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The Effect of Milling Parameters on Laminated Carbon Fibre Reinforced Plastic (CFRP)

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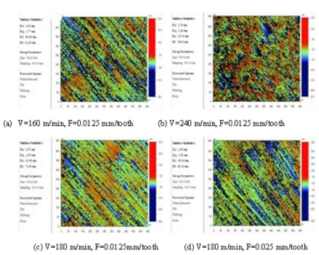
Graphical abstract



Abstract

The demand is high in various applications for an inexpensive and feasible alternative to engineering material, namely, the carbon fibre reinforced plastic (CFRP) composite. CFRP is one of the main materials used as a substitute for glass and aramid in aerospace industries. However, many problems arise during machining. Abrasive wear, poor surface finish, burr, and de-lamination, among others, are the common difficulties encountered by the machinist. These problems occur because of the existence of carbon in the CFRP that affects the performance of the tool and the surface quality of the end product. A solid uncoated carbide end mill cutting tool and a CFRP panel with fibre orientation of 0/45° were used to investigate the machinability of CFRP composite during milling; a cutting speed of 16 m/min to 240 m/min with a feed rate of 0.0125 mm/tooth to 0.0125 mm/tooth were set. At higher cutting speed and feed rate, the performance of carbide cutting tool worsens, similar to the de-lamination factor. Tool life is longer at lower cutting speed and feed rate, but a better quality surface is achieved at higher cutting speed. The dimensional precision of CFRP is also better at higher cutting speed and lower feed rate.

Keywords: Carbon fibre reinforced plastic (CFRP); abrasive wear; surface quality; de-lamination factor

Abstrak

Permintaan yang tinggi dalam pelbagai aplikasi untuk alternatif yang murah dan boleh dilaksanakan kepada bahan kejuruteraan, iaitu, bertetulang gentian karbon plastik (CFRP) komposit. CFRP adalah salah satu bahan utama yang digunakan sebagai pengganti untuk kaca dan Aramid dalam industri aeroangkasa. Walau bagaimanapun, banyak masalah timbul semasa pemesinan. Haus lelas, kemasan permukaan yang lemah, burr, dan de-laminasi, antara lain, adalah masalah biasa yang dihadapi oleh juru mesin. Masalah-masalah ini berlaku kerana kewujudan karbon dalam CFRP yang memberi kesan kepada prestasi alat dan kualiti permukaan produk akhir. Suatu pepejal tidak bersalut karbida akhir kilang memotong alat dan panel CFRP dengan orientasi gentian 0/450 telah digunakan untuk menyiasat di mesin CFRP komposit semasa pengilangan; kelajuan pemotongan 16 m / min hingga 240 m / min dengan kadar suapan 0,0125 mm / gigi 0,0125 mm / gigi telah ditetapkan. Pada kelajuan pemotongan yang lebih tinggi dan kadar suapan, prestasi karbida memotong menjadi lebih teruk alat, sama seperti faktor de-salutan. Hayat alat yang lebih lama pada kelajuan pemotongan yang lebih rendah dan kadar suapan, tetapi kualiti permukaan yang lebih baik dicapai pada kelajuan pemotongan yang lebih tinggi. Ketepatan dimensi CFRP adalah juga lebih baik pada kelajuan pemotongan yang lebih tinggi dan kadar suapan yang lebih rendah.

Keywords: Carbon fiber plastik diperkuatkan (CFRP); haus lelas; permukaan kualiti; de-faktor salutan

1.0 INTRODUCTION

Carbon fibre reinforced plastic (CFRP), which is a polymer composite, has been widely used in industries since its development in the mid-20th century. CFRP has been an alternative to stainless steel and other materials, especially in corrosive industrial application [1]. CFRP is stronger than steel and is also stiffer than titanium while retaining its lighter weight. Thus, carbon fibre is commonly used for structural components on aircrafts, resulting in improved fuel economy) [2].

CFRP composites contain two phases of materials with drastically distinguished mechanical and thermal properties, causing complicated interactions between the matrix and the reinforcement during machining [3]. CFRP composites are usually fabricated by a molding process such as hand winding and filament winding. However, milling and drilling are the main machining processes required to obtain a close fit and to achieve a near-net shape [4].

