MULTI AXIS MACHINING OF HIGH PERFORMANCE CFRP FOR AEROSPACE INDUSTRY

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Keywords: *Carbon fiber reinforced plastic, surface machining, milling, surface quality*

1. Introduction

In recent years, the use of carbon fiber reinforced plastics (CFRP) has increased considerably especially in aerospace industries. Nowadays, many aircraft parts are made of composites. For example, about 50% of the weight of the Boeing 787 aircraft is made from composite materials such as carbon/epoxy and graphite/ titanium [1]. CFRP composites are widely used for different parts of aircrafts such as wing boxes, fuselage, ailerons, wing, spoilers, vertical stabilizers, traps and struts [2]. CFRP materials have many advantages compared to other materials. They have higher strength and stiffness, a longer fatigue life, a low density and better corrosion and wear resistances. Because of a negative coefficient of thermal expansion along the axis of carbon fibers, carbon reinforced composites can be patterned to minimize the thermal expansion over a wide range of surface finish and properties of the material [4, 5]. In addition, these composites are extremely abrasive and tool wear is one of the major problems encountered in CFRP machining. Poor cutting conditions produce increased specific cutting energies and higher tool temperatures, thus resulting in higher tool wear rates [6]. Therefore, choosing the appropriate conditions such as feed rate, cutting speed, and lead angle in the case of multi axis machining becomes very important.

In recent years, many studies have been carried out to provide a better understanding about the effects of cutting conditions in CFRP machining on the quality of machined surfaces.

Devim and Reis[7]investigated the effects of milling parameters on surface roughness and machining damage. They concluded that the surface roughness (R_a) increases with feed rate and decreases with cutting speed. It was also found that feed rate temperatures. This is very important for aerospace structures [3].

CFRP components are usually produced to near net-shape but machining is often required to remove the excess of material and produce high quality surfaces with controlled tolerances. In particular, drilling and trimming are extensively used to remove excessive material, produce cutouts, or holes that are required for the product function or components assembly. High precision surface milling of Carbon Fiber Reinforced Plastics particularly finds its applications for the assembly of complex components requiring accurate mating surfaces, but also for the surface repair or mold finishing. Surface milling of CFRP is a challenging operation because of the heterogeneity and anisotropic nature of these composites, which is the source of some damages such as delamination, fibers pullout, fiber-fragmentation, burring, fuzzing, or thermally affected matrix which may affect the presents the highest statistical and physical influence on surface roughness and on delamination factor, respectively. In another study, El-Hofy et al. [8] investigated the effects of different slotting parameters such as tool materials (WC & PCD) and cutting environment (chilled air& dry) on the surface roughness and integrity using 3D roughness parameters (S_a and S_t). According to the results of their research, the combination of low cutting speeds and high feed rates was recommended in view of improving surface roughness, with feed rate being a significant factor. The effect of feed rate on surface roughness was also found to be significant from the study that was carried out by Chatelain et al [9]. Sheikh-Ahmad et al. [10] carried out an experimental study to determine the effects of cutting conditions on machining quality during edge trimming of CFRP. They demonstrated that the surface roughness and average delamination depth

increase with an increase in feed rate and decreases with an increase in spindle speed.

Cutting forces are one of the important factors in machining that influence the process stability, part quality, cutting temperature, and tool wearing condition [11]. Colligan and Ramulu [12] studied the edge trimming of graphite/ epoxy with diamond abrasive cutters and demonstrated that cutting forces increase with material removal rate (MRR), expressed as follow:

$$MRR = V \times f \times d \quad (1)$$

Where, V is cutting speed, f is feed rate and d is depth of cut.

