SURFACE INTEGRITY OF MACHINED CFRP STRUCTURES

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Abstract

CFRP components and CFRP / metal compounds are increasingly applied for safety sensitive and high investment products (e.g. aircrafts and, in the near future, for wind power stations as well) for which the requirements regarding surface integrity allow no level of degradation of service life relative to the original component design. In this contribution we present experimental results of the surface and subsurface damage of CFRP structures due to cutting processes. Besides cutting process dependent delaminations, fiber and matrix failure modes resulting in fiber cracking, also a thermal influence on the fiber matrix structure was found which could contribute to a widening of the cutting parameter window by an adjusted tool design.

1 Introduction

The use of composite materials is increasing rapidly in the aeronautical and aerospace industry. Their weight specific strength and stiffness, as well as their relative light weight compared to metallic alloys provide them a net advantage for the production of lighter aircrafts. Even though composite components are produced to near-net-shape, additional machining operations are often required for joining parts as well as for assembly purposes. The most frequent machining operations are drilling boreholes for rivets and screws, as well as milling for trimming of openings or edges according to specific sizes and geometrical tolerances [1]. Unlike metallic materials, composite materials raise some specific problems during machining. Fibers used as reinforcement cause fast abrasive tool wear and tend to delaminate at edges of machined surfaces [2]. Damages such as delamination, cracks or matrix thermal degradation are also observed as the result of tool wear or improper machining conditions [3, 4]. These quality problems, which severely affect the mechanical properties of parts, are the reason for a significant rejection rate of machined composite parts. Thus the assessment of proper machining methodologies and conditions for the production of composite components becomes a necessity to produce parts with full surface integrity [5, 6].

In this contribution results of a surface integrity analysis of CFRP material machined by drilling and milling operations will be presented. Conventional drilling of multiple layer CFRP was carried out to identify the conditions and details of deficient surface integrity for the most frequent industrial CFRP cutting process. The milling process applied on unidirectional CFRP was employed to analyze the details of material removal conditions, such as the carbon fiber orientation relative to the cutting direction, and their impact on the surface integrity.

2 Materials and experimental setups

Two different CFRP materials were employed in the subsequently described experiments, a multiple layer CFRP with carbon fiber orientations of 0° and 90° as well as an unidirectional CFRP material of which specimens were cut out with 4 different fiber orientations relative to its length (the intended cutting direction, cf. center of figure 1).

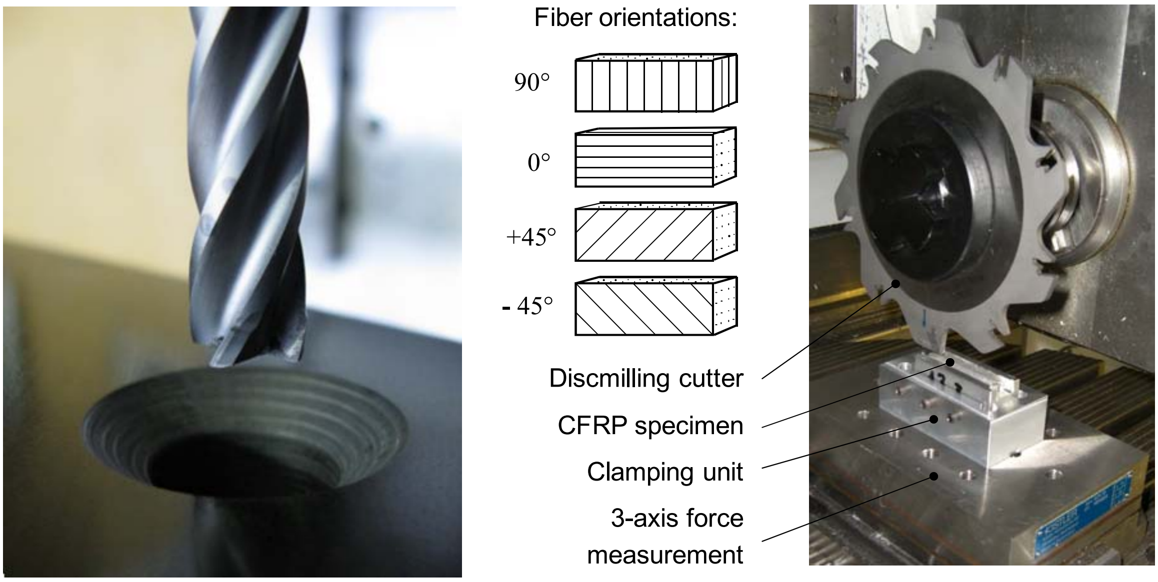

Figure 1. Experimental setup used for drilling of multiple layer CFRP (left) and slot milling of unidirectional CFRP (right)

