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# Influence of weave structure on delamination when milling CFRP

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ABSTRACT

The increasing use of carbon-fiber-reinforced plastic (CFRP) is, in addition to weight reduction, driven by decorative elements especially in the automotive industry. Different kinds of woven CFRP laminates are applied for visual effects, which, however, demand a high level of surface quality of the workpiece including the trimmed edges. This study is the first to investigate the correlations between weave induced fiber undulation and delamination when machining CFRP with a woven fabric. In order to analyze the influence of the undulation, several slots were milled into CFRP with a plain weave structure using polycrystalline diamond cutters. The relative position of the trimmed edge to the weave undulation was varied by inclining the milling path slightly relative to the fiber orientation. Surface damage and fiber protrusion from the trimmed edge were determined separately. To identify the fiber undulation angle and thickness of the top matrix layer, tomographic measurements of the laminate were used. Additionally, a theoretical model for maximum fiber protrusion was established. It became apparent that the combination of fiber undulation angle and thickness of the top matrix layer are responsible for different occurrences of delamination. The influence of tool geometry on delamination is less significant.



## 1. Introduction

The use of components made of carbon-fiber-reinforced plastic (CFRP) has risen sharply in recent years. Studies assume that this trend will continue in the future (Roberts, 2011). Lässig (2012) reported that in the automotive sector, in addition to being used for weight-reduction measures, CFRP with a woven fabric is also being used for visual effects in decorative elements. In this case, the visible surfaces of the components must meet very high standards (Schubel et al., 2006).

In many instances, the components are manufactured using a resin transfer molding (RTM) process or an autoclave process. In both cases, it is commonly necessary for the components to undergo further processing to provide the final shape (Sheikh-Ahmad, 2009). This is frequently done using machining processes such as milling or drilling. As reported by Yashiro et al. (2013), the non-homogeneous material structure and the low temperature resistance of the matrix present considerable challenges for the machining processes in terms of achievable edge quality.

When milling CFRP with a weave structure, the undulation of the fiber rovings results in a heterogeneous cutting behavior at the cutting edge. Depending on the position of the milled edge relative to the undulation, this will either promote or prevent edge damage in the form of delamination. This influence is the subject of the following study.

### *1.1. Delamination when milling CFRP*

Most published studies involving milling of CFRP are focused on non-crimp fabrics. According to Hintze and Hartmann (2013), delamination in the top layers occurs during the cutting action of the milling tool, which bends the fibers outward and deflects them away from the plane of the laminate. This induces stress between the layers of the laminate, causing the layers to separate. Colligan and Ramulu (1991) have classified the resulting delamination in various types. Type I delamination describes a surface break-out of fiber bundles at the trimmed edge that extends in the plane of the top layer. Type II, by contrast, is characterized by fibers that protrude beyond the trimmed edge without causing perceptible damage on the surface. While the type II fiber protrusions can easily be rectified, correcting type I break-outs is critical (König and Graß,

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1989). A mixed form of types I and II involving both mechanisms is frequently encountered in which the fiber bundles protrude beyond the trimmed edge accompanied by significant surface damage in the material. Which of the respective types occurs depends to a considerable degree on the fiber orientation in the top layer (Puw and Hocheng, 1993).

According to Hintze et al. (2011), in full-groove cuts, the delamination is induced at the point of the initial contact between the fiber and the cutter, where the first cutting of the fiber occurs. It therefore follows that the maximum length of the fiber protrusion is the distance between the initial contact and the milled edge in the longitudinal direction of the fiber.

Another significant factor for the quality of the workpiece edge is the wear condition of the tool. Ferreira et al. (1999) has demonstrated that the feed force increases significantly with increasing wear. Karpat et al. (2012) found that the increased feed force is accompanied by a greater degree of delamination. Due to the high abrasiveness of the fibers, Teti (2002) and Karpat et al. (2012) have suggested using polycrystalline diamond (PCD) as a cutting material.

The edge quality is also significantly influenced by the parameters of feed per tooth and cutting speed as well as by tool geometry. Colligan and Ramulu (1991) found that the surface roughness and delamination are negatively affected by increasing feed per tooth. According to Davim and Reis (2005) as well as Puw and Hocheng (1993), an increase of the cutting speed can result in greater degrees of delamination and surface roughness. When it comes to the tool, a helix angle unequal 0° produces an axial force perpendicular to the laminate surface (Kalla et al., 2010). According to Karpat and Polat (2013), this force produces a significantly better machining result at the edge where the axial force is oriented inward. But on the opposite side, an increase in delamination occurs, as reported by Hosokawa et al. (2014).

