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Influence of milling process parameters on the surface integrity of CFRP

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Abstract

To improve the performance of mobile vehicles like aircrafts and cars or to increase the performance of wind power plants the intensified lightweight design of structural components comes along with the substitution of metallic materials by composites such as fiber-reinforced plastics. The application of such materials allows no degradation of the components service life and hence no reduction of the surface and component integrity. During machining of such heterogeneous materials, damage to the surface and sub-surface structure can be induced as the machining properties of fibers and matrix differ significantly. In the present study a circumferential milling process of unidirectional CFRP was investigated. For this purpose the cutting parameters and conditions such like cutting speed, fiber orientation and workpiece temperature have been varied. The examination of cross-sectional micrographs shows that the damage mechanism as well as the depth of sub-surface damages is strongly dependent on the fiber orientation of the CRFP material. A significant reduction of sub-surface damages was observed for higher workpiece temperatures which could provide a potential for higher process performance by maintaining the components integrity at the same time. Furthermore it was found that higher cutting speeds result in fiber bending in the sub-surface region of the milled surfaces. For lower workpiece temperatures a crucial raise of cutting forces was found.

Keywords: Machining, milling, CFRP, surface integrity

1. Introduction

Because of their excellent weight-specific properties fiber reinforced plastics count among the most high-performance materials in the field of light-weight design. The high specific strength and stiffness make them particularly interesting for structural components in the aircraft and space industry [1]. Fiber reinforced plastics are also increasingly used in the sector of automotive, medical and general engineering where they allow for new opportunities regarding construction and design of products [2,3].

Components made of CFRP (carbon fiber reinforced plastics) are usually manufactured near-net-shape, however they have to be machined to produce bore holes or notches in the workpiece and to improve the quality of contact or functional surfaces [4]. The machining process is often done by milling, drilling or grinding. The machining characteristics of CFRP are fundamentally different compared to metallic alloys and the cutting mechanism are relatively unknown yet [3,5,6,7,8]. The machinability is mainly influenced by the mechanical properties of the CFRP which is determined by the type of fiber, the matrix material, the fiber volume content, the fiber orientation and the manufacturing process. This large number of influencing factors makes it difficult to find relations with general validity. Due to the inhomogeneous and anisotropic material properties machining of CFRP comes along with certain difficulties like fiber pull-out, delamination and decomposition of matrix material which leads to a degradation of the surface quality and the material properties. Especially the mechanical properties of matrix material are strongly dependent on thermal influences [9]. Carbon fibers on the other hand endure temperatures up to 3000°C until degradation of the structure is initiated.

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In the present study an up-cut milling process of unidirectional CFRP is investigated. The objective of this research is to find a relation between the cutting parameters and conditions and the surface integrity of the milled workpiece. Therefore the cutting speed, fiber orientation and workpiece temperature have been varied. To identify potential damages at the machined surface, cross-sectional micrographs of the specimen are analyzed.

2. Experimental procedure

All cutting experiments have been carried out on a three-axis CNC machine Hermle U630T using a discmilling cutter with a diameter of 160mm. The discmill was equipped with solid carbide inserts with a rake angle of -12°, a clearance angle of 7° and a cutting edge radius of about 35 µm. An up-cut milling process was applied under dry conditions to machine a slot into the CFRP specimens. Within the investigations the cutting speed, the fiber orientation and the workpiece temperature were varied according to table 1. The feed per tooth f_z as well as depth of cut a_e have been kept constant with a value of 0.1 mm and 0.6 mm respectively. The resultant maximum of chip thickness is 12.5 µm.

