FACULTY OF CIVIL ENGINEERING & TECHNOLOGY FKTA
Universiti Malaysia Perlis (UniMAP)
FKTA Postgraduate Colloquium 2025
UNIVERSITI MALAYSIA PERLIS UniMAP

Investigating the Influence of Fiber Orientation and Tool Flute Geometry on Delamination During Milling of Glass Fiber-Reinforced Plastics (GFRP)

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KEYWORDS

GFRP machining
Delamination
Fiber orientation
Tool flute geometry
Milling parameters

ABSTRACT

Fibre reinforced polymer (FRP) composites are widely employed in advanced engineering applications, where milling operations are often necessary to achieve precise geometrical configurations and dimensional tolerances. However, the heterogeneous and abrasive nature of FRPs makes significant challenges during machining. A clear understanding of how fibre orientation and end mill flute affect delamination is crucial to improve machinability and surface quality. This review examines the influence of fibre orientation and flute geometry on delamination during milling of glass fibre-reinforced plastics (GFRP The study summarizes findings from experimental works on various fibre angles (0°, 45°, 90°, 135°) and flute counts (2, 3, 4 flutes), to understand their influence on delamination under specified milling conditions. Overall, delamination decreases as flute count increases across all fibre orientations, owing to the distribution of chip load over multiple teeth and the reduced engagement time per tooth.

1. INTRODUCTION

Delamination is recognized as one of the most critical defects during the machining of glass fiber-reinforced plastics (GFRP), directly impacting the structural integrity, surface quality, and overall performance of the finished component. It typically occurs when the stresses exerted on the material during processes such as milling, drilling, or cutting exceed the interlaminar strength, resulting in the separation of layers, fibre pull-outs, or matrix cracking. According to Hintze et al. [1], the delamination phenomena during machining are highly dependent on the fiber orientation, with fiber angles significantly influencing the stress distribution experienced by the composite. Their research illustrated that the occurrence and propagation of delamination are closely linked to fiber orientation and tool edge conditions, with a higher propensity for damage observed at certain angles, notably at 90°, due to the increased normal and shear forces acting perpendicular to the fibers.

Fiber orientation significantly influences the damage mechanisms during milling operations. The orientation of fibers with respect to the cutting direction affects the propensity for fiber pull-out, uncut fibers, and matrix fragmentation. Behera et al. [2] used artificial neural network models to predict delamination, confirming that fiber angle is a primary parameter affecting damage severity; particularly, orientations at angles like 45° and 135° tend to induce higher delamination due to the increased shear stresses along the fiber direction. Nguyen et al. [3] observed that different ply angles, such as 0°, 45°, 90°, and 135°, result in varied levels of damage, with 45° and 135° orientations experiencing more delamination owing to their complex stress distributions. Conversely, orientations aligned with the cutting direction, like 0° and 90°, tend to produce less delamination, owing to more favorable load transfer along the fiber length.

The influence of tool geometry, particularly flute number and cutting-edge design, has also been investigated extensively. Priya and Singhal [4] reported that increasing the number of flutes generally enhances surface finish quality but may introduce higher cutting forces at certain angles, thereby increasing the risk of delamination. Ling et al. [5] observed that tools with more flutes tend to produce finer surfaces but can lead to increased tool wear and potential fibre pull-out due to more engagement points between the tool and the workpiece. Kiliçkap and Yardimeden [6] compared tools with varying flute numbers and found that a four-flute geometry often results in reduced delamination severity when cutting across fiber orientations, attributable to better chip evacuation and more stable cutting conditions.

The literature review reveals that while numerous studies have identified the key parameters influencing delamination, such as fiber orientation, tool geometry, feed rate, and cutting speed, there remain research gaps in comprehensively understanding their combined effects. Most investigations focus on isolated factors, whereas the interactions between fiber orientation and tool design require further exploration. For instance, Mugundhu et al. [7] highlighted fiber pull-out mechanisms during milling, which are directly affected by the tool's cutting-edge condition and fiber arrangement. Similarly, Priya and Singhal [4] suggested that optimizing fiber angle and tool geometry together could significantly reduce delamination, but practical guidelines for such combined optimization are lacking. Additionally, the effect of fiber

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orientation on cutting forces and temperature, as studied by Wang et al. [8], points toward the need for multi-parameter optimization strategies that incorporate both the mechanical and thermal aspects of machining.

Ling et al. [5] reported that when using 3 or 4-flute drills, the delamination severity could reduce under specific conditions, especially when combined with optimized spindle speeds. These configurations tend to provide a more stable cutting action, lessening interlaminar stresses, especially at fiber angles that are prone to delamination. Yet, the potential for accelerated tool wear with higher flute numbers must be balanced against the benefits of reduced delamination, as wear can lead to uneven cutting edges and increased damage [6].

