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Investigation of surface properties in milling of SiC particle reinforced aluminium matrix composites (AMCs)

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Abstract

AMCs offer a high potential for lightweight applications, but represent difficult-to-machine materials especially regarding the increased tool wear and imperfections on the generated surface. Based on a fractional factorial design using CVD diamond tipped tools, the influence of the cutting parameters (cutting speed, feed per tooth) on the surface structure (roughness, imperfections) and the residual stress state is investigated. Increasing the cutting speed up to 200 m/min enables a reduced void formation and strongly compressive residual stresses, whereas a further increase results in scaling effects. Moreover, a feed per tooth of up to 0.015 mm benefits compressive residual stresses, but leads to higher surface roughness values. As the feed is further increased void formation occurs involving a reduction of the compressive residual stresses.

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Keywords: Aluminium; Metal matrix composite; Milling; Residual stress; Silicon carbide; Surface integrity

1. Introduction

There is a consistent demand for increased performance and efficiency of modern technological products. Frequently, lightweight designs are applied, on the other hand using lightweight materials (e. g. aluminium alloys) represents a suitable approach. For the reason of increasingly complex operating characteristics in many cases unreinforced, microscopically homogeneous materials are not able to meet the technological requirements anymore. Thus composite materials are used enabling the customisation of the operating characteristics according to a certain profile of requirements. Most widely ceramic particles (e. g. Al_2O_3, SiC) are used as reinforcement of the matrix alloy, which leads to adjustable and more appropriate operational characteristics. However, the heterogeneous structure of the composites and the presence of the comparably hard particles results in challenges during the cutting process. On the one hand surface imperfections can occur on the generated surface. Furthermore, the tool wear is highly accelerated and primarily defined by abrasive wear mechanisms due to the presence of the particles [1, 2]. Despite improved casting and forming processes for AMCs, finish operations cannot be omitted. Due to the highly abrasive nature of the ceramic particles a cutting material with a higher hardness compared to the reinforcement is required to provide a continuous and moderate progress of tool wear.

Heath concluded that diamond represents the most suitable cutting material in machining of silicon carbide reinforced AMCs [3]. Wang et al. investigated the milling of a 65 % volume proportion AMC with PCD tools achieving roughness values *Ra* below 0.5 µm [4]. Bian et al. investigated the precision machining of high volume proportion AMCs using MCD tipped tools. Mirror like surfaces with roughness values *Ra* below 0.1 µm could be achieved [5].

However, there are no publications investigating the surface integrity in milling of AMCs respecting surface structure, surface imperfections and residual stress state. Thus the aim is to investigate cutting parameters allowing a stable machining with low roughness values, reduced surface imperfections and strongly compressive residual stresses.

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Nomenclature

A_g	Fracture elongation
d_{90}	Diameter for 90 % of particles
E	Young's modulus
f_z	Feed per tooth
HV	Vickers hardness
r_n	Cutting edge radius
r_ε	Cutting corner radius
R_{kin}	Kinematic roughness
R_m	Ultimate tensile strength
$R_{p0.2}$	Yield strength
Ra	Mean surface roughness
Rz	Surface roughness depth
v_c	Cutting speed
Vvv	Valley void volume
α_o	Clearance angle of the major cutting edge
α_o'	Clearance angle of the minor cutting edge
γ_o	Rake angle
ε_r	Tool included angle
κ_r'	Tool cutting edge angle of the minor cutting edge
λ_c	Cut-off wavelength
$\sigma_{rs,f}$	Residual stresses in the feed direction
$\sigma_{rs,fN}$	Residual stresses in the direction perpendicular to the feed motion
$\sigma_{rs,I}$	First principal residual stress

2. Experiment

Side milling tests were realised examining the influence of selected cutting parameters (cutting speed, feed per tooth) and different kinematics (up milling and down milling) on the resulting surface properties. An evaluation of the machined surfaces thus is based on the surface structure in terms of surface roughness and surface imperfections as well as the residual stress state in the surface layer. The experiments were realised using a particle reinforced aluminium matrix composite. The matrix material is an aluminium alloy comparable to the AA2017 alloy (AlCu3.9Mg0.7Mn0.6). The reinforcement is represented by SiC particles with 10 % volume proportion and a particle size of $d_{90} < 2$ µm, in which 90 % of the particles are provided with a diameter of less than 2 µm. The composite material is produced by a powder metallurgical route. The matrix alloy and the particles are mixed, high energy ball milled, pressed hot isostatically and extruded (extrusion ratio 42 : 1). Subsequently, a heat treatment T4 was applied to improve the mechanical properties [6]. The extrusion process leads to an increase of the tensile strength and the Young's modulus in the direction of extrusion. Table 1 represents averaged values of the mechanical properties of the AMC used.