The Sreejith et al.'s [13] experiments regarding face turning of FRP showed that the variation of cutting forces/ specific cutting pressure is not uniform over the cutting speed and the moderate cutting speeds (200-300 m/min) were more suited for machining of CFRP. Zhang [14] investigated the machining of long fiber reinforced polymer matrix composite and found that cutting forces became greater with depth of cut increase. Rusinek [15] studied the milling process of CFRP and concluded that cutting force rises with increasing of feed rate. Wang et al. [16] studied CFRP milling using a PCD tool and showed that good surface quality and low delamination could be achieved in high speed milling of CFRP by using PCD tool. They found that cutting forces are an important factor for controlling surface roughness. It was also observed that surface roughness became worst with the increase of up to 250 N in cutting forces, and decreased with the increase of cutting forces over 250 N.

The lead angle is the rotation of the tool axis about the cross-feed axis [17] (Fig. 1). This angle has a significant effect on process mechanics and dynamics, which have not been studied in CFRP milling until now. The study of the effect of lead angle in metal milling showed that the cutting geometry, mechanics, and dynamics vary drastically and non-linearly with lead angle [17].

In spite of the many research works that have been carried out for better understanding of machining of fiber reinforced polymers, there are still many challenges with CFRP machining. This work presents some experiments that have been carried out on CFRP to study the optimum condition of multi-axis milling of these materials and investigate the effects of different parameters such as the cutting speed, the feed rate, and the lead angle on the resulting cutting forces, surface quality, and machining damages.

2 Methodology

In order to provide better understanding about the effects of machining parameters on surface quality and cutting forces, a set of experiments was carried out.