Table 1. Testplan for the cutting trials

trial no.	cutting speed v_c in m/min	fiber orientation ϕ in °	workpiece temperature T_w in °C
1-4	100	0/90/+45/-45	20
5-6	20/200	90	20
7-10	20	90	-40/20/80/120
11-14	100	90	-40/20/80/120
15-18	200	90	-40/20/80/120

To minimize the influence of vibrations and to ensure an adequate clamping of the CFRP specimens they were embedded into aluminium shells which were clamped on a multidirectional force measurement platform. The test setup is shown in figure 1. The specimens with a dimension of 10x10x50 mm^3 were separated from a unidirectional laminated CFRP plate using an abrasive cut-off machine. The plate consists of high tensile carbon fibers and a thermoset epoxy resin matrix manufactured in a mould vacuum injection process. The fiber volume content is about 50%. The maximum operational temperature of the epoxy resin is set to -60 till 80°C. The development of the glass transition temperature is given with 60°C. To reach the specified workpiece temperatures an in-process cooling and respectively heating was used. The cooling was done with a carbon dioxide nozzle while the

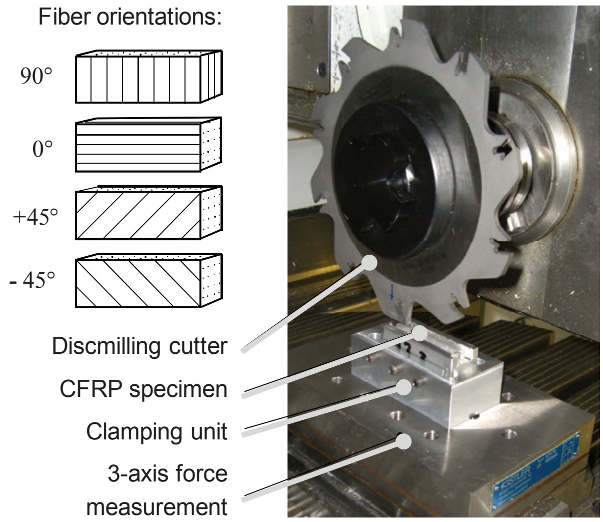

Fig. 1. Experimental setup used for slot milling

heating was performed by a hot air stream. Additionally the workpiece temperature was measured close to the cutting zone by two Ni-Cr/Ni thermocouples of type K.

3. Results and discussion

3.1. Influence of the fiber orientation on the surface integrity and process forces

Besides cutting force measurements the surfaces were analyzed on basis of micrographs. Figure 2 shows the fiber structure at the surface area along the arc of contact with the discmilling cutter. Four specimens with different fiber orientations were machined at otherwise identical milling conditions (see table 1, trial no. 1-4). Visible damages can be found for specimens with a fiber orientation of 90° and -45° while the surface for 0° and +45° appears to be very consistent and nearly free of cracks or other damages. Specimens with 90° fiber orientation are showing cracks extending frequently from the milled surface at an angle of 18° into the material at intervals of about 200 microns. These cracks are caused by the brittle material behaviour of the CFRP. The worst results were found for a fiber orientation of -45°. The micrograph shows a large crack parallel to the surface as well as recurring cracks with a length of about 300 µm extending from the surface into the material in direction of the fibers. This behaviour is well known from other literature [2]. During the cutting process the fibers are bent by the cutting edge in the direction of the free surface. This causes a high tensile load perpdendicular to the fiber direction. In this direction the tensile strenght of the unidirectional CFRP is very low (matrix properties are dominating) which causes large cracks parallel to the fiber orientation. At a certain bending the fibers are breaking beneath the surface and induce a crack parallel to the surface. By contrast for a fiber orientation of +45° the tensile load is applied nearly in fiber direction were the tensile stenght is maximal. This also causes very high cutting forces compared to a fiber orientation of -45° (see figure 3).