For the conventional drilling of the multiple layer CFRP a diamond coated carbide drill of 5.1 mm in diameter without lubrication was employed. The milling of the unidirectional CFRP material was carried out by a disc milling cutter with a diameter of 160 mm using one uncoated carbide cutting insert, applying dry up-cut milling conditions (cf. figure 1, right).

3 Experimental results and observations

3.1 Surface integrity in drilling of multiple layer CFRP

Figure 2a) shows a micrograph of the subsurface structure of a borehole in the CFRP material.

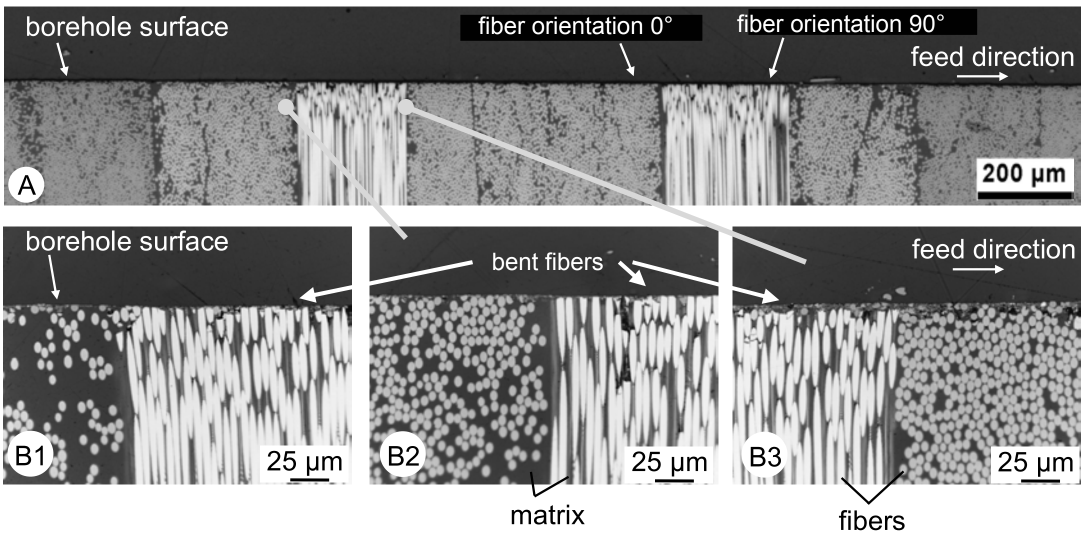

Figure 2. Micrographs of the subsurface structure of a borehole in multi-layered CFRP (cut at v_c= 40 m/min and v_{fa} = 500 mm/min)

The direction of the axial feed, i.e. the drilling direction, was from left to right and the cutting direction perpendicular to the view plane of the figure. Accordingly the multiple layers are aligned vertically. Layers with 0° fiber orientation show bright circular dots and layers with 90° fiber orientation bright vertical lines. Each layer has a thickness of about 250 microns and the diameter of the fibers is about 6 microns. The hole was drilled at a cutting speed v_c of 40 m/min and an axial feed v_{fa} of 500 mm/min which results in a feed per rotation of about 200 microns. For this condition the lowest temperature was measured (T = 112.9°C) but the largest axial feed force (F_a = 204.3 N) (for further details see [7]). For the produced surface a sharp surface edge is characteristic. No noticeable damages can be detected, but near the surface the fibers with 0° orientation are bent in cutting direction (perpendicular to figure), which leads to the oval fiber cross-sections in this region.