Users of CFRP experience such disadvantages as high abrasive wear on the tool, low quality of surface roughness, fibre pull out, and others during machining, and its machinability is completely different from that of conventional material. Therefore, the knowledge and the experiences acquired for conventional materials cannot be applied to this new material [5]. Thus, to overcome the problems that arise during machining, the cutting mechanisms of material removal and the kinetics of machining processes that affect cutting tools [6] and surface quality should be understood. Tool wear and de-lamination are strongly dependent on cutting parameters, tool geometry, and cutting force [7]. Either the angle of fibre orientation [8], high cutting speed, and increase in feed rate can result in high surface finish [12].

The carbide tool performance on CFRP, surface roughness, de-lamination factor, and others are studied using different cutting parameters during the milling operation in the present work.

2.0 EXPERIMENT PROCEDURE

The experiments were conducted on the laminate panel of CFRP, which consists of 8 alternating layers of carbon fibres. The panels with a dimension of 300 mm x 250 mm x 3 mm were made using the hand lay-up winding method. The orientation of the long carbon fibre used in the laminate panel is 0 / 45^{o}. A two-flute solid uncoated carbide end mill with a diameter of 8 mm, helix angle of 30^{o}, and length of 60 mm was used in the experiment. A CNC machine (MAZAK VCN-410A) with 7.5 kW spindle power and maximum spindle speed of 12000 rpm was used in this experiment. Table 1 shows the experimental conditions for CFRP cutting. A clamping method was used to avoid displacement and bending. Figure 1 shows the experiment setup of the CFRP panel. Tool wear was measured using Nikon Measuring Microscope MM-40. Data were recorded several times, one time for each distance (100 mm), as shown in Figure 2. The milling operation was aborted, and the cutting tool was discarded when flank wear, *VB*, or nose wear, *VC*, reached 0.3 mm or 0.5 mm, a standard recommended value in defining tool life testing in milling (ISO 1989). Using a tool marker microscope, photographs of the tool wear were taken, and a clearer view of the tool microstructure was obtained using a scanning electron microscope (SEM) as the tool reached the allowable limit for machining .The Optical Surface Roughness Measurement Machine Wyco 1100 was used to view the topography photograph of the CFRP surface after the milling operation.

Table 1 Physical properties of CFRP

Tool material	Solid uncoated carbide
Work material	Carbon fibre reinforced plastic
Cutting speed (m/min)	160, 180,200,220, and 240
Feed rate (mm/tooth)	0.0125 and 0.025
Depth of Cut (mm)	0.05

3.0 RESULT AND DISCUSSION

3.1 Analysis of Tool Wear

Tool wear is an important aspect of machining. Based on Figures. 3 and 4, the tool wear of carbide increased as the cutting speed increased. At a cutting speed of 200 m/min and 220 m/min for feed rates of 0.0125 mm/tooth and 0.025 mm/tooth, respectively, the wear drastically increased as the cutting tool travelled and reached a distance of approximately 500 mm. At this point, the tool wear almost reached its critical point, and the cutting speed became more significant [4]. The histogram in