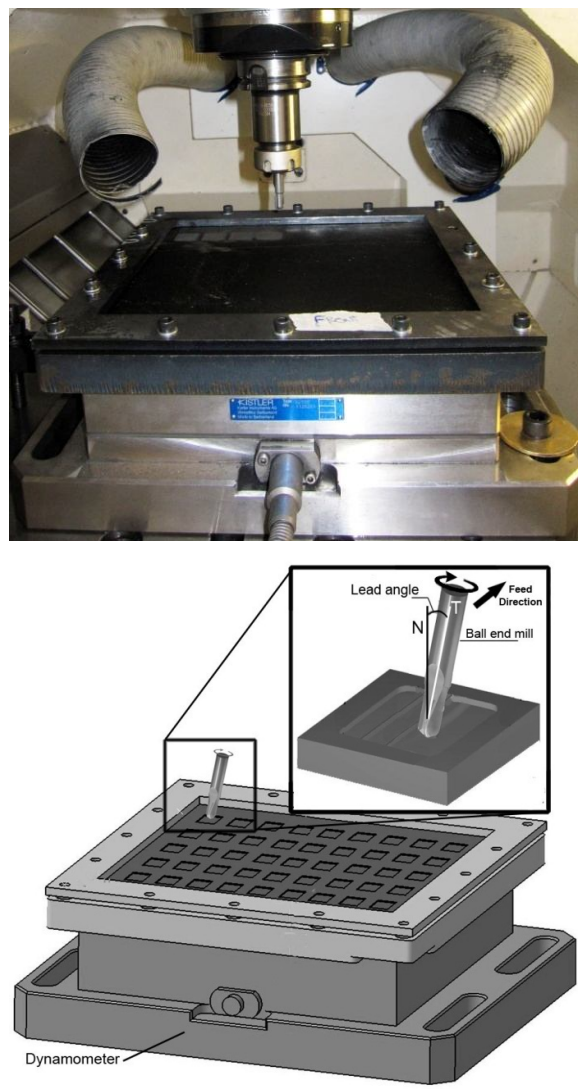

Fig. 1. Experimental setup for machining of CFRP

A high performance carbon fiber epoxy prepreg having a fiber volume content of 64% was used to produce stacks of 24 plies that were autoclave-cured to give composite plates having a final average thickness of approximately 3.5 mm.
Quasi-isotopic laminates are an important class of composites and most familiar to the aerospace industries [18].The symmetric stacking sequence [(90˚,-45˚,45˚,0˚,45˚,-45˚,45˚,-45˚,0˚,-45˚,45˚,90˚)] of the plies was such as to provide a laminate with in-plane quasi-isotropic properties.
The experiments were carried out using a Huron K2X8 five-axis CNC machine with a maximum spindle speed of 24,000 rpm under different cutting speeds, feed rates and lead angles, while keeping the depth of cut constant.
The cutting mode was up-milling with a 3/8 inch diameter ball end mill having two flutes with polycrystalline diamond (PCD) brazed inserts (Fig. 2).
Different cutting conditions were studied including: the cutting speed (100 to 500 m/min), the feed rate (0.063 to 0.254 mm/rev) and the lead angle (-10 to +10º), as can be seen in Table 1. Each experimental run is repeated three times with same conditions to evaluate the repeatability of the experiments. A Kistler 9255B(#3) three-axis dynamometer table was used for measuring the cutting forces during machining. The experimental setup is shown in fig.1.
The roughness of machined surfaces was measured using a Mitutoyo SJ400 contact profilometer (Fig.3).

Fig. 2. Two-flute polycrystalline diamond (PCD) ball end mills

Table 1. Cutting parameters

Cutting speed (m/min)	Spindle speed (RPM)	Feed rate (mm/rev)	Lead angle (º)
100	3341	0.063	-10
175	5848	0.158	-5
250	8354	0.254	0
375	12531		5
500	16709		10

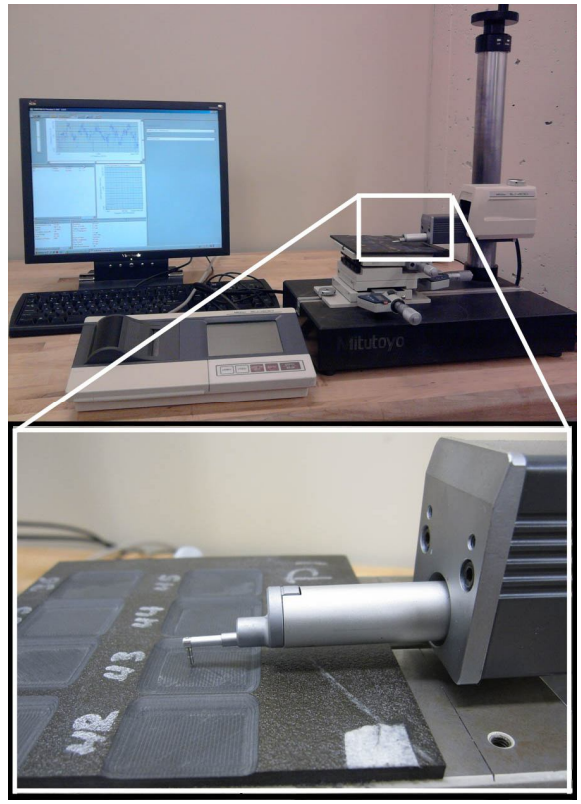

Fig.3. Measuring of surface roughness

Three readings were taken for each surface over an evaluation length of 12.5 mm at regular intervals in a transverse direction to the cutting and their average was calculated. The measured values of R_a (arithmetic average height) and R_t (ten-point average height) in different cutting conditions were compared to investigate the effect of cutting conditions on the surface quality.
The surfaces were also examined using a Keyence VHC-600+500F type optical microscope, and a Hitachi S-3600N electronic microscope(scanning electron microscopy - SEM).

3 Results

3.1 Effects of feed rate and cutting speed on surface roughness

Surface morphology and integrity depend on the machining process and workpiece characteristics such as the cutting speed, the feed rate, the fiber type

and volume content, the fiber orientation and matrix type [3].

Fig. 4 shows the effect of feed rate and cutting speed on the surface roughness. Fig. 5 illustrates the effects of feed rate and cutting speed on R_t. When comparing the figures 4 and 5, it is obvious that the variation of R_t and R_a over the cutting speed have the same trends. Thus, all the roughness results will be discussed for R_a values. As can be seen, R_a increases with an increase of the feed rate. The dependence of surface roughness to cutting speed is more complex compared to feed rate.