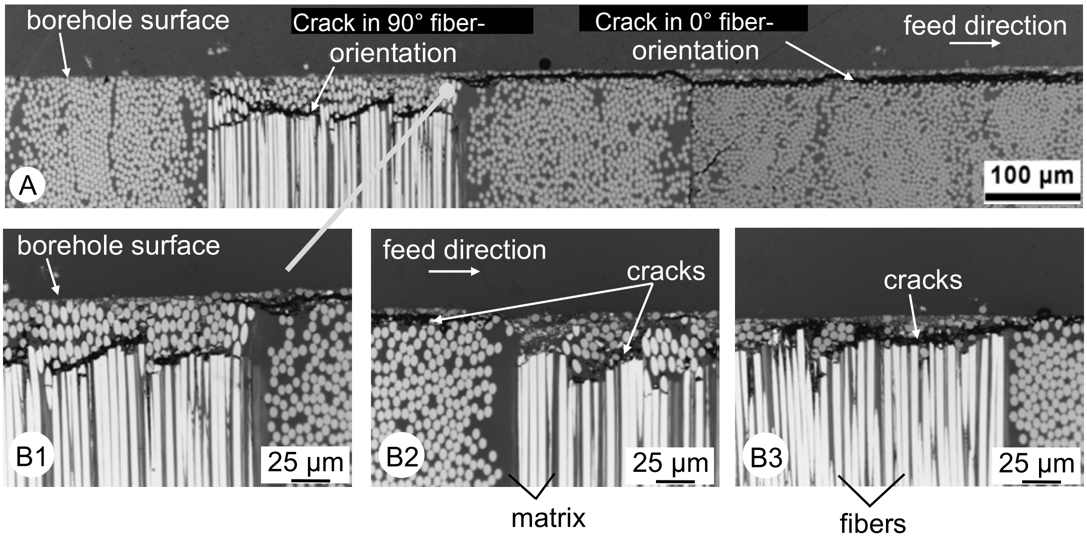

Figure 3. Micrographs of the subsurface structure of a borehole in multi-layered CFRP (cut at v_c= 120 m/min and v_{fa} = 200 mm/min)

Figure 3 shows micrographs of the subsurface structure of a borehole in multi-layered CFRP drilled from left to right at a cutting speed v_c of 120 m/min and an axial feed v_{fa} of 200 mm/min In this case the feed rate and cutting speed result in 26.7 microns per rotation which led to a measured drilling temperature of up to 191.6°C and a axial feed force of only 95.6 N. Conspicuous changes of the surface layer can be detected in terms of changes of the fiber orientation and cracks. The damages differ with fiber orientation and are maximal for fiber layers with 90° orientation. Cracks in depth of 50 µm under the surface occurred. At the surface the fibers with originally 90° orientation exhibit a new orientation between 30° and 0° after cutting (cf. B2, figure 3). Since no transition zone from 0° to 60° or 90° can be detected (e.g. like the bent 90° fibers in figure 2), the fibers must be broken and turned into this new orientation together with a significantly deformed matrix. The cracks in the cut surface layer region occur often in this region between the original, deeper lying undeformed fiber layers and the affected surface layer. On the other hand, this surface shows a low roughness of Ra less than 1.6 µm, which could be due to a smearing effect of fiber particles and matrix at the higher temperature. It is interesting to notice, that the fibers cut at the more mechanical load conditions (high feed rate, low cutting speed) bent in cutting direction, even over a larger depth, than the breaking and turning of the 90° fibers is observed for the more thermal load conditions (low feed rate, high cutting speed).

3.2 Surface integrity in side milling of unidirectional CFRP

In order to identify the relevant material removal processes responsible for the observed degradation of the surface integrity of boreholes in CFRP, side milling experiments using unidirectional CFRP were carried out. Depending on the fiber orientation, the cutting direction was either along horizontally lying fibers (0°), at +/- 45° or across vertically oriented fibers (90°) applying dry up-cut milling conditions. Figure 4 shows micrographs prepared at the bottom of the milled slots (cf. figure 1). These experiments were carried out at a cutting speed v_c of 100 m/min, a depth of cut a_e of 0.6 mm and a feed per tooth f_z of 0.1 mm/rev.