The interplay between fiber orientation and tool flute number critically determines the delamination severity during GFRP milling. Customizing tool design, such as the selection of an optimal number of flutes in relation to fiber orientation and cutting parameters, provides a strategic approach to improve the quality of machining and the longevity of composite components. Achieving a balance between these factors is vital for minimizing damage and ensuring the structural integrity of machined GFRP parts. In this study, the effects of fibre orientation and flute number (two, three, and four flutes) on the surface responses of glass FRP composite (delamination factor) were investigated. A glass FRP composite was prepared using an epoxy resin and an E-glass fabric for the milling test. The delamination factor of glass FRP composite were determined after the milling test. The variations of the delamination factor of the glass FRP composite were studied.

2. EXPERIMENTAL PROCEDURE

The fabrication of GFRP laminates was performed using the Vacuum Assisted Resin Transfer Molding (VARTM) process, which is widely recognized for producing high-quality composite materials with consistent fiber volume fractions and minimal void content. The orientation sequence included 0°, 45°, 90°, and 135° ply angles and the lamination consisted of 19 layers of unidirectional E-glass fibers mat with a size of 300 mm x 300 mm were laid on a flat glass mould with vacuum bagging, as shown in Figure 1. The epoxy resin and hardener were mixed in the ratio of 4:1. The mixture was infused into the unidirectional E-glass fabric (comprising 19 layers) during the vacuum-assisted resin transfer molding process (VARTM) under a vacuum pressure of approximately 15 mbar (1.5 kPa). The infused composite panel was allowed to cure for a minimum duration of 12 hours at ambient temperature. After the panel is obtained, the laminates were then cut into a desirable shape, which is 140mm x 99mm using a 'water-cooled' diamond saw for subsequent machining experiments.

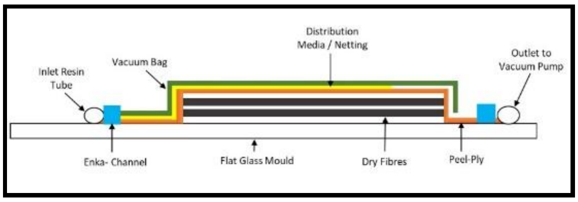

Figure 1. Schematic diagram of VARTM process [9].

The milling test was carried out on a 3-axes computer numerical control milling machine (AKIRA SEIKI Performa SR3 XP with 30KW spindle power and 11000 rpm maximum spindle speed) under dry conditions. High speed steel (HSS) cutters with 2, 3, and 4 cutting flutes were used in this study. The spindle speed was set at two levels, 4000 rpm and 8000 rpm, while feed rate and axial depth of cut were held constant at 750 mm min^{-1} and 1.5 mm, respectively.

The delamination factor of the glass FRP composite was determined using a digital low power IMTcam FHD optical microscope after the milling test. The delamination factor is calculated by the ratio of the maximum width of the delamination damage area to the nominal width of the original cut area. The delamination factor (Fd) was determined using the equation presented below [10]. Figure 2 illustrates the delamination damage factor, Fd, of the GFRP obtained from the milling trials.

$$F_d = \frac{Wmax}{W} \tag{1}$$

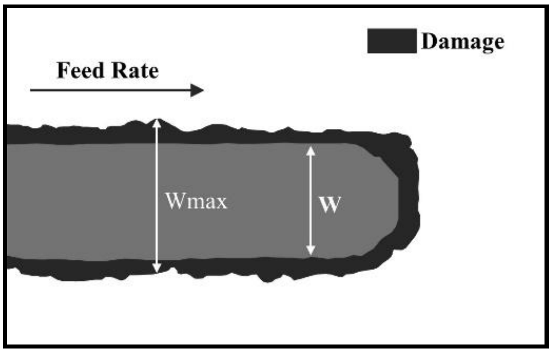

Figure 2. Delamination of GFRP under microscope [7].

3. RESULTS AND DISCUSSION

The delamination deformation is caused during the milling machining, that resulting on the fibre pull out or uncut fibres as shown in Figure 3. This is a common type of deformation that occurs during machining on FRP composite product [7].

Figure 3. Delamination on GFRP.

