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Procedia CIRP 45 (2016) 75 – 78

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3rd CIRP Conference on Surface Integrity (CIRP CSI)

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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Keywords: CFRP Machining, Cutting Force, Surface Roughness

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

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doi:10.1016/j.procir.2016.03.091

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 0^0 fiber direction and are higher than the radial forces measured on 45^0 fiber directions. The greatest tangential forces were observed when machining laminate of 135^0 fiber direction, the smallest tangential forces are observed on 45^0 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 10^0 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

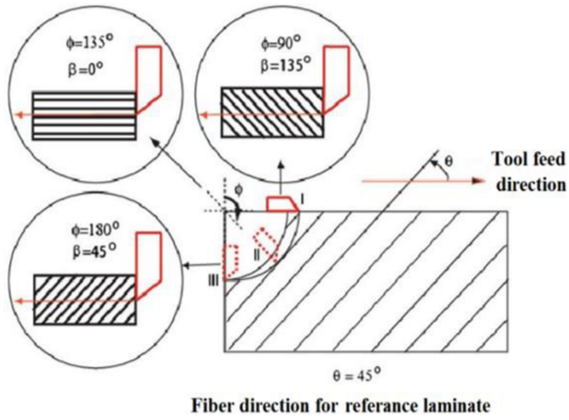

Fig. 1. Fiber cutting angle definition [5].

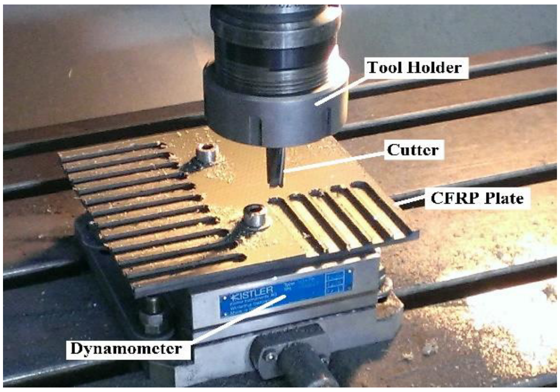

Fig. 2. Experiment setup.

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)

$$\overline{F}_q = \overline{F}_{qc}\, c + \overline{F}_{qe}\,, \qquad (q = x, y, z) \tag{1}$$

$$\overline{F}_x = \frac{Na}{4} K_{rc} c - \frac{Na}{\pi} K_{re} \tag{2}$$

$$\overline{F}_y = \frac{Na}{4}K_{tc}c - \frac{Na}{\pi}K_{te} \quad (3)$$

In equations, N is the number of tooth on the cutter, a is the axial depth of cut and, c is the feed rate. The average cutting force is a linear function of feed per tooth (c), and the components of cutting and edge forces ($\overline{F}_{qc}, \overline{F}_{qe}$) see Eq. 1. The average cutting forces are measured for each feed rate. Cutting and edge components are determined via linear regression. Cutting and edge force coefficients are obtained for tangential (K_{tc}, K_{te}), radial (K_{rc}, K_{re}) and axial directions (K_{ac}, K_{ae}) results are given in Table 3.

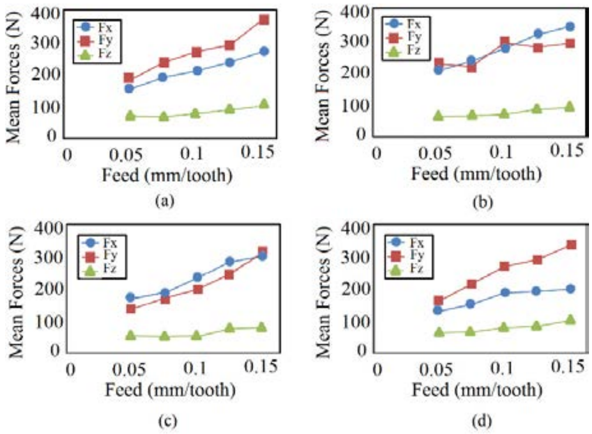

Fig. 3. (a) 50m/min-45; (b) 50m/min-135; (c) 100m/min-135; (d) 100m/min-45.

Table 3. The coefficients of cutting, edge and axial forces.

Cutting velocity, Fiber cutting angle		Cutting Coefficients (N/mm^2)		Edge Coefficients (N/mm)
50 m/min, β = 45	K_{tc}	574,66	K_{te}	25,60
	K_{rc}	372	K_{re}	26,33
	K_{ac}	90,05	K_{ae}	7,8
100 m/min, β = 45	K_{tc}	569,33	K_{tc}	23,87
	K_{rc}	238,66	K_{rc}	28,32
	K_{ac}	98,43	K_{ac}	8
50 m/min, β = 135	K_{tc}	540	K_{tc}	39,26
	K_{rc}	282,66	K_{rc}	55,60
	K_{ac}	90,0	K_{ac}	8,93
100 m/min, β = 135	K_{tc}	438	K_{tc}	17,43
	K_{rc}	522,66	K_{rc}	29,42
	K_{ac}	64,92	K_{ac}	9,2

2.2. 3D surface profile measurements

A Nanovea ST400 Optical profilometer was used for surface quality measurements. Each slot was scanned over an area of 2 x 0,5 mm, at a location 10 mm inside from the beginning of the cut, and measurements show the surface damage. Surface roughness values (Ra) measured for the area shown in Fig. 5.

