Experimental analysis the effect of end mill flutes on delamination in milling of synthetic FRP composite

M C H Ling*, N H Haliah1, C L Tan1, A Azmi 1

1 Faculty of Mechanical Engineering Technology, Universiti Malaysia Perlis, Kampus Tetap Pauh Putra, 026000 Arau, Perlis, Malaysia

*chyelih@unimap.edu.my

Abstract. Fibre reinforced polymer (FRP) composites often employed the milling process to achieve the final geometrical shapes and dimensional tolerances. However, the random variations material properties and abrasiveness of FRP composite make the milling process become a challenge. An experimental approach has been committed in this study to analysis the effect of tool geometry in end-milling on unidirectional FRP composites with its machinability indices. The experiment methodology was conducted by altering the cutting tool geometry (number of flutes) and types of reinforcement fibres. Overall, the milling experiments induced various damages on FRP composite such as fibre pull-out, delamination and epoxy matrix interfacial de-bonding are associated to the rapid deterioration of tool sharpness. Besides that, the performance of four flutes end mill tool is distinguished with better surface finish when machining across carbon fibre orientation under same spindle speed and feed rate. This is likely due to the tool engagement during cutting process and nature properties of carbon FRP composite.

Keywords: Carbon FRP composites, Delamination, End milling machinability, Glass FRP composite, Number of Flutes.

1. Introduction
Synthetic fibre-reinforced polymer (FRP) have been recognized as advanced engineering materials and widely apply in various structural and functional application. This is likely due to the appealing properties of FRP composite can be tailored based on the application requirements which is difficult to obtain from metallic materials. In common practise, the FRP composite compoenets are endeavoured to be fabricated to near-net shapes. However, the secondary process, particularly the milling operation are inevitably essential to achieve the functional requirements of the final products [1]. Thus, any machining defects arising on the milling surface may lead to expensive loss to the industry. Unfortunately, the poor machinability of FRP composite often lead to many serious defects such as delamination, which eventually increases maintenance cost. This is well known that, cutting mechanisms of FRP composites are unlike the conventional metallic materials. This is attributed to the FRP composite consist of some unique characteristics such as heterogeneous, anisotropic, no plastic deformation, abrasiveness of the fibre reinforcements, and consisting dissimilar phases of a material (hard reinforced fibres within soft polymer matrix) [2]. With such material, it has been a challenge to maintain the consistent machining qualities if improper parameter setting and tool geometry are selected.
The earliest literature regarding milling of FRP composites was on the cutting of uni-directional CFRP composites using a single square carbide insert reported by Hocheng and Piuw [3]. Experiments were conducted at the cutting speeds ranging from 31.4-188.4 m/min with constant depth of 1mm and a table feed of 50-150 mm/min. According to the article, the authors asserted that workpiece fibre orientation has a significant effect on the formation of burrs and surface roughness. Clean cut was shown when the tool was fed along the fibre orientation of 0˚. When machining at 90˚ and 45˚ fibre angle, many uncut fibres were observed since the cutting tool is liable to slip over the fibres during cutting process.

Prashanth et al.[4] have well discussed on the influence of cutting speed, feed rate and depth of cut on delamination damage and surface roughness of unidirectional glass FRP composites using three different geometry of end mill cutters. On the other hand, Azmi et al. [5] have also reported the machinability glass FRP composites during end milling through Taguchi design of experiment method. Their work aimed to elucidate the machinability of glass FRP composites with respect to surface roughness, tool life and machining forces at different level of cutting parameters. Based on the review of literature reveals that a lot experimental efforts have been conducted to improve the machinability of FRP composites under different setting of milling processes. Yet, very little has considered the effect of the end mill flutes on different type of reinforcement fibre in composite. Hence, this paper presents the machinability of synthetic glass FRP and Carbon FRP composite on milling process under different number of mill flutes in order to improve the delamination damage.

2. Material and experiment methods

2.1. Materials

The end milling experiments were conducted on the unidirectional E-glass and carbon FRP composite. The epoxy EpoxAmite 100 resin and 103 slow hardener were selected as the matrix for this composite which is suitable for resin infusion process. All the fabrication materials were provided by MechaSolve Engineering Sdn. Bhd.

2.2. Preparation of FRP composites

The laminate composite panels in this study were fabricated using vacuum assisted resin transfer molding (VARTM), which is categorised as a closed-mold process and a very cost-effective fabrication method for FRP composites. The 19 layers of unidirectional E-glass fibre and 28 layers of carbon fibre 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 mixture of epoxy resin and hardener at the ratio of 4:1 was then infused into the dry fabrics under a vacuum pressure of approximately 15 mbar. Those infused panels were left cured for a minimum of 12 hours at room temperature. The laminates were then cut into smaller specimens of 200 mm x 75 mm using a ‘water-cooled’ diamond saw for subsequent machining experiments.