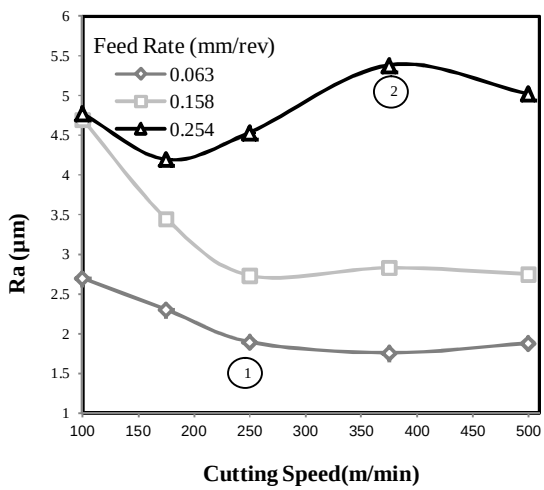

Fig. 4. Effect of feed rate and cutting speed on the R_a, 0º lead angle.

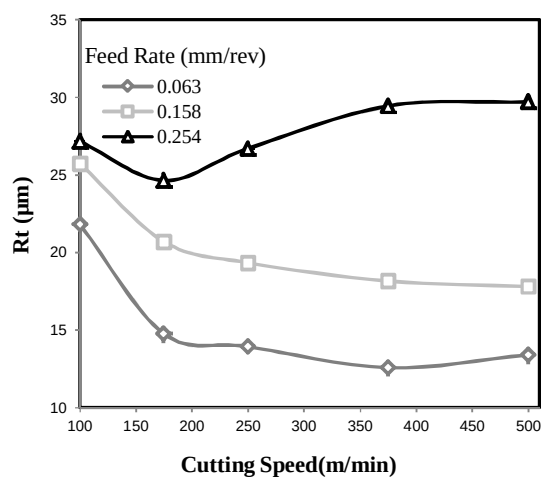

Fig. 5. Effect of feed rate and cutting speed on the R_t, 0º lead angle.

However, generally it could be concluded that in lower cutting speeds (100 and 175 m/min), surface roughness decreases by increasing of cutting speed.

An increase in cutting speed for a fixed feed rate and tool diameter (D) causes a decrease in chip per tooth, a_f, which results in a decrease in surface roughness according to the following equations [3]:

$$R_a \cong \frac{a_f^2}{32(D/2)} \quad (2)$$

$$R_t \cong \frac{a_f^2}{8(D/2)} \quad (3)$$

Increasing the cutting speed to more than 250 m/min does not have a significant effect on surface roughness for lower feed rates (0.063 and 0.158 mm/rev).

The minimum surface roughness values were achieved with a low feed rate (0.063 mm/rev) and higher cutting speed (250-500 m/min). In the case of a higher feed rate (0.254 mm/rev), the roughness diagram has a minimum point at 175 m/min and a maximum point (point 2) at 375 m/min cutting speed. Increasing the feed rate and cutting speed increases the cutting temperature [13], which can lead to softening and burning of matrix material [19]. Therefore, decreasing the surface roughness for higher feed rates (0.158 and 0.254 mm/rev) at a 500 m/min cutting speed might be explained by adhering of the uncut fibers to the softened matrix under high cutting temperatures.