Figure 1 Experiment setup

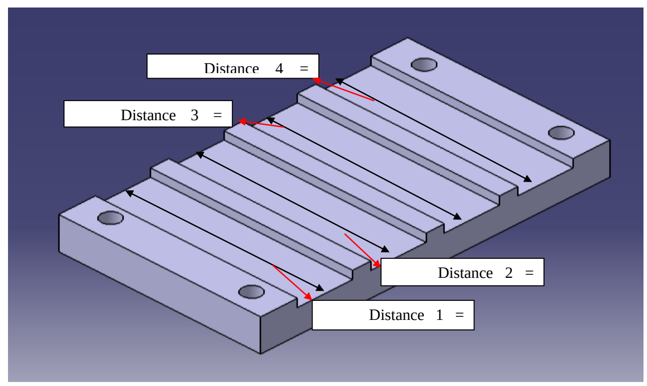


Figure 2 Distance travelled during the machining of CFRP

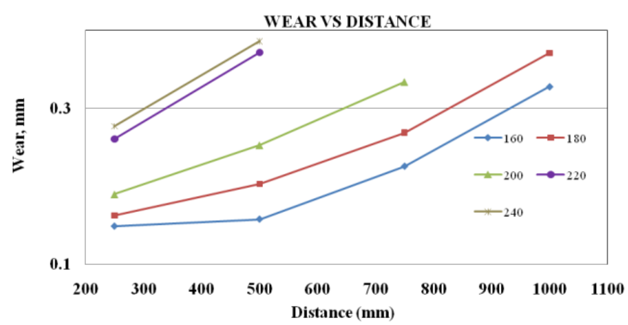


Figure 3 Relationship between wear and distance at a feed rate of 0.0125 mm/tooth

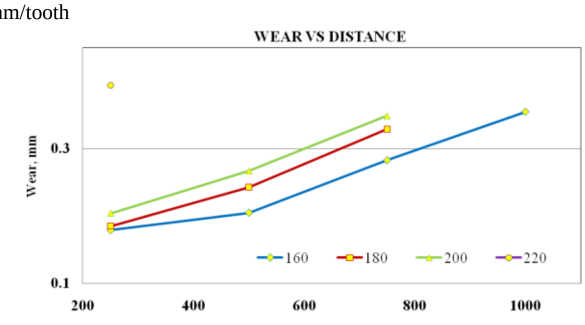


Figure 4 Relationship between wear and distance at a feed rate of 0.025 mm/tooth

Figure 5 shows that the wear taken at the first line of cutting was 250 mm. The lowest and the highest values of tool wear are at a cutting speed of 160 m/min and 220 m/min with a feed rate of 0.0125 mm/tooth and 0.025 mm/tooth, respectively. The wear at a lower feed rate of 0.0125 mm/tooth was better compared with that at a feed rate of 0.025 mm/tooth, and the wear became prominent as the cutting speed increased.

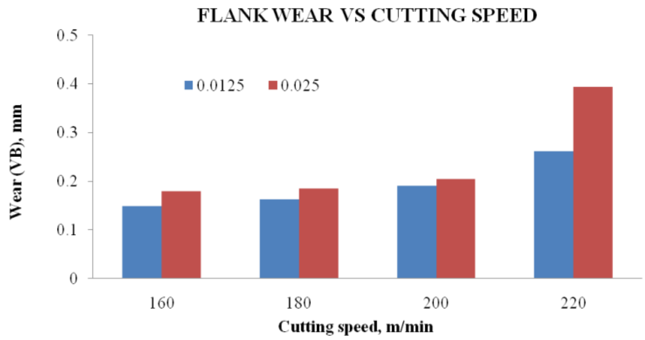
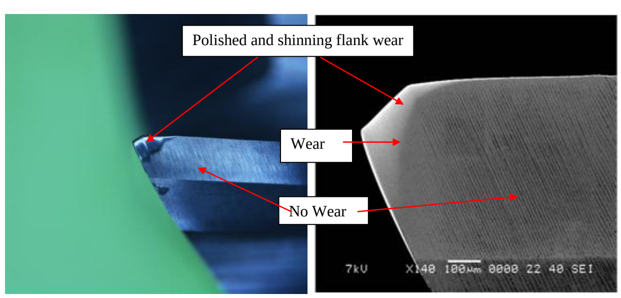


Figure 5 Comparison of wear with various cutting speeds and feed rates

Figure 6 shows the polished and shinning flank wear of the cutting edge under the electron microscope and SEM. The photograph of the wear was taken at a feed rate of 0.025 mm/tooth and cutting speed of 160 m/min as flank wear reached 0.3 mm because of the excessive wear of the side relief face and the abrasion that arose from the action between the carbon and the edge of the cutting tool [3]. As the cutting speed increased from 160 m/min to 200 m/min, flank wear increased. Figure 7 shows the tool wear at a cutting speed of 160 m/min and 200 m/min under the SEM with a feed rate of 0.025 mm/tooth. Tool wear increases when the cutting speed increases because of the brittle property of fibre and the hardness of the matrix [13]. A higher cutting speed leads to a high deformation rate of fibre in the composite, subsequently producing severe tool wear [5].