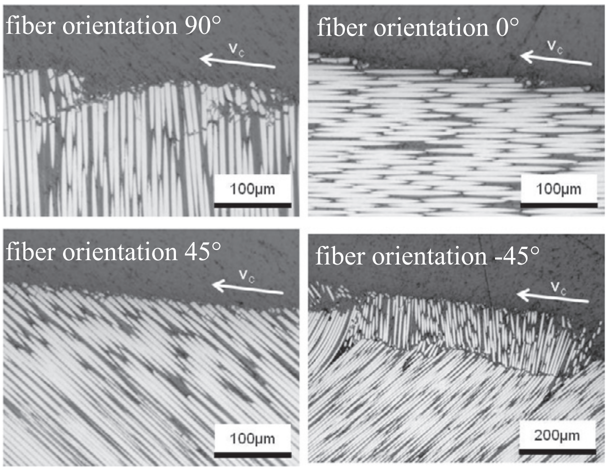

Fig. 2. Micrographs of specimens with different fiber orientations

The resultant cutting forces related to the different fiber orientations are shown in figure 3. The influence of the fiber orientation is considerably high. The most significant difference can be found between +45° with a cutting force of 300 N and -45° with 60 N which is about 80% less. Additionally the cutting forces for the machining of pure matrix material were measured. In this context it is particularly worth mentioning that the cutting forces for machining of pure epoxy resin was as high as for the machining of CFRP with a fiber orientation of -45°. This also indicates that a cutting process in -45° is dominated by the material properties of the matrix material.

3.2. Influence of the cutting speed on the surface integrity and process forces

According to trials no. 5, 6, 9 and 17 in table 1, figure 4 shows the micrographs in the area of the milled slot surfaces of four specimens machined with a cutting speed of 20 and 200 m/min and a workpiece temperature of 20°C and 80°C respectively. The fiber orientation for all specimens was 90°. A smooth surface could be achieved for all cutting parameters. However fiber bending with different dimensions is visible in cutting direction for micrographs b), c) and d). While no fiber bending is found for the lowest cutting speed of 20 m/min and temperature of 20°C, the bending extension is getting larger with increasing workpiece temperature and cutting speed. That indicates that fiber bending is caused by thermo-mechanical loads. While higher cutting speed resulted in a clearly visible fiber bending very close to the surface, a raise of the workpiece temperature led to an increasing extension into the material with less intensive bending.

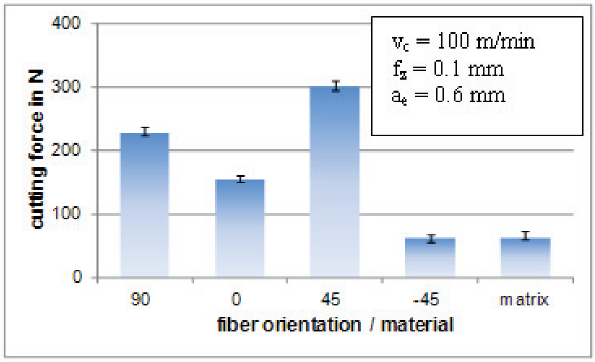

Fig. 3. Resultant cutting forces depending on the fiber orientation

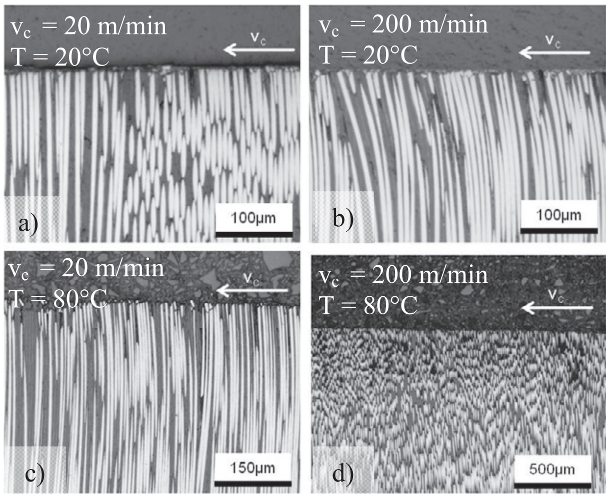

Fig. 4. Micrographs of specimens machined with different cutting speeds and workpiece temperatures

3.3. Influence of the workpiece temperature on the surface integrity and process forces

Four specimens with a fiber orientation of 90° have been machined at different temperatures of -40°C, 20°C, 80°C and 120°C to investigate the influence of the CFRP workpiece temperature on the surface integrity. The cutting parameters can be found in table 1, trial no. 11-14. Figure 5 shows the micrographs of 4 specimens machined at a cutting speed of 100 m/min. For the temperatures -40°C as well as 20°C the characteristic cracks with an inclination of about 18° to the surface and a length of up to 200 µm can be found periodically along the machined surface. For the higher workpiece temperatures of 80°C and 120°C these cracks are not occurring any longer which is possibly due to a loss of brittleness of the matrix material. The surface is relatively smooth and does not show severe damages. The surface shape is slightly curved for a temperature of 80°C. For a workpiece temperature of 120°C an altered structure is visible in an area up to 500 µm beneath the surface. At a closer look it appears that fibers were broken out of this region. This might be a consequence of thermally damaged matrix material which cannot support the fibers anymore.