3.2 Effects of feed rate and cutting speed on cutting force

According to literature, cutting forces generally increase with an increase in the feed rate, but the dependence of cutting forces on cutting speed is not uniform for different types of fiber reinforced plastics[3]. Fig. 6 illustrates the effect of feed rate and cutting speed on resultant cutting force from our experiments. It can be seen that the cutting force increases with an increase in the feed rate and there is a greater influence on cutting force for higher cutting speeds. The variation of cutting forces is not uniform over the cutting speed and can be studied in

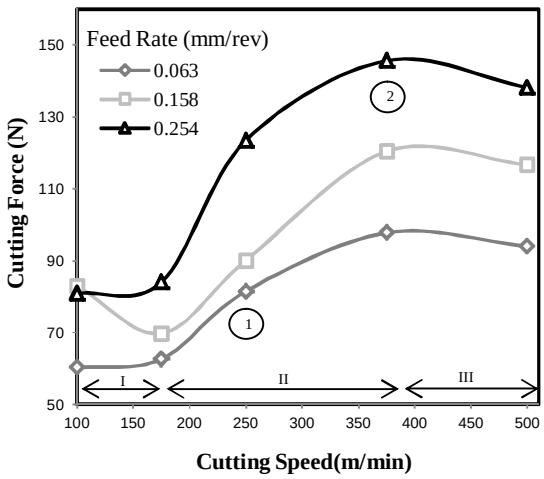

Fig. 6. Effects of feed rate and cutting speed on the cutting force, 0º lead angle

three cutting speed ranges including: I. low cutting speeds (100-175 m/min), II. moderate cutting speeds (175-375 m/min), and III. high cutting speeds (375-500 m/min). In range I, the effect of cutting speed on resultant cutting force is not significant but in range II, cutting force rises with cutting speed. In the third range, cutting force reduces when cutting speed increases. The non-uniform variation of cutting force to cutting speed is consistent with other studies[3, 14, 19].The rate of variation of the cutting forces with cutting speed is related to cutting temperatures. At low cutting speeds, cutting temperatures are not high enough for softening of polymer binder and dry friction predominates. The softening/degrading of the matrix in cutting zone occurs at a critical speed and causes reduction in cutting forces [3]. Fig. 6 shows that the critical speed is probably reached in range III, where the cutting forces become almost independent of cutting speed and the minimum cutting force is achieved in these ranges.

Among conditions that result in the lower roughness (feed rate 0.063 mm/rev and cutting speeds 250-500 m/min), point 1 in figures 4 and 6 has the lowest cutting force that results in greater process stability and part quality. Therefore, this condition is recommended for surface machining of CFRP with this cutting tool. The comparison of the surface quality in point 1 with that in point 2 (the point with the highest surface roughness and cutting force) in fig. 7 shows that many damages occur using a high feed rate.

3.3 Effects of lead angle on surface roughness and cutting force

The study of the effect of the lead angle on surface roughness in this research showed that surface roughness varies non-linearly with the lead angle and that variation depends on cutting speed. The minimum R_a and R_t are achieved for a lead angle of 5° and 0° in low cutting speeds (100 and 175 m/min) and higher cutting speeds, respectively.