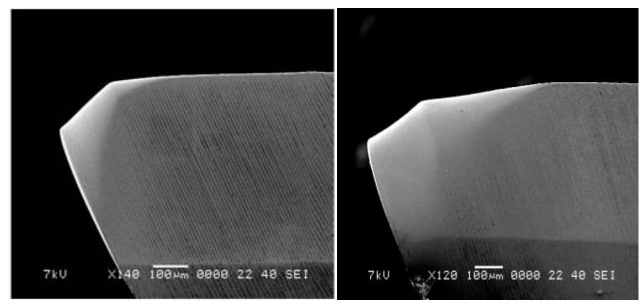


a b

Figure 6 Comparison of wear at a feed rate of 0.025 mm/tooth under a) electron microscope b) scanning electron microscope (SEM) at a cutting speed of 160 m/min

3.2 Analysis of Tool Life and Material Removal Rate (Mrr)

Figure 8 shows the tool life of the carbide tool during CFRP machining. Tool life is measured as the flank wear reached 0.3 mm, which is the ISO standard for milling operation (ISO, 1989) [11]. A cutting speed of 160 m/min gives the longest tool life, the value of which decreases as the cutting speed and feed rate increase. Tool life at the lowest cutting speed, 160 m/min, is 363.82 s and 156.605 s for feed rates of 0.0125 mm/tooth and 0.025 mm/tooth, respectively. These values are 1.77 and 1.61 times longer, compared with the highest cutting speed, which is 200 m/min, for feed rates of 0.0125 mm/tooth and 0.025 mm/tooth, respectively. At a cutting speed of 160, 180, and 200 m/min, tool life at the feed rate of 0.0125 mm/tooth is more than 2 times higher than the tool life of the tool at a feed rate of 0.025 mm/tooth. The histogram in Figure 9 shows the comparison of material removal rate (MRR)/tool life. The value of MRR/tool life decreases as the cutting speed and feed rate increase. The cutting speed of 160 m/min with a feed rate of 0.0125 m/min is the highest value among other cutting parameters that are 65.2% higher than the cutting speed of 240 m/min at a feed rate of 0.0125 mm/tooth. At a feed rate of 0.025 mm/tooth, the MMR/tool life value at a cutting speed 200 m/min is 25% less than the cutting speed of 160 m/min with the same feed rate of 0.025 mm/tooth.



(a) (b)

Figure 7 Comparison of wear at feed rate of a) 160 m/min and b) 200 m/min under scanning electron microscope (SEM) with a feed rate of 0.025 mm/tooth

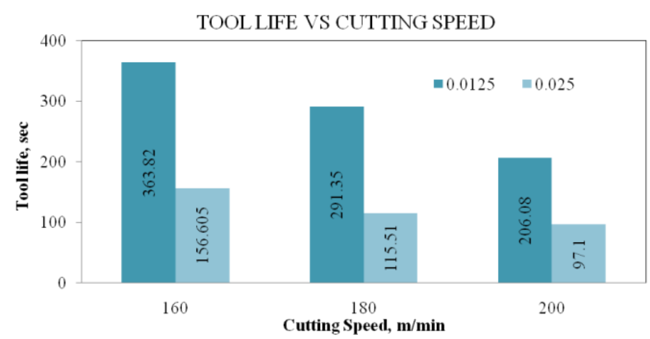


Figure 8 Comparison of tool life for feed rates of 0.0125 and 0.025 mm/tooth at different cutting speeds

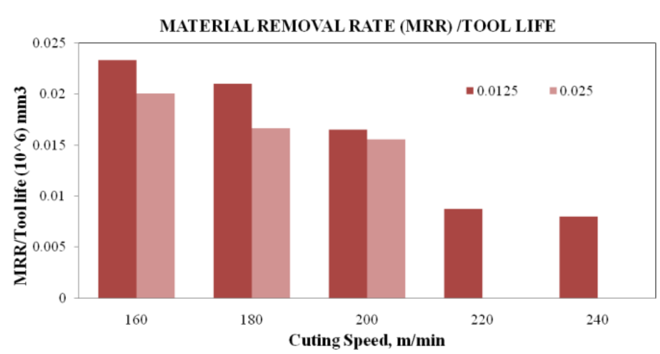


Figure 9 Comparison of material removal rate (MRR) for feed rates of 0.0125 and 0.025 mm/tooth at different cutting speeds