Table 1. Mechanical properties of the aluminium matrix composite

Mechanical parameter	Value
Yield strength $R_{p0.2}$	405 MPa
Ultimate tensile strength R_m	577 MPa
Young's modulus E	86 GPa
Fracture elongation A_g	12 %
Vickers hardness HV	174 HV

For the experimental investigations the cutting speed and the feed per tooth were varied according to five levels in a range typical for finish machining operations. Additionally, different process kinematics (up milling and down milling) were examined. Depth of cut and width of cut were kept constant at 0.45 mm and 1.2 mm respectively. The milling tests are based on a fractional factorial design. Each combination of process parameters was applied for three specimens. Table 2 presents an overview of the parameters varied.

Table 2. Process parameters varied in the experimental investigations

Cutting speed v_c (m/min)				
100	150	200	250	300
Feed per tooth f_z (mm)				
0.005	0.010	0.015	0.020	0.025
Kinematics				
Down milling		Up milling		

For the realisation of the side milling tests a double-edged CVD (chemical vapour deposition) diamond tipped end milling cutter with a diameter of 3 mm was used. Polished rake faces benefit the reduction of the tendency for built-up edge formation. Moreover, the cutting tips provide a comparably sharp cutting edge with a radius of the cutting edge r_n of about 3 µm. Furthermore, each cutting tip features a rounded cutting corner with a radius r_ε of 0.3 mm and a tool included angle ε_r of 88°. Each tip has a rake angle γ_o of 0°, a clearance angle α_o for the major and α_o' for the minor cutting edge of 15° as well as a cutting edge angle of the minor cutting edge κ_r' of 2°.

Fig. 1 represents scanning electron microscopy (SEM) images of a milling cutter with an identical tool geometry as used in the experimental investigations.

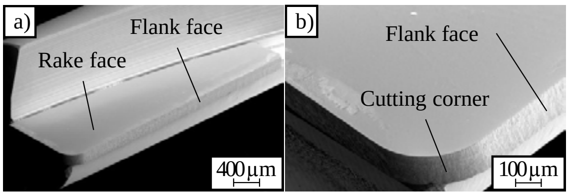

Fig. 1. Milling cutter geometry a) Tool faces and b) Cutting corner

All cutting tests were realised using a minimum quantity lubrication (MQL) system based on a polyolester (Lubri Fluid 100) as lubricant with a volumetric flow rate of 27 ml/h.

The evaluation process of the generated surfaces is based on qualitative and quantitative methods focused on the surface structure as well as the residual stress state. Regarding a quantitative evaluation the surface roughness depth Rz is determined in the direction of the feed motion as well as in the direction perpendicular to the feed motion. The measurements are based on data from 3D laser scanning microscopy, including a measuring field of 2 mm × 2 mm for each surface generated. The surface data acquired are filtered using a cut-off wavelength λ_c of 0.25 mm. Selected surfaces are evaluated with regard to the valley void volume. X-ray diffraction analysis enables the estimation of the residual stresses in the matrix material of the generated surfaces. Furthermore, a qualitative assessment of the surface structure is based on SEM images.

3. Results and discussion

First of all the influence of the kinematics was investigated. Down milling resulted in significantly smaller surface roughness values and a reduced void formation. Consequently, all subsequent tests were realised applying this milling strategy. A variation of the cutting speed results in no clear trends concerning the surface roughness depth. Therefore the assigned diagrams are not presented explicitly, yet *Rz* values of beneath 1 µm were achieved for each combination. Additionally, the influence of the cutting speed on the generation of surface imperfections was investigated. Respecting the number of voids on a generated surface as well as the volume of each void the valley void volume *Vvv* according to ISO 25178 part 2 was used for evaluation. Fig. 2 presents specific *Vvv* values resulting from different cutting speeds.

