stationary cooling of the exit edge has a minor influence on the surface quality (concepts B, C, D). Using this cooling strategy, the cooling media cannot influence the surface to machine significantly, because the nozzles are aligned to the exit edge. This leads to comparable results as when milling without any coolant supply. In contrast, the application of the cooling strategy moved with the feed motion (concept D) shows a significant influence on surface quality. Here, the cooling media is supplied near the contact zone between the tool and the workpiece. Before the material is cut by the tool, it is cooled down which results in a reduced ductility. Because of that adhesion is reduced. Adhesion can lead to a damage of the surface when material deposits remain at the tool and furrow the created surface. Depending on the higher strength of the cooled material, the feed marks are not squeezed by the axial force. The effects described are more obvious when machining the wrought alloy than when machining the cast alloy. This can be explained by differences in the microstructure of the alloys used. When a mechanical load occurs at low temperatures, which occurs in machining processes using the process cooling, the movement of dislocations is complicated. Here, a lower thermal activation and a complicated diffusion of vacancies is resulting. This leads to an accumulation of dislocations and an increasing strength. Because of the inhomogeneities of the cast alloy in comparison to that of the wrought alloy, these effects are of minor importance when machining the cast alloy. Another benefit offered by the cooling device moved with the feed motion of the tool is its higher flexibility compared to that when using stationary cooling of the workpiece edge. When machining more complex workpieces, only this cooling strategy ensures a cooling of each area of the machined face.

3.3 Influence of the process cooling on burr formation

To evaluate burr formation, measurements of burr height h_0 were carried out by confocal 3D whitelight microscopy. Here, the workpiece exit edge was measured at three positions, each having a length of s = 4.8 mm. The influence of the cooling concepts on burr formation is presented in Fig. 4.