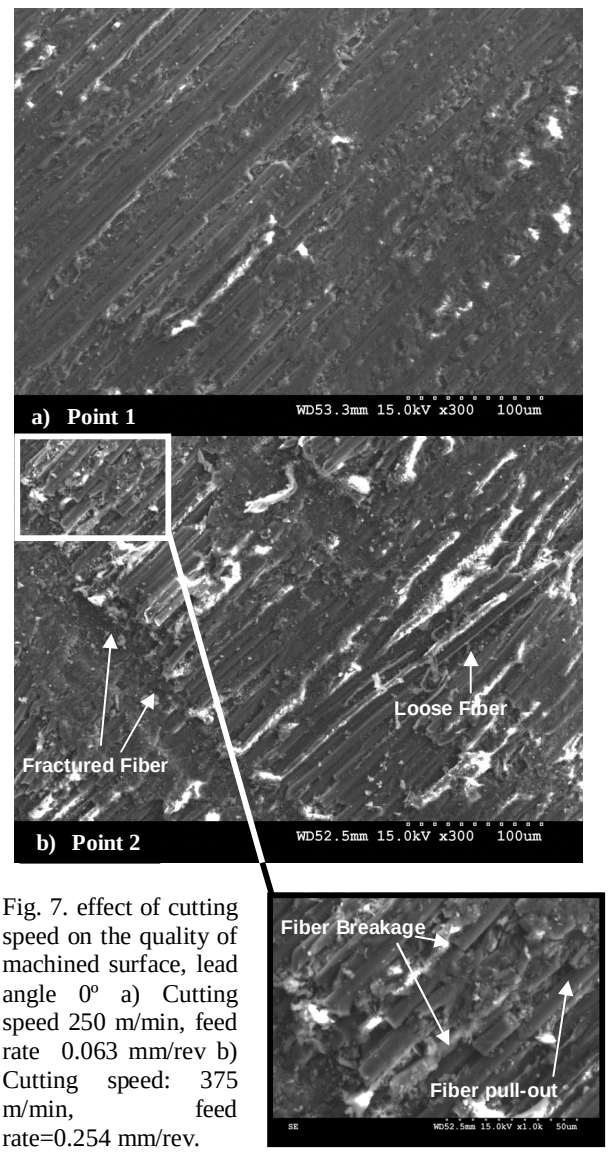

Fig. 7. effect of cutting speed on the quality of machined surface, lead angle 0º a) Cutting speed 250 m/min, feed rate 0.063 mm/rev b) Cutting speed: 375 m/min, feed rate=0.254 mm/rev.

Figure 8 shows the effect of the lead angle on the surface roughness for different cutting speeds and feed rate of 0.0635 mm/rev. As can be seen in fig. 8, the variation of cutting force with lead angle is not uniform for all cutting forces. However, the minimum cutting forces were achieved at the lead angle 0º and -10º for low cutting speeds (100, and 175 m/min) and higher cutting speeds (250, 375 and 500 m/min), respectively. This diagram illustrates that the variability in roughness curves is higher for negative lead angles. It is shown that roughness curves for lower cutting speeds have high amplitudes (100, 175 and 250 m/min) compared to higher cutting speeds (375 and 500 m/min). In other words, sensitivity of roughness to the lead angle is higher for the low cutting speeds.

Figure 9 shows the effect of the lead angle on the resultant cutting forces for a cutting speed of 250 m/min and a feed rate of 0.063 mm/rev. Fig. 10 shows the SEM images of a machined surface with different lead angles. As can be seen in this figure, the best quality surface was achieved with lead angle equal to 0 and -10 degree where the roughness and cutting force are at minimum values, respectively. More damage, such as fiber breakage, fiber de-cohesion and matrix damage is observed in the case of lead angle of 5º while the roughness and cutting force have maximum values.

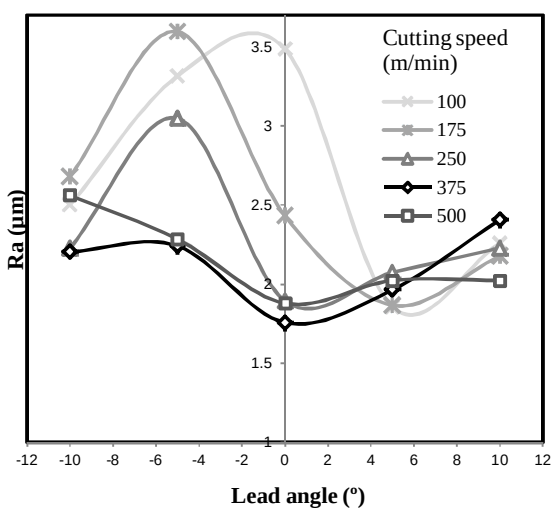

Fig.8. Effect of lead angle on the roughness R_a for different cutting speeds (feed=0.0635 mm/rev)