3.3 Analysis of Surface Roughness

Figure 10 shows the comparison of surface roughness of the CFRP for a distance of 250 mm. The feed rate of 0.0125 mm/tooth produces a better outcome in surface roughness than the feed rate of 0.025 mm/tooth. The difference can be easily distinguished as the cutting speed increases. Based on the topography in Figures 11a and 11b, the surface roughness at a higher cutting speed of 240 m/min is slightly better than that at a lower cutting speed of 160 m/min. At a low velocity of machining, the cutting is dominated by the plowing of CFRP particles, resulting in the perfect shearing of fibre, whereas at a higher velocity of machining, the cutting is steady. Both conditions result in good surface finish [5]. Based on the topography in Figs. 11c and 11d, at a lower feed rate of 0.0125 mm/tooth, the peak of the fibre is approximately at the same height as that at a higher feed rate of 0.025 mm/tooth. The fractures are less violent and more controllable because the strain is low at a low feed rate [5]. At a feed rate of 0.025 mm/tooth, the machined surface of the FRP composite is similar to crests and valleys. The fibre of the peak is not evenly distributed on the machined surface because of incomplete machining. This occurrence also shows that the increase in feed rate also increases the chatter and produces incomplete machining at a faster traverse, leading to higher surface roughness.

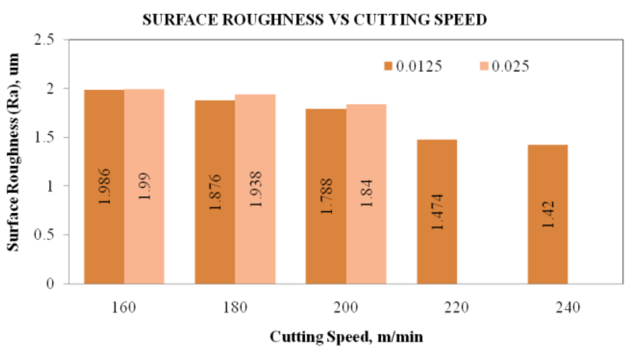
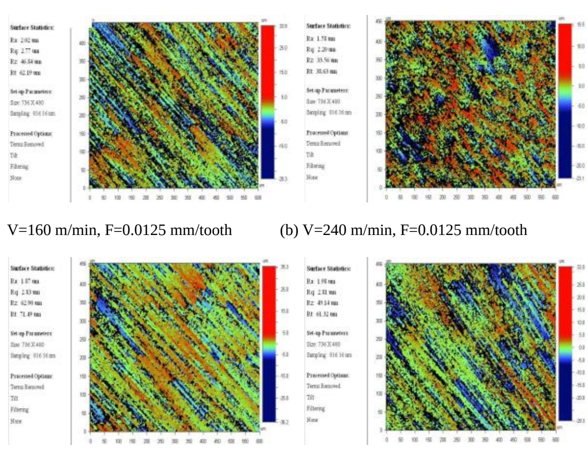


Figure 10 Comparison of surface roughness at different cutting parameters



(a) V=160 m/min, F=0.0125 mm/tooth (b) V=240 m/min, F=0.0125 mm/tooth

(c) V=180 m/min, F=0.0125mm/tooth (d) V=180 m/min, F=0.025 mm/tooth

Figure 11 Topography of surface roughness at different cutting parameters

3.4 Analysis of De-Lamination Factor (Fd) and International Dimension Precision (It)

De-lamination is a failure mode for composite materials [9]. It is defined as the quotient between the maximum width of damage (W_{max}) and the width of cut (W), as shown in Figure 12. The value of the de-lamination factor (Fd) can be obtained by Equation (1) [7].

$$Fd = \frac{W_{max}}{W} \quad (1)$$

W_{max} = maximum width of the damage (μm) and W = width of cut (μm).