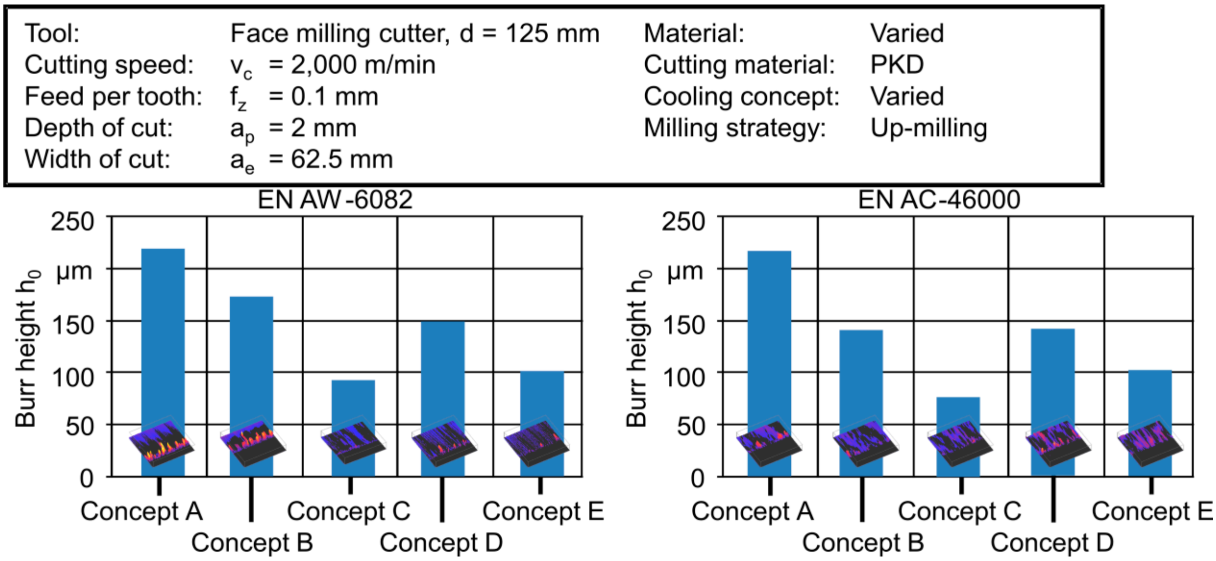


Fig. 4: Influence of the cooling concept on burr formation

Depending on the cooling strategy used, the burr formation can be influenced significantly. Here, an influence of the cooling medium used and the cooling capacity is obvious. In dry machining burr heights of h_0 = 220 µm occurs when machining the wrought alloy as well as the cast alloy. Using cooling strategy B, the burr formation is reduced to h_0 = 174 µm when machining EN AW-6082, and h_0 = 140 µm when milling EN AC-46000. Due to the low cooling capacity of compressed air ,which is used as cooling medium in cooling concept B, the reduction in burr formation is on a lower level. A further improvement of the workpiece edge shape can be achieved by using carbon dioxide snow. When using the stationary cooling, the use of the nozzles with the lower cooling capacity (concept C) leads to a significant burr reduction. Here, the reduction in burr formation is based on two effects. First, the process cooling leads to a change in material properties. In comparison to dry machining, the strengthening of the material is higher when using the cooling. Based on this increase in strength, burr formation mechanisms begin at a minor remaining wall thickness which leads to smaller burrs. The second effect is based on a mechanical impulse of the carbon dioxide snow blast on the created burr. Using this impulse an in-process deburring of instable burrs is possible. In comparison to concept D, where nozzles with a higher cooling capacity are used, the advantage of cooling concept C concerning burr reduction can be explained by the higher exit velocity of the carbon dioxide snow blast and the resulting higher mechanical impulse. Using the nozzles with the higher cooling capacity, a larger area is influenced by the cooling media. Instead, the concentration of the snow blast directly at the workpiece edge is lower. When using the cooling device, which is moved with the feed motion of the tool (concepts E), also an improvement of the workpiece edge shape can be achieved. Using this cooling strategy, the nozzles are used to affect material properties near the tool contact zone, without influencing the cutting process directly. The orientation of the nozzles is based on the zone in which the burr formation mechanisms are expected. Mechanical stresses generated in the cutting process accumulate at the workpiece edge. Because of the work-hardening based on the cooling, a smaller zone can withstand the occurring mechanical loads before the burr formation mechanisms take place. Founded in the orientation of the nozzles using this cooling strategy, a significant burr reduction can be achieved, burr heights of $h_0 = 100$ µm milling the wrought alloy and $h_0 = 77$ µm machining the cast alloy occurs. In comparison to concept C, this cooling concept is adequate for burr reduction at any workpiece edges when machining components with a more complex shape. This is based on nozzles, arranged circularly around the face milling cutter.

4. Conclusions

The workpiece quality in face milling of aluminum alloys can be influenced significantly by using a process cooling. In comparison to dry machining, the surface quality can be enhanced, and the burr formation can be reduced by using a carbon dioxide process cooling. In this context, the use of a circular cooling device which is moved with the feed motion of the tool has shown the most convenient results concerning the measures mentioned above. Using a stationary cooling with compressed air as a cooling medium, no significant influence on workpiece quality was observed. In contrast to that, the use of the stationary cooling with carbon dioxide snow only influences the burr formation. Both, using the stationary cooling with compressed air as well as the one using carbon dioxide snow, the cooling media only influences the workpiece edge and does not affect the machined surface. Another benefit of the cooling device which is moved with the feed motion of the tool is its capability for the machining of complex workpiece geometries. When using carbon dioxide snow as a cooling medium, two effects occurs. Because of the higher cooling capacity of this cooling medium, the workpiece is cooled down significantly. In combination with the mechanical loads occurring in the machining process, the low workpiece temperatures lead to a higher strengthening than those when dry machining. Because of this work-hardening, a minor remaining wall thickness at the workpiece edge can withstand the mechanical loads before a plastically deformation occurs that leads to burr formation. The second effect is a deburring of instable burrs founded in a mechanical impulse by the carbon dioxide snow blast. Especially the deburring of instable burrs is of great importance, because these burrs can break loose in operation which can lead to malfunction and additional costs.

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