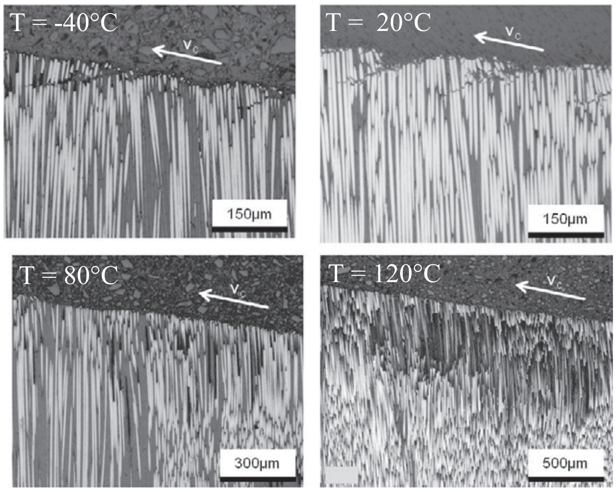

Fig. 5. Micrographs of specimens machined at different temperatures

The influence of the workpiece temperature on the cutting force is given in figure 6 for three different cutting speeds.

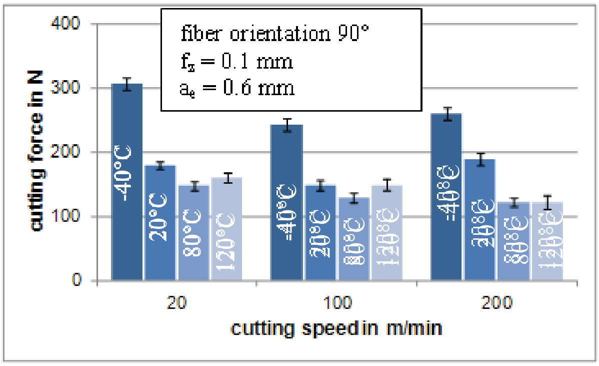

Fig. 6. Resultant cutting force depending on the workpiece temperature and cutting speed

In general a regressive cutting force progression is found with increasing workpiece temperature. The highest cutting force of 310 N was measured at a cutting speed of 20 m/min and a workpiece temperature of -40°C. A slight decrease of cutting force can be found with increasing cutting speed. It is noticeable that the influence of the cutting speed to the cutting forces is the highest for the lowest workpiece temperature of -40°C. The influence of the cutting speed to the remaining specimens was marginal.

4. Conclusion

In the present study the influence of different cutting parameters and conditions on the surface integrity of milled CFRP specimen was investigated. The surface quality was evaluated on basis of micrographs of the milled surfaces. Regarding the fiber orientation a smooth surface was found for milling in 0° and +45°, however under -45° and 90° the micrographs are partially showing serious damage in the form of cracks and segmentations. It was found that the cutting mechanism is different for each fiber orientation. This finding is also supported by significant differences in the measured resultant cutting forces for the four fiber orientations.

Furthermore it was found that high cutting speeds result in fiber bending in cutting direction close to the machined surface. This is caused by a thermo-mechanical load during the cutting process which means that the level of damage is rising with increasing cutting speed and workpiece temperature. At the same time it could be shown that frequently occurring cracks which were induced at low workpiece temperatures of -40°C and 20°C can be avoided with higher temperatures. On the other hand for a temperature of 120°C a severe alteration in the sub-surface region was found which indicates thermal damage. That means the optimal operation temperature, which prevents crack formation in the subsurface region, leading to low cutting forces and avoids thermal damage at the same time, must be in between. Milling the CFRP at 80°C led to the best results, which is close to the glass transition temperature of its epoxy resin.

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