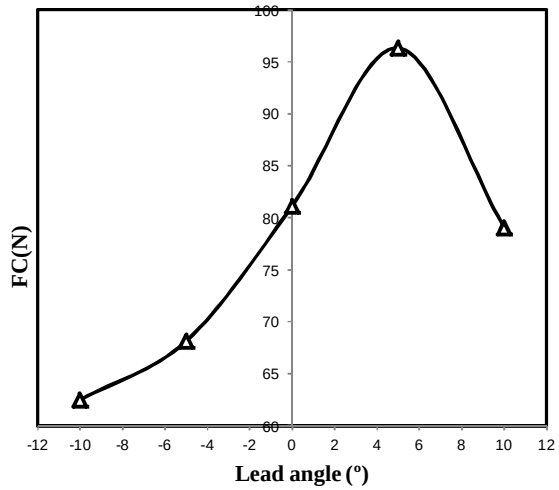

Fig. 9. Effect of lead angle on the cutting force, Cutting speed: 250 m/min (feed= 0.063 mm/rev)

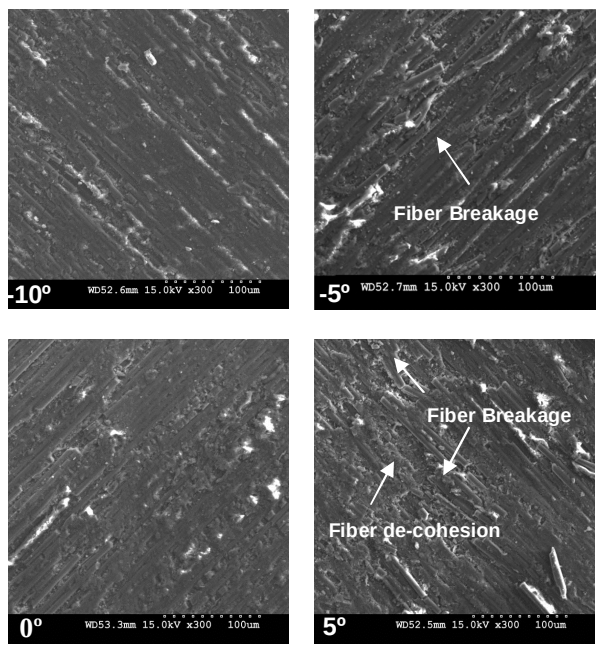

Fig. 10. SEM images of machined surface with different lead angles (cutting speed 250 m/min, feed rate 0.063 mm/rev.)

4 Conclusions

In this paper, surface milling experiments were carried out on carbon fiber reinforced plastic to

study the effects of cutting parameters on cutting force and surface quality and to find the optimum condition for this operation type using a PCD two flutes ball nose end mill. Based on the presented results, the following conclusions are drawn:

- The surface roughness increases with an increase in the feed rate.
- In lower cutting speeds (100 and 175 m/min), surface roughness decreases with an increase in cutting speed, while increasing the cutting speed to more than 250 m/min has no significant effect on surface roughness for lower feed rates (0.0635 and 0.15875 mm/rev).
- The cutting force increases with feed rate but the variation of cutting forces has no consistent trend over the cutting speed. However, the effect of cutting speed on cutting force is more significant for moderate values of cutting speed (175-375 m/min)while improving the cutting force.
- The variation of cutting force and surface roughness with lead angle is non-linear and the minimum values are found for the 250 m/min speed and 0.0635 mm/rev feed rate, for lead angles equal to 0º and -10º, respectively. This latter value is surprising since it is quite an unusual lead angle in multi-axis machining.
- Instability in the roughness diagram increases when using a negative lead angle. On the other hand, using a positive lead angle produces higher cutting forces.

Acknowledgment

This research was funded by the Consortium for Research and Innovation in Aerospace in Quebec (CRIAQ) and its partners, the Natural Science and Engineering Research Council of Canada (NSERC), MITACS, Bombardier Aerospace, Avior Integrated Products, Delastek and AV&R Vision & Robotics.

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