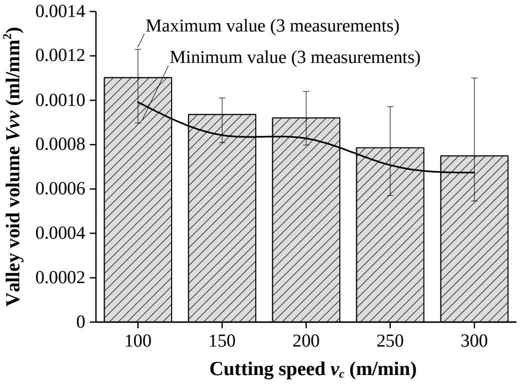

Fig. 2. Influence of the cutting speed on the valley void volume ($a_e = 1.2$ mm, $a_p = 0.45$ mm, $f_z = 0.015$ mm, down milling)

On average there is a significant decrease of the valley void volume as the cutting speed is increased. This is mainly attributed to higher temperatures in the cutting zone leading to improved plasticity of the matrix material. However, there is a considerable fluctuation in the determined specific values. Fig. 3 shows SEM images of the generated surfaces depending on the cutting speed.

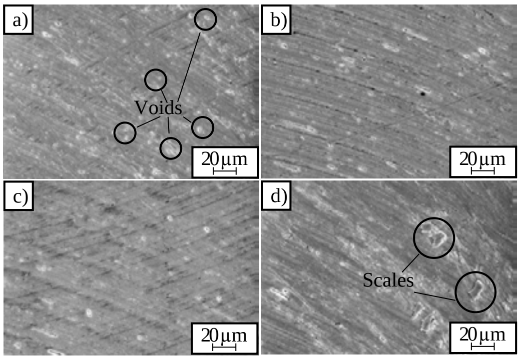

Fig. 3. Influence of the cutting speed on the surface structure and surface imperfections a) 100 m/min, b) 150 m/min, c) 200 m/min, d) 250 m/min ($a_e = 1.2$ mm, $a_p = 0.45$ mm, $f_z = 0.015$ mm, down milling)

Referring to Fig. 3 an increase of the cutting speed v_c results in a reduction of voids on the surface generated. It is assumed that the increased plasticity of the workpiece material reduces the formation of voids and benefits the void closure in the machining process. However, especially for a cutting speed of 250 m/min strong scaling appears.

Besides the surface structure the residual stress state of the surface layer is affected during the cutting process. In addition to the cutting parameters the resulting residual stresses are influenced by the tool wear as well. The presented results were achieved with a milling cutter that exhibited a width of flank wear land of approximately 14 µm. Fig. 4 represents the residual stresses measured depending on the cutting speed applied.

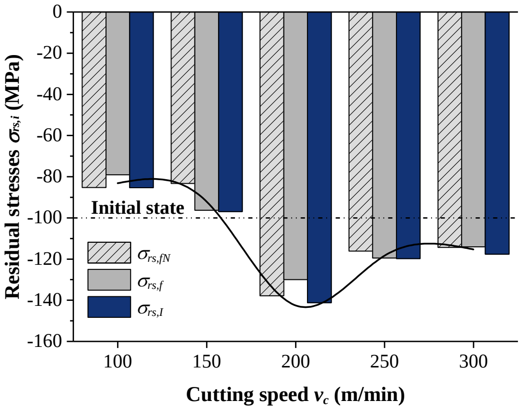

Fig. 4. Residual stresses depending on the cutting speed ($a_e = 1.2$ mm, $a_p = 0.45$ mm, $f_z = 0.015$ mm, down milling)

In milling of AMCs for the described experimental conditions only compressive residual stresses occur in the surfaces generated. These were determined in the direction of the feed motion as well as perpendicularly to the feed motion. Moreover, the first principal residual stress $\sigma_{rs,I}$ was determined. However, there are already compressive residual stresses of about -100 MPa inherent in the workpiece material prior to the cutting operations. With reference to Fig. 4 increasing the cutting speed up to 200 m/min provides the strongest compressive residual stresses. This is attributed to a reduced formation of voids in difference to lower cutting speeds. Compared to the initial stress state higher absolute values of the compressive residual stresses were achieved. Lower cutting speeds however result in reduced absolute values of the compressive residual stresses even below the initial stress state. With the cutting speed above 200 m/min increased thermal effects result in a decrease of the absolute values of the compressive residual stresses as well, yet in difference remaining above the initial stress state. Scaling effects that especially occur at a cutting speed of 250 m/min also lead to a reduction of the compressive residual stresses. This is mainly attributed to a decreased structural integrity of the surface layer benefiting the degradation of inherent residual stresses.