At a spindle speed of 8000 rpm (Figure 4), delamination decreases consistently with increasing flute count for all fibre orientations. With 2 flutes, the highest delamination occurs at 45° (1.23) and the lowest at 90° (1.15), moving to 3 flutes reduces delamination across orientations, reaching 1.11 at 90°. At 4 flutes, the values become similar, with 0° and 90° both at 1.09 while 45° remains slightly higher (1.15). Fibre orientation was found to influence damage severity, with 45° fibres exhibiting the highest tendency for delamination and 90° the lowest; at 4 flutes, the delamination factors for 0° and 90° orientations are both approximately 1.09. As the flute count increases, the cutting load is distributed across more edges leading to smoother cutting and reducing delamination, consistent with Kiliçkap and Yardimeden [6], who reported that four-flute tools often reduce delamination across fibre orientations, due to improved chip evacuation and more stable cutting conditions.

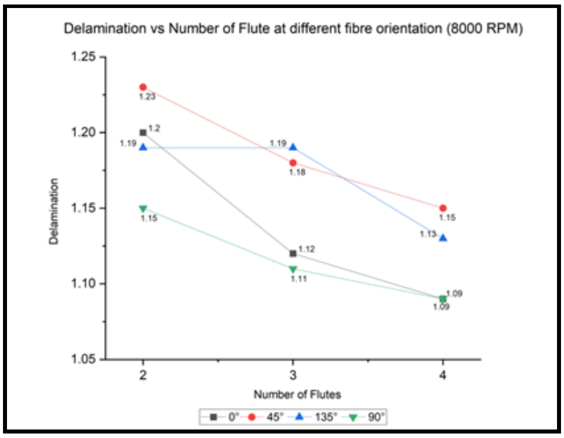

Figure 4. Delamination vs Number of Flutes at different fibre orientation for 8000 RPM.

From the Figure 5, at a spindle speed of 4000 rpm, delamination decreases progressively with the increase in flute count for all fibre orientations. With 2 flutes, the highest delamination occurs at 0° (1.47) and the lowest at 90° (1.19). Increasing to 3 flutes results in a clear reduction across all orientations, with delamination values of 1.45 (0°), 1.31 (45°), 1.20 (135°), and 1.17 (90°). When the flute number increases to 4, delamination further decreases, reaching 1.30 (0°), 1.25 (45°), 1.16 (135°), and 1.12 (90°), respectively. This consistent downward trend indicates that higher flute counts effectively reduce delamination by distributing cutting loads more evenly and minimizing fibre pull-out. Among the fibre angles, 90° delaminates the least, indicating that fibres oriented across the cutting direction resist damage more effectively, consistent with Nguyen et al. [3], who reported that 90° orientations exhibit lower delamination.

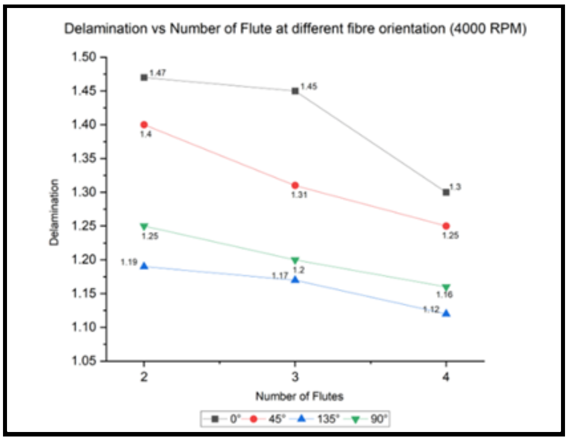

Figure 5. Delamination vs Number of Flutes at different fibre orientation for 4000 RPM.

At both spindle speeds, tools with a higher number of flutes tend to reduce the delamination factor. This is because they can cut more efficiently and with less force, thereby minimizing the stress concentrations that lead to delamination [6]. The ranking by fibre orientation remains consistent at both spindle speeds, where 45° exhibits the highest delamination and 90° the lowest across all flute counts. This trend aligns with the findings of Voss et al. [11], who explained that at approximately 45° the fibres tend to bend from the cutting edge, encouraging push-out effects. In contrast, at 90°, the tool primarily shears the fibres transversely, reducing interlaminar opening and minimizing delamination.

4. CONCLUSION

This study evaluated the effects of fibre orientation (0°, 45°, 90°, 135°) and tool flute geometry (2, 3, and 4 flutes) on delamination in GFRP, identifying the optimal parameter combinations that effectively minimize machining-induced damage. In conclusion, the results indicate that increasing the number of flutes effectively reduces delamination by promoting smoother cutting and lowering stress concentrations during milling, with tools featuring three to four flutes and operating near 90° fibre engagement minimizes delamination and enhances the surface integrity of milled GFRP. The present findings indicate that optimal combination of flute geometry and fibre orientation plays a crucial role in minimizing delamination during the milling of GFRP composites, leading to improved surface integrity and machining quality.

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