![Figure 1: Schematic diagram of VARTM process [6]](image-url)
2.3. Machine tool setup and data acquisition

In the present study, a series of the end milling tests were conducted on the AKIRA SEIKI Performa SR3 XP (30KW spindle power and 11000 rpm maximum spindle speed) machine centre under dry conditions. Meanwhile, uncoated tungsten carbide end mills with diameter of 12 mm were used in the experiments. After milling test, the delamination damage, surface quality and tool wear condition were precisely measured using a low power digital microscope IMTcamFHD. The delamination damage measurement in this milling experiment is crucial thus equation below was used to determine the delamination Factor (Fd) \[7\]:

\[F_d = \frac{W_{max}}{W}\]  \hspace{1cm} (1)

where Wmax is the width of maximum damage (mm) surface and W is the nominal width of the cut (mm) surface. The quantitative evaluation of the delamination damage at the two edges of milled slot were measured at nine different fractions on both GFRP and CFRP specimens, referring to Figure 2.

![Figure 2: Divided fractions of FRP laminate for F_d measurement](image)

2.4. Design of experiment and selection of parameters

Different number of mill flutes for uncoated cemented carbide cutter and types of reinforcement fibres (Table 1) were utilised in this research in order to investigate and compare the machinability of FRP composite as per objectives. As indicated in previous studies pertaining to milling performance for FRP composites, the lower feed rate and higher spindle speed were the desired setting for minimising surface damage [3–5]. Therefore, without compromising the tool life and production rate, the feed rate, spindle speed and depth of cut were kept constant throughout the whole study at medium level, which is feed rate 750 mm/min, spindle speed 4000 RPM and 1.5 mm depth of cut. In accordance with the information presented in Table 1, a full factorial experiment consisting of total 6 trials would be needed to complete this entire study, as shown in Table 2.

| Factors/Level          | Level      |
|-----------------------|-----------|
|                       | 1         | 2       | 3       |
| A: Number of flutes   | Two flutes| Three flutes| Four flutes|
| B: Type of FRP composites | E-glass | Carbon | -       |

Table 1: Experimental parameters and level
3. Results and discussion

Table 2 shows the glass FRP and carbon FRP delamination factors obtained from different number of mill flutes under constant milling condition. It can be see that the average of delamination factors for glass FRP and carbon FRP composites lie within the range of 1.19 to 1.23 and 1.04 to 1.07, respectively. A more severe delamination damage is detected when milling with two flutes tool on unidirectional glass FRP composite. In short, the combinations of carbon FRP composites and four-flute end mill are the most preferable in order to attain minimal delamination damage, as shown in Figure 3.

| No | Tool geometry | Average,Fd Glass FRP composite | Average,Fd Carbon FRP composite |
|----|---------------|--------------------------------|--------------------------------|
| 1. | 2 flutes      | 1.23                           | 1.07                           |
| 2  | 3 flutes      | 1.21                           | 1.06                           |
| 3  | 4 flutes      | 1.19                           | 1.04                           |

Figure 3: Delamination damages for glass FRP and carbon FRP samples at 750 mm/min and 4000 rpm
This finding is in agreement with previous study on milling woven Glass FRP composite, in which increasing number of flutes results in a decrease in the delamination factor. It is well known that, the widening of delamination damage on milling surface is likely due to the uncut laminate has insufficient inter-laminate strength to withstand the cutting force generated during cutting process [6-7]. From this, it can be understood that changing of number of flutes from two to four flute resulted in less engagement of end mill cutting edges within a revolution, as illustrated in Figure 4 [13]. The feed per tooth (ft) for two flute end mill is multiplied for four flute end mill. To sum things up, best delamination factor values were obtained by four flute end mills as cutting force were estimated reducing by more flutes participated in the cutting process. Surprisingly, this finding contradicted with the one of the previous study on milling of woven carbon FRP composite, in which the six-flute end mill displays much critical delamination factor than the two-flute end mill [14]. It may due to the delamination damage was not only affected by the number of flutes but also the tool wear problem such as cutting edge roundness [15].

![Figure 4: Schematic views of cutting processes for glass FRP laminates (a) two flute end mills and (b) four flute end mills [13].](image)

Comparatively, the delamination factors for unidirectional glass FRP composite and unidirectional carbon FRP composite are depicted in Table 2. As expected, the glass FRP composite has highest delamination factor as compared with the carbon FRP composite. In the previous studies, it has been revealed that the carbon FRP composite is a high specific strength material, has higher critical energy release rate as compared to the glass FRP composite, and also it is sufficient to withstand the cutting force [11]. Therefore, glass fibres tend to break off easily causing more severe damages on surfaces when similar loading conditions are imposed in both composite structures, as shown in Figure 3.

4. Conclusion

In this study, the damages induced in end milling of both FRP composites using two, three and four flute end mills were experimentally investigated. Smoother slot surfaces (as in lower delamination factor) were machined with increasing number of flutes. This is mainly attributed to decreasing feed per tooth as greater participation of cutting edges per revolution was observed during four flute end milling process. Besides that, it should be noted that the carbon FRP composite also shows high machinability in milling process and lower delamination factor when compared with the Glass FRP composite.

5. References

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