Additionally, the influence of the feed per tooth was investigated. Fig. 5 represents the surface roughness depth *Rz* achieved with different feeds per tooth in the direction of the feed motion and perpendicularly to the feed motion.

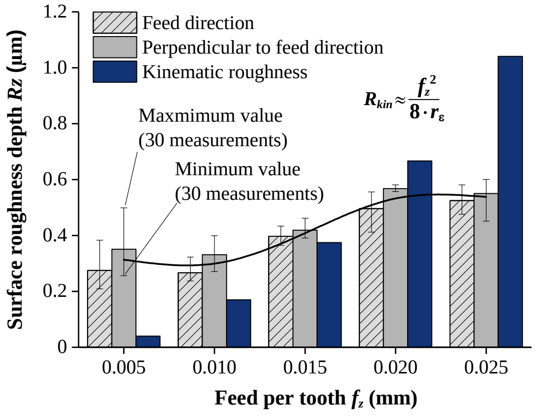

Fig. 5. Influence of the feed per tooth on the surface roughness depth (a_e = 1.2 mm, a_p = 0.45 mm, v_c = 200 m/min, down milling)

Referring to Fig. 5 the increase of the feed per tooth results in higher surface roughness values for both directions. The investigations revealed that the surface is generated mainly by one of the cutting edges. Moreover, especially for a feed per tooth of 0.015 mm and 0.020 mm respectively, the actual roughness values can be estimated in a good approximation according to the kinematic roughness R_{kin}. In case of a lower feed the roughness is underestimated, whereas a higher feed per tooth leads to an overestimation of the surface roughness values. This is mainly attributed to the use of a double-edged milling cutter. The trim cuts of one of the two cutting edges on the generated surface remain mathematically unconsidered. Additionally, the residual stress state is influenced by the feed per tooth as well. Fig. 6 represents the determined residual stresses in the generated surfaces.

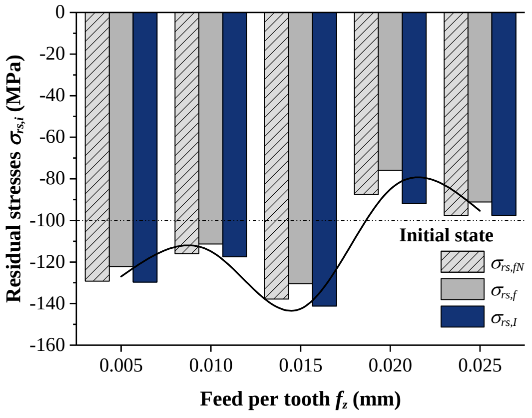

Fig. 6. Influence of the feed per tooth on the residual stress state (a_e = 1.2 mm, a_p = 0.45 mm, v_c = 200 m/min, down milling)

Feeds per tooth of up to 0.015 mm result in stronger absolute values of the compressive residual stresses compared to the initial stress state. A further increase leads to reduced compressive residual stresses. This is mainly attributed to an increased void formation. A higher number of voids benefit the stress relaxation and lead to reduced averaged stresses determined by X-ray diffraction analysis.

4. Summary and conclusions

Based on a fractional factorial design milling tests of SiC particle reinforced AMCs were realised using a double-edged CVD-tipped milling cutter. An increased cutting speed up to 200 m/min results in a reduced void formation and higher absolute values of the compressive residual stresses. Higher v_c values result in more pronounced scaling effects on the generated surface and reduced absolute values of the compressive residual stresses. An increased feed per tooth results in higher surface roughness depths as the kinematic roughness rises. For a feed per tooth of 0.015 mm and 0.02 mm the actual roughness values can be estimated in a good approximation according to the mathematical description of the kinematic roughness. Moreover, the strongest compressive residual stresses are achieved with a feed per tooth of 0.015 mm. The presented research provides a more comprehensive approach in investigating the relation between the machining operation and the surface properties respecting surface roughness, surface imperfections and residual stress state. Further experimental investigation shall transfer this approach to the influence of specific cutting tool geometries (e. g. clearance angle, cutting edge angle, cutting corner geometry) on the surface integrity of AMCs. Monocrystalline diamond (MCD) tipped tools will be used allowing a more appropriate and precise modification of these geometry elements. Reduced surface flaws and even stronger compressive residual stresses shall be achieved aiming for an overall improved fatigue behaviour.

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