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Cutting Forces and 3D Surface Analysis of CFRP Milling with PCD Cutting Tools

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Abstract

This paper provides a study on the milling of carbon fiber reinforced laminated composites. A set of milling experiments were carried out under various conditions. Cutting force results were measured and analyzed (based on the cutting coefficients modelling). 3D surface topographies of machined areas were measured. The cutting forces and surface roughness results were analyzed and better average surface roughness values were obtained from the process conditions of high cutting velocity and low feed rate. The influences of fiber orientation on the surface quality were evaluated. The tool flank wear was measured by an optic microscope periodically and the results were interpreted.

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1. Introduction

Carbon-fiber reinforced composites have seen rising application in advanced manufacturing sector. Generally composites are manufactured for their near-net-shape with using specific manufacturing methods, however they need limited traditional machining methods (drilling, milling etc.) to achieve shape accuracy or to accomplish deburring.

Beside high specific strength and specific toughness, composite materials have different properties such as low thermal expansion coefficient, vibration damping. In addition to these, they have many advantages in comparison with the metals. On the other hand, because of their brittleness, composites are not deformed plastically and fractured easily. These reasons make the machining of composites difficult.

Non-homogeneous structure of composites leads various difficulties during machining such as excessive temperature, tool wear and undesired surface quality [2]. These difficulties result in fiber pull-out, delamination. For these reasons surface quality is affected badly [3,6]. The damage and machining precision of the CFRP are dependent on machining parameters especially cutting velocity and feed rate.

Davim and Reis [4], performed milling tests on CFRP laminate plates using two-flute and six-flute end mills with several cutting conditions. They showed that it is possible to get surface quality values by changing cutting parameters. Surface roughness is increased with feed rate and decreased with cutting velocity. They showed that feed rate is the cutting parameter presents the highest statistical and physical influence on surface roughness and delamination. Rahman et al. [8] performed turning studies on two type of composites, short discontinuous and long continuous fiber reinforced polymers. Ceramic, tungsten carbide and CBN cutting inserts were used for experiments. They showed tool wear, surface quality and cutting forces change with respect to depth of cut, feed rate and cutting speed for short fiber reinforced composites. For long fiber reinforced composites, tool wear is minimizes by low cutting speeds. Additionally CBN inserts showed superior tool wear properties and better surface roughness values when compared to tungsten carbide and ceramic inserts. El-Hofy et al. [9], studied slotting, routing process on CFRP using both WC and PCD cutting tools under dry and chilled air environment conditions. They obtained SEM views and 3D topographic maps and analyzed them using the Taguchi

experiment method. Statistical analysis showed that PCD tools provided significantly increased productivity compared to coated WC tools. Moreover, the combination of low cutting speed and high feed rate improved surface roughness. Karpat et al. [5], proposed mechanistic cutting force model for milling of CFRP laminates. By using the data obtained from the slot milling tests, radial and tangential cutting force coefficients were calculated as a function of fiber cutting angle. They observed that radial forces peak for the 0° fiber direction and are higher than the radial forces measured on 45° fiber directions. The greatest tangential forces were observed when machining laminate of 135° fiber direction, the smallest tangential forces are observed on 45° fiber direction.

In this study milling experiments are done for a range of cutting parameters. Cutting force data was used for mechanistic force modelling and cutting coefficients were evaluated for different conditions. The influence of process parameters and fiber cutting angles on cutting forces and surface roughness was investigated. 3D surface profiles were measured and used to quantify surface damage and inclusions.

2. Experimental study and procedures

For this experimental study, a Hartford VMC550 vertical machining center was used. A Seco B28 jarbo (PCD Coated) milling tool, 10 mm diameter and 10° helix angle was also used. The tool mounted to the machining center with a BT 40 type tool holder, shown Fig. 2. To measure cutting forces a Kistler 9722-A 3 axis dynamometer, a National Instruments BNC 2120 signal receiver and a NI 6062E Data Acquisition card were used. The experiments were performed over the laminated composite plate with 2 fiber cutting angles, 2 cutting velocities and 5 feed rates, (see Table 1).

Table 1. The experiment plan

| No | Cutting velocity (V - m/min) | Fiber cutting angle (β - degree) | Feed rate (f - mm/tooth) |
|-------|------------------------------|---|---------------------------|
| 1-5 | 50 | 45° | 0.05/0.075/0.1/0.125/0.15 |
| 6-10 | 100 | 45° | 0.05/0.075/0.1/0.125/0.15 |
| 11-15 | 50 | 135° | 0.05/0.075/0.1/0.125/0.15 |
| 16-20 | 100 | 135° | 0.05/0.075/0.1/0.125/0.15 |

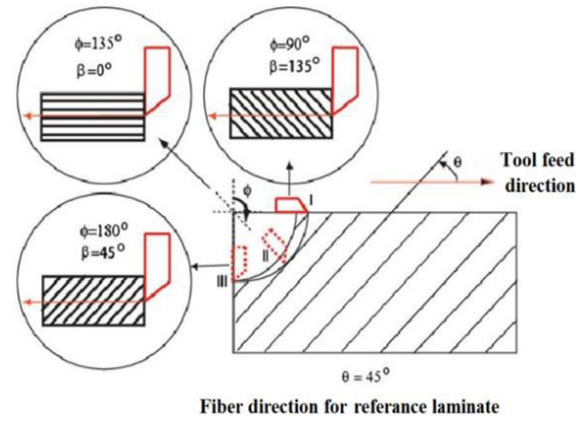


Fig. 1. Fiber cutting angle definition [5].

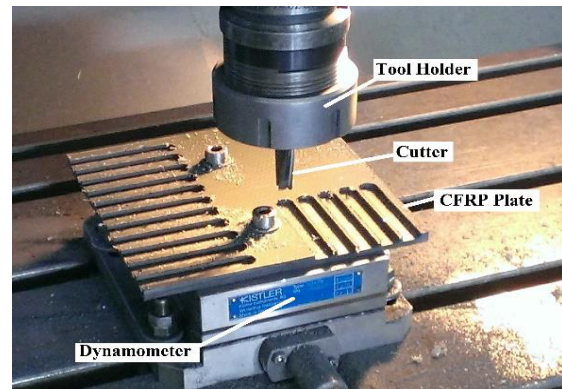


Fig. 2. Experiment setup.

The properties of composite plate are shown in Table 2. The laminated plate has 32 laminates and the theoretical laminate thickness is 0.184 mm.

Table 2. Workpiece material properties

| Resin Content (%) | Strength (MPa) | Modulus (GPa) | Density (g/cm^3) |
|-------------------|----------------|---------------|-----------------------------|
| 34 ± 2 | 1850 | 135 | 1.59 |

2.1. Mechanistic force modelling

Mechanistic force modelling is a technique that milling forces can be determined based on integration of cutting force coefficients over the tool geometry [5,7]. Several milling tests were performed with a variety of feed rates but constant depth of cut. The average cutting force per tooth is measured. Cutting force coefficients are defined as force per unit area, they can be determined analytically from experimentally obtained average cutting force data. (Shown in Fig. 3. And following equations)

$$\bar{F}_q = \bar{F}_{qc} c + \bar{F}_{qe} e, \quad (q = x, y, z) \quad (1)$$

$$\bar{F}_x = \frac{Na}{4} K_{rc} c - \frac{Na}{\pi} K_{re} e \quad (2)$$

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