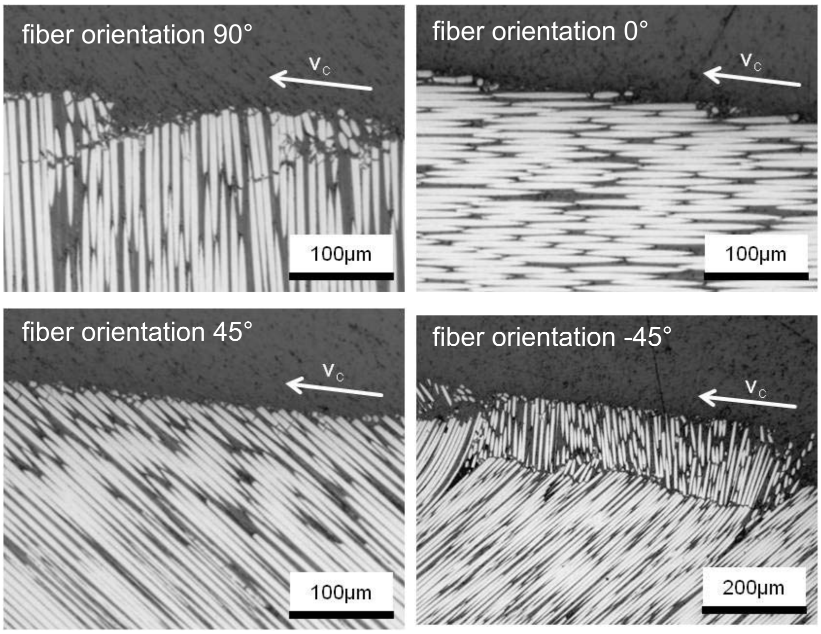

Figure 4. Micrographs of CFRP specimens with different fiber orientations after slot milling

Figure 4 shows the fiber structure below surfaces at the bottom of milled slots of four specimens with different fiber orientation at otherwise identical milling parameters. The milled surface of the specimen with vertically oriented fibers (90°, figure 4 top left) is somewhat rougher than those with horizontally lying fibers (0°). While the specimens with 90° fiber orientation show cracks extending frequently from the milled surface at an angle of about 18° into the material at intervals of about 200 microns, the surface of the specimen with horizontal fibers (0°, figure 4 top right) shows no cracks and are very smooth. The micrographs further show that the fiber structure of the specimens with 0° fiber orientation is hardly altered at all. Usually only the very top surface fibers are broken into pieces as the magnification in figure 5a) shows. The specimen with the fiber orientation +45° (figure 4, bottom left) resulted also in a very smooth surface but cutting and thrust forces were up to double as large than those for the specimens with 0° fiber orientation. A more detailed look at the fiber ends at the surface revealed cracks as well as incipient fiber cracks in a range of 10 microns below the surface (cf. figure 5b).

The micrographs of the specimens with a fiber orientation of -45° showed the most complex subsurface damage mode of all four orientations. Regions of fiber were broken at a depth of about 150 to 200 microns and sheared in cutting direction so as to exhibit a new fiber orientation. Further these regions start and end at an interface crack running as depth as 250 to 300 microns into the CFRP along fiber direction. A closer look of such an interface crack region (cf. figure 5c) shows a strong bending of fibers which opens up the crack at tensile interface stresses. The bending intensity could be close to maximum fiber bending capability, otherwise the subsurface crack would have extended further and would not stop propagating.

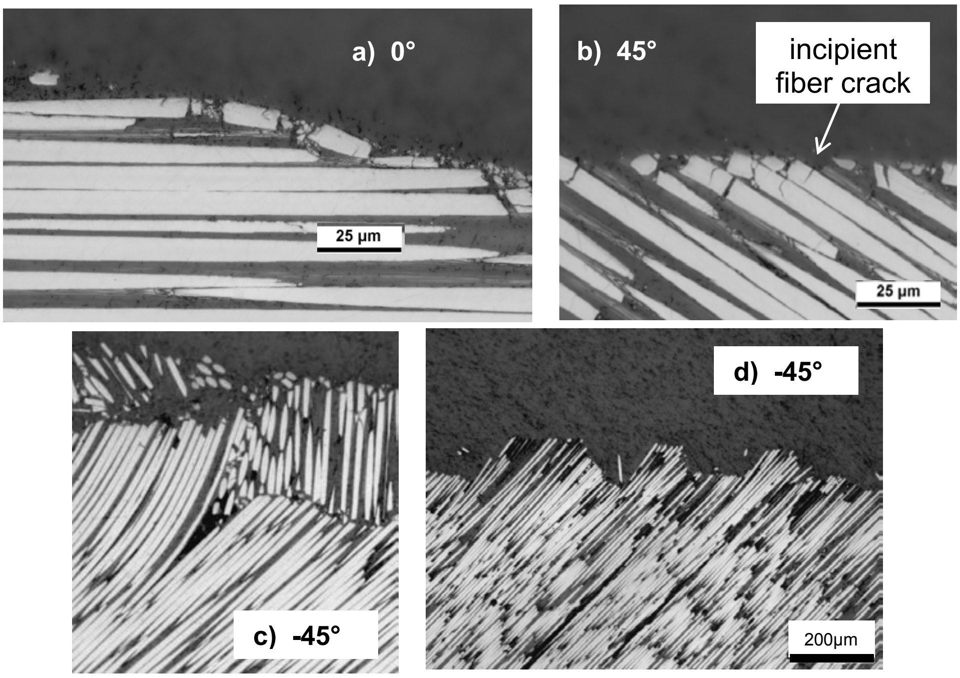

Figure 5. CFRP fiber / matrix microstructures at bottom of milled slots in specimens with different fiber orientation (cutting from right to left)

Because of the crack formation parallel to the surface, these regions of broken and sheared fiber / matrix material have little bonding, if at all, and can fall off. In that case a very rough surface is observed as shown in figure 5d).

In analogy to the observed fiber bending at the surface of the layers with 90° orientation (cf. figure 2), fiber bending was also observed in side milling of the slots. Figure 6 shows a micrograph of a cut specimen with 90° fiber orientation, which shows the bending of the fibers in cutting direction at the surface. These experiments were carried out at a cutting speed v_c of 200 m/min, a depth of cut a_e of 0.6 mm and a feed per tooth f_z of 100 microns/rev. In [8] and [9] a strain rate sensitivity of epoxy resin in tensile and shear loading is discussed which could provide the explanation for the observed fiber bending at larger feed rates.

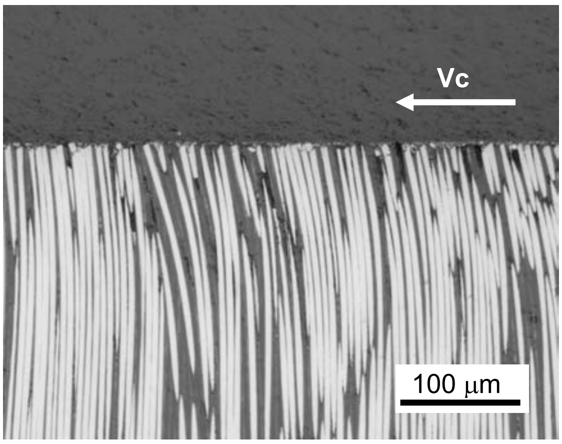

Figure 6. Micrographs of a specimen with 90° fiber orientation after slot milling with v_c=200 m/min and f_z = 100 microns/rev. ($T_{workpiece}$ = 20°C)

4 Summary and Conclusions

In conventional drilling of multi-layer CFRP material a small feed rate together with a relatively high cutting speed leads to a high thermal load of the epoxy matrix. Despite a very low surface roughness, for this condition subsurface cracks are observed which extend parallel to the surface. Temperatures up to 191°C were measured. The glass transition temperature of the resin of 180°C is exceeded and a degradation of its properties can be expected. Subsurface fiber fracture might be then the response of the material to a reduced support capability by the epoxy matrix. However when the cutting speed was reduced and the axial feed increased in conventional drilling of CFRP, the subsurface cracks were not observed anymore, but a fiber bending in cutting direction of those fibers cut perpendicular.

The milling experiments at unidirectional CFRP confirmed different levels of subsurface damage of the fiber / matrix structure as a function of the fiber orientation relative to the cutting direction. Cutting the fibers perpendicular or against their orientation (negative angle) can result into crack formation, a low integrity surface structure with hardly any strength to carry load or very rough surfaces. Like for the 90° fiber orientation in drilling multi-layer CFRP, the fiber bending at the surface was also observed during side milling of specimens with a fiber orientation of 90°.

Although not as much applied as conventional drilling, orbital drilling can improve surface integrity due to its kinematics and its effect towards reducing the thermal load resulting from the drilling itself (cf. references).

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