Surface integrity of machined surface in end milling of CFRP

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Abstract. In this study, the processing methods and conditions that enable high-precision processing of carbon fiber-reinforced plastic (CFRP) by using general purpose and conventional machine tools were investigated. The applied cutting force and the roughness of the machined surface were measured under different processing conditions of sideway cutting of CFRP, and the obtained results were analyzed. Furthermore, the surface profile was measured in detail with the optical 3D measurement system. The cutting speed and the chip of CFRP discharges were found to be important factors affecting. In addition, a three-point bending test of sideway cutting processed CFRP was conducted. The interlaminar shear strength was measured, and its correlation with surface profile was confirmed.

1. Introduction

Carbon fiber-reinforced plastic (CFRP), has high specific strength and stiffness, and has attracted attention as a structural material for transport machines from the viewpoint of improving fuel efficiency through weight reduction. However, the exiting CFRP processing methods have several disadvantages such as high cost, tool wear due to formation of hard chips during cutting, fiber pull-out, and occurrence of delamination that degrades processing accuracy [1,2]. Furthermore, non-homogeneous structure of composites leads various difficulties during machining such as excessive temperature and undesired surface quality [3]. These limitations impede the practical application of CFRP. To solve these problems, milling tests on CFRP plates were carried out using tools with different number of flutes [4]. Furthermore, experiments were carried out by using eight carbide end mills with different shape and coatings obtained from different producers [5].

On the other hand, it is considered that the surface integrity of the machined surface in end milling is very important when CFRP plates are used for construction. Therefore, it is necessary to clarify the relationship between the delamination and the surface integrity of machined surface. The delamination occurring in CFRP is considered to correlate with interlaminar shear strength.

The purpose of this study is to investigate the effect of the machined surface on the interlaminar shear strength after CFRP end milling tests. For this purpose, cutting tests were conducted under various conditions. Furthermore, three-point bending tests were conducted using the machined workpiece. Finally, the relationship between the profile of machined surface and the interlaminar shear strength was investigated.

2. Experimental Procedure

2.1 Cutting tests

Figure 1 shows the experimental apparatus used for the cutting tests. The cutting tests were performed using a vertical machining center. The workpiece plate was made of carbon-fiber reinforce plastic (CFRP). The top and bottom surfaces of the CFRP plate are plain weaved carbon at 0/90°. On the other hand, the interior of the CFRP plate are laminated with carbon fiber at 0/90/45/-45°. The thickness of the CFRP plate is 6 mm. Table 1 shows the cutting conditions. Two different types of tools were used in the cutting tests. One is an end mill coated with DLC, which have flutes with different helix angles at tip and flute base suppresses burrs on top and bottom surfaces of work during trimming. Another is a trim cutter whose flutes are coated with diamond. Two types of tool were shown in Fig.2.

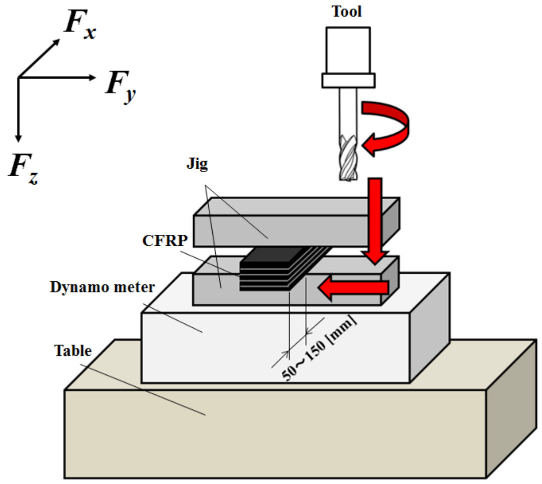
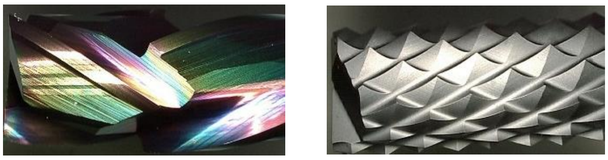


Fig. 1 Experimental setup

Table 1 Cutting conditions

Tool	End mill	Trim cutter
Number of teeth	3	11
Tool diameter [mm]	6	
Spindle speed [min^{-1}]	1800, 4000, 6000, 8000	
Feed rate f [mm/rev]	0.055, 0.065, 0.075	
Radial depth of cut b [mm]	0.2, 0.6, 1.0	



(a) End mill (b) Trim cutter

Fig. 2 Cutting tools

Measurements of cutting forces *Fx*, *Fy*, *Fz* were performed using a Kistler 9257A 3 axis dynamometer. The dynamometer is a piezoelectric quartz force transducer affixed to a table of machining center.

After each cutting test, the profile of the machined surface was measured using a contact type contour measuring instrument and a non-contact optical 3D surface measurement system.

2.2 Three-point bending tests

Interlaminar shear strength is very important when CFRP plate is used as structural material. Figure 3 shows the illustration of the interlaminar shear strength when a force is applied to three points of the CFRP plate. Three-point bending tests were carried out to investigate the effect of the machined surface profile on the interlaminar shear strength. Figure 4 shows the diagram of the three-point bending tests. The three-point bending tests were performed using a universal testing machine. The interlaminar shear strength, τ, is express as follows:

$$\tau = \frac{3P}{4bh} \tag{1}$$

Here, *P* is the load, *B* is the width of the specimen, *H* is the thickness of the specimen.

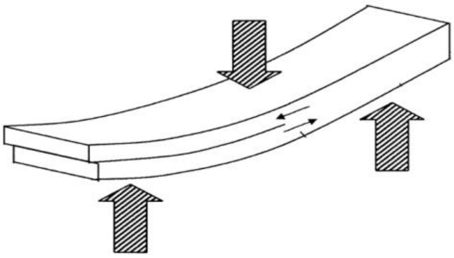