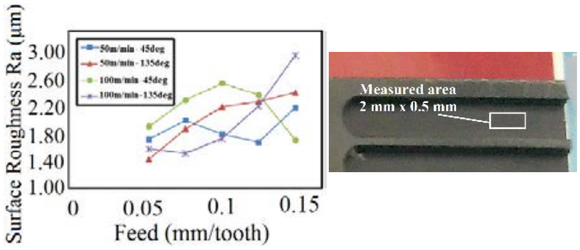

Fig. 4. Surface roughness values and measured profile area.

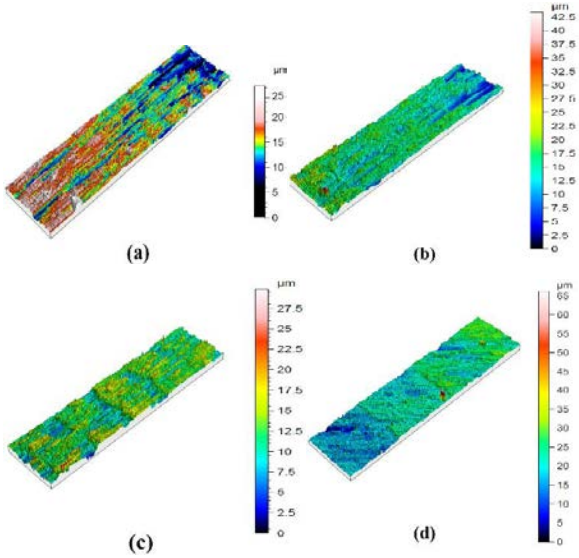

Fig. 5. (a) 50 m/min cutting velocity, 135° fiber cutting angle, 0.05 mm/tooth feed rate (Ra=1.48); (b) 100 m/min cutting velocity, 135° fiber cutting angle, 0.05 mm/tooth feed rate (Ra= 1.62); (c) 100 m/min cutting velocity, 135° fiber cutting angle, 0.075 mm/tooth feed rate (Ra= 1.56); (d) 100 m/min cutting velocity, 135° fiber cutting angle, 0.15 mm/tooth feed rate (Ra= 2.87).

3. Results and discussions

Referring to Fig.3. lower cutting forces occur for a fiber cutting angle of 45^0 than of 135^0. At the 135^0 fiber cutting angle, the tool's rake face starts machining parallel to fibers. For the 45^0 fiber cutting angle, the tool's rake face starts cutting perpendicular to the fibers.

The surface roughness values decrease with increasing of cutting velocity and decreasing feed rate. Better surface roughness values were obtained at the minimum value of feed rate 0.05 mm/tooth. Fig. 5. (a) shows the surface roughness value at 50 m/min cutting velocity, 135^0 fiber cutting angle and 0.05 mm/tooth feed rate, (Ra 1.48 µm). The second finest surface roughness value was obtained at 100 m/min cutting velocity, 135^0 fiber cutting angle and 0.05 mm/tooth feed rate, (Ra 1.62 µm), see Fig. 5. (b). The surface (shown in Fig. 5. (c)) machined at 100 m/min cutting velocity, 135^0 fiber cutting angle and 0.075 mm/tooth feed rate. Here the surface roughness value (Ra) was measured 1.56 µm. The maximum surface roughness value 2.87 µm was obtained under the conditions of maximum feed rate 0.15 mm/tooth. The fibers from sub laminates and cutting inclusions can be shown over this surface Fig. 5. (d).

To show and understand tool wear, milling tests were carried out with constant conditions (4 mm depth of cut, 0.1 mm/tooth feed rate and 100 m/min cutting velocity). During the milling tests, after each 150 mm distance of machining, the tool's flank wear was measured using an optical microscope. Tool wear is approximately 440 µm after 45 seconds of machining time and 805 µm after 63 seconds. On the other hand after 63 seconds there was seen serious fracture on the tool nose (see Fig. 6.).

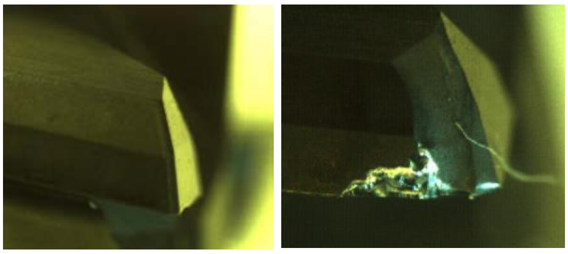

Fig. 6. Optical microscope images of tool wear and fracture.

4. Conclusion

Slot milling of CFRP laminates for different cutting conditions and fiber directions were performed to understand their effects on cutting forces and surface quality. The conclusions are as follows; the lowest cutting forces were measured at higher cutting velocities and lower feed rates. Moreover, better cutting coefficients values were calculated when machining with 4. 5^0 fiber cutting angle. Surface qualities were directly affected by the cutting velocity and feed rate. Surface roughness values (Ra) increased with increasing feed rate and decreasing cutting velocity.

Acknowledgements

This study was supported by The Scientific Research Council of Suleyman Demirel University (Grand Number: 4003-YL1-14). The authors also would like to thank SECOTOOLS, Afyon Kocatepe UNIVERSITY and TAI-TUSAŞ A.Ş. companies for their support to this study.

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