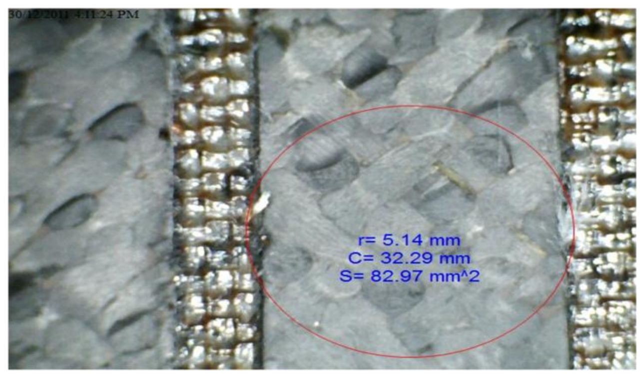


Figure 12 Measurement of the maximum damage width using a USB microscope

Figure 13 shows the result of the de-lamination factor of the CFRP in which the tool wear is acceptable for machining. The de-lamination factor increases as the cutting speed and feed rate increase because of the high cutting force during machining [10]. Slowly, increments in the de-lamination factor occur as the distance increases. In CFRP machining, bending, shearing, and rupture of the fibre will occur. The International Dimensional Precision (IT), which can be obtained from Equation (2), is the empirical equation according to UNI ISO 3963/2 [7], and it is used to measure the dimensional precision of the machined surface.

$$IT \cong 30 \times Ra \quad (2)$$

Ra is the roughness in μm

Figure 14 shows that the value of IT for the feed rate of 0.0125 mm/tooth is better compared with that for the feed rate of 0.025 mm/tooth. The surface presents IT between 43 μm and 60 μm, and between 55 μm and 60 μm for a feed rate of 0.0125 mm/tooth and 0.025 mm/tooth, respectively.

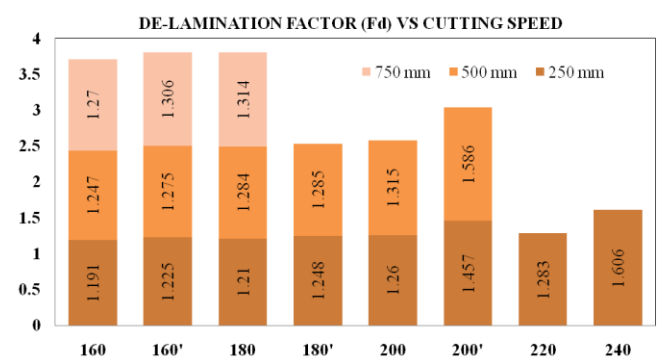


Figure 13 De-lamination factor at different cutting speeds with feed rates of 0.0125 and 0.025 mm/tooth

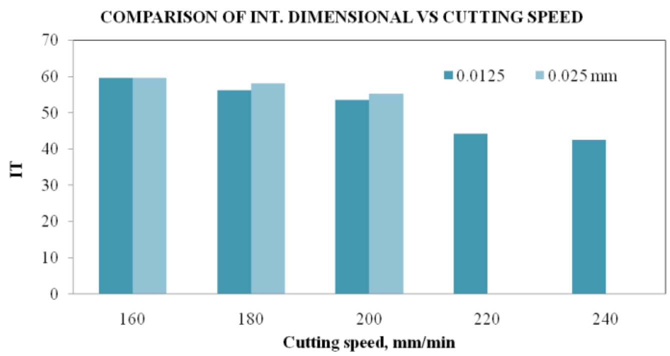


Figure 14 International dimensional precision (IT) for different cutting speeds at feed rates of 0.0125 and 0.025 mm/tooth

■4.0 CONCLUSION

The following conclusions are drawn from the result of this experiment:

1. CFRP machining is better done at a lower cutting speed and feed rate because more abrasive and excessive wear occur at a higher cutting speed and especially at a higher feed rate.
2. More CFRP can be removed during a milling operation at a lower cutting speed and feed rate because tool life is longer.
3. In terms of surface roughness and dimensional precision, the results are better at a higher cutting speed and lower feed rate because of the fibre-removal condition during machining.

The failure mode for CFRP is high as the cutting speed and feed rate increase

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