Only a few studies on machining of CFRP have used a woven fabric. König and Graß (1989) studied the edge quality in drilling of plain and satin weaves. They observed a dispersion of the delamination depending on the random position of the hole relative to the weave. The delamination extended at most to the closest intersecting point of the yarns since the crossing fibers prevent the damage from propagating further. Faraz (2011) came to the same conclusion when studying delamination on the exit-ply when drilling. He also observed an elliptical spread of damage in the direction of the fiber. No previous study has focused on the influence of the woven structure on the occurrence of delamination in milling. In a variance analysis, Davim and Reis (2005) studied the influence of various process parameters on different quality variables in the milling of CFRP with twill weave. Azmi et al. (2013) recognized feed rate, depth of cut, number of teeth and cutting speed as main influencing parameters on delamination when milling GFRP with plain weave using unworn tools. Both studies do not consider any influence by the position of the milled edge relative to the yarn undulation.

### *1.2. Construction of plain weave laminate*

Textile technology differentiates weaves based on their float. This refers to the number of crossing yarns that lie under or over an unbound length of yarn. A float of one results in a plain weave. When examining the unit cell of a plain weave, Naik and Shembekar (1992) as well as Tang and Whitcomb (2003) derived further parameters for characterizing the weave (Fig. 1).

A basic distinction is drawn between warp yarn and fill yarn; in a plain weave with uniform yarns, there are no differences in the individual properties. Starting from the surface of the workpiece, the first element is a thin resin layer with a thickness of $t_m$. The thickness varies over the path of the yarn. The yarn follows

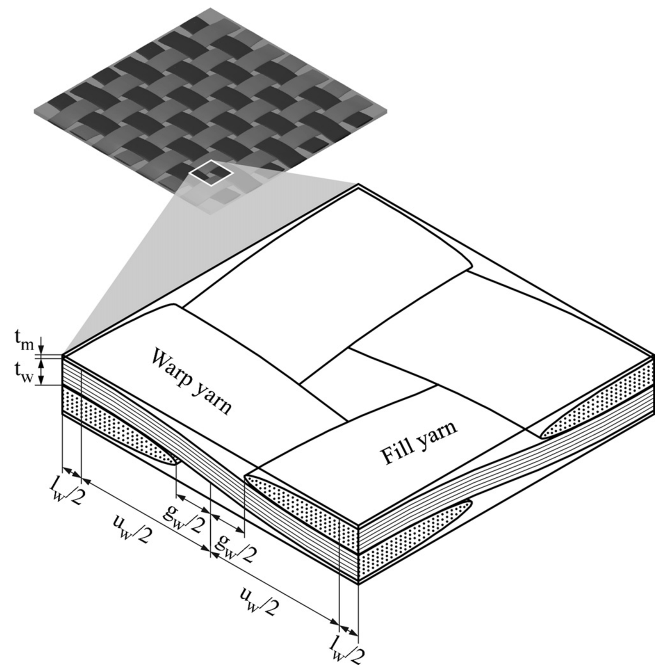


**Fig. 1.** Unit cell of plain weave (1 × 1) fabric inside a cuboid of matrix material.

with a thickness of $t_w$. The wavelength $\lambda_w$ occurs in the laminate plane, after which the fiber path repeats itself. A half wavelength is composed of the flattened region $l_w$ at the uppermost point and the undulation region $u_w$. If the laminate is observed from above, the flattened region, the upper undulation region, and part of the lower undulation region are visible. The two undulation regions are separated by the turning point of the yarn, which is situated in the middle between the likewise visible weave interstices $g_w$, which represent local agglomerations of resin. According to Huang (2000), the undulation path of warp and fill yarns in a plain weave can be approximately described with a sine function.

## 2. Experimental setup and materials

In order to study the influence of the woven structure on the edge quality full-groove cuts were milled into CFRP with a plain weave fabric. The milling path was oriented at an angle of 1° relative to the fill yarn. This was used to study the influence of the undulation at discrete distances $x_d$ at fiber orientation angles $\psi$ of approximately 0° and 90°, respectively (Fig. 2). The slight deviation of the fiber orientation angle of 0° and 90°, respectively, exerts no significant influence on the cutting mechanisms and is ignored below.

The distance $x_d$ describes the remaining length of the warp yarn from the trimmed edge until the next dip below the crossing fill yarn. At $x_d = 0$, the fiber orientation angle of the top yarn changes by 90° and the dipped yarn is no longer relevant to the damage to the surface.

The CFRP plates used were manufactured using RTM. The laminate is composed of five woven layers, which are rotated by 45° relative to one another. The overall thickness was 2 mm. The technical data are shown in Table 1.

The slots were milled using a Röders RFM600 milling machine with a spindle power of 10 kW and a maximum rotational speed of 42,000 rpm. In order to minimize the influence of vibrations, the plates were fixed over a large area on both sides of the slots using a vacuum clamping device. The tools used were dual-bladed PCD end-milling cutters with various diameters and helix angles (Table 2).