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Occurrence and propagation of delamination during the machining of carbon fibre reinforced plastics (CFRPs) – An experimental study

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ABSTRACT

The machining of carbon fibre reinforced plastics (CFRPs) is often accompanied by delamination of the top layers of the machined edges. Such damage necessitates time-consuming and costly post-machining and in some cases leads to rejection of components. The work described in this paper systematically investigates the occurrence of delamination of the top layers during the machining of CFRP tape, with the focus being on the process of contour milling. The occurrence and propagation of delamination were studied by milling slots in unidirectional CFRP specimens having different fibre orientations and mainly analysing the slot tip. This allowed the key mechanisms to be clarified. The results show that delamination is highly dependent on the fibre orientation and the tool sharpness. The experiments allow derivation of a novel system for describing the occurrence and propagation of delamination during milling. Furthermore, the principles also apply for drilling. The results allow customisation of the machining procedure to reduce and in some cases totally avoid delamination, leading to a significant increase in the quality of components.

1. Introduction

During the manufacture of components from carbon fibre reinforced plastic (CFRP), it is usually necessary to carry out a post-machining step after curing in order to meet the required tolerances and to manufacture fitting and joining surfaces. Classical production processes such as milling and drilling are mainly used for this.

Regardless of the production process, damage in the form of delamination can occur during the processing of CFRPs. This characteristic production defect in CFRPs is particularly prevalent in the top layers of the laminate as these are only supported on one side. Top and bottom plies of a multiaxial CFRP tape are even more critical than those of woven fabric, where crossing fibres are mutually supported. The fibres are cut by the tool in an undefined way, deflect under the action of the cutting edge and consequently delamination occurs in the form of fibre overhang and fibre break-out at the cut edges. Such damage must be absolutely avoided, because this requires time-consuming and costly post-machining to rectify and in some cases leads to rejection of components.

Although delamination during the drilling of CFRPs has already been the subject of numerous publications [1,2,6–8,10,13,14,16,21–23,25–27,29,30], little attention has been put on milling processes up until now. Colligan and Ramulu [3,4] characterised typical forms of delamination during contour milling and developed a classification system. They also established that delamination during machining mainly results from poor support of the top laminate layers.

Rummenhöller [24] and Hohensee [15] identified tool sharpness as a decisive factor for the cutting process. They also observed that fibres, in particular in the top layers of the laminate, delaminate. Davim [5] analysed the effect of the cutting parameters on the component quality when milling CFRPs. They came to the conclusion that increasing the feed per tooth leads to increased damage in the form of delamination, although the authors gave no reason for this.

The mentioned study highlighted the significance of fibre orientation as an important factor when machining CFRPs. Zhang et. al. [30] investigated damage that occurs when drilling CFRP components. They found that delamination depends on the angle between the cutting direction and fibre direction. However, the authors did not show there to be a systematic relationship between this angle and the delaminated regions. For contour milling, Hohensee [15] called this angle the fibre cutting angle θ (Fig. 1b). In contrast to the fibre orientation angle Φ (Fig. 1a), which is measured between the feed direction and the fibre orientation, the fibre cutting angle changes continuously during the engagement of the cutting edge (Fig. 1c). The reason for this is the rotary cutting motion of the tool.

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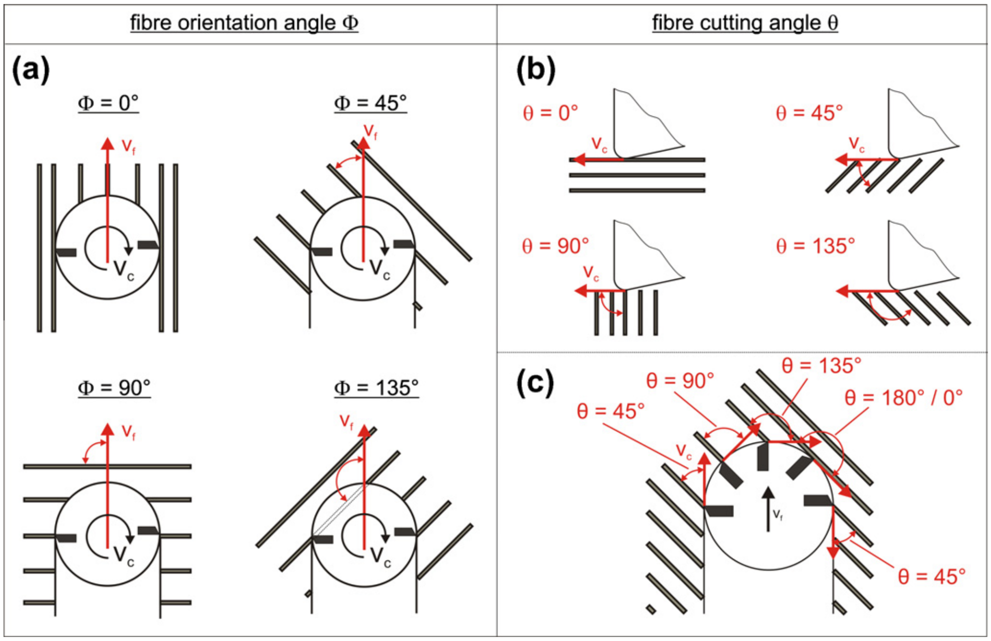

Fig. 1. Difference between the fibre orientation angle and the fibre cutting angle.

A major reason for the occurrence of delamination when machining FRPs is tool wear [4,6,9,15]. Due to the increasing cutting edge radius r_n, which is the main type of wear in CFRP machining [7,15,18,20], the machining forces increase and defined cutting of the fibres becomes more difficult [11].

With regard to the drilling of CFRP fabric, Faraz et al. [7] recently characterised the extend of delamination by the ratio of the delaminated area around the drilled hole and the nominal area of the drilled hole. They found correlations between this parameter and the maximum thrust force for each type of drill, which do not indicate a unique thrust force limit for delamination occurrence as stated in [13] but a strong influence of the drill geometry.

From drilling with twist drills it is well known, that delamination at the exit side of the workpiece is initiated already by the chisel edge [13,14,21,23]. Subsequently, during exit of the major cutting edges delamination propagates until the cutting edge corners have left the workpiece. In edge milling, such history of delamination propagation of the top layers is not considered in the scientific literature up to now [15,17,19,24,28]. These studies mostly deal with damage of the inner laminate plies at the machined surface.

This experimental work focuses on delamination of the laminate top layers in edge milling. It highlights for the first time delamination propagation effects, which are essential for the understanding of frequently observed damage at finished workpiece edges. For that, the motion of the cutting edge along the whole engagement angle has to be considered.

The work reported mainly investigates the milling of CFRPs as a function of increasing tool wear. Using new and worn tools, the effect of fibre orientation on the delamination is studied. In contrast to previous studies, the interplay between wear and fibre orientation on the delamination is systematically investigated and is represented in a novel system for describing delamination.

The knowledge that has been gained has high practical relevance as it allows reduction or avoidance of delamination despite progressive tool wear when trimming CFRP components by contour milling.

2. Materials and methods

In order to evaluate the delamination, slots were milled in unidirectionally reinforced CFRP specimens (prepreg, HT fibre, 65% fibre volume fraction, epoxy resin Cycom® 977-2). This procedure provided information about the location of delamination and also about the extent of the delamination because the slot end remained in tact. By deliberately aligning the fibres at Φ = 0°, 45°, 90° and 135° to the feed direction (Fig. 1), the effect of fibre orientation was systematically studied.

The machining tests were carried out using a milling machine made by Röders (Röders RFM 600) with a spindle power of 10 kW and a maximum speed of 42,000 rpm. For carrying out the tests, a cutting speed (v_c) of 800 m/min and a feed (f) of 0.06 mm were chosen. The work pieces were secured with clamping claws. Typical double-edged PCD end mills (diameter = 12 mm, angle of twist = 0°) were used. A coolant was not used. Fig. 2 shows the experimental set-up.

As tool wear has a major effect on delamination, tools were used in the new state and in a state of defined wear. By trimming the CFRP test specimen over a longer feed path, a defined cutting edge radius of r_n = 45 μm and r_n = 90 μm could be set at which

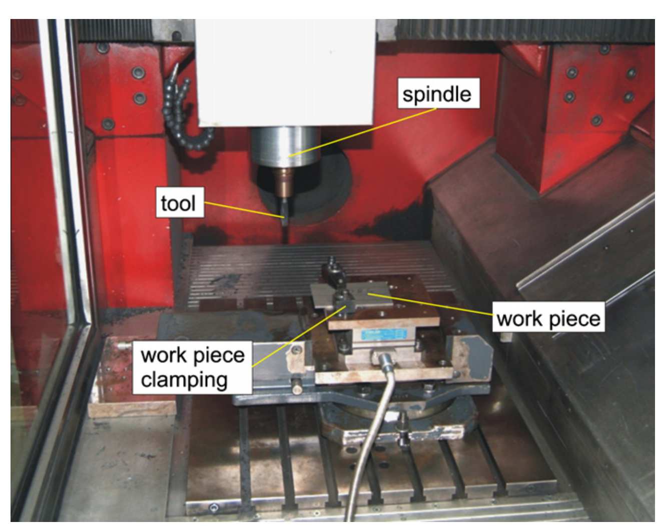

Fig. 2. Experimental set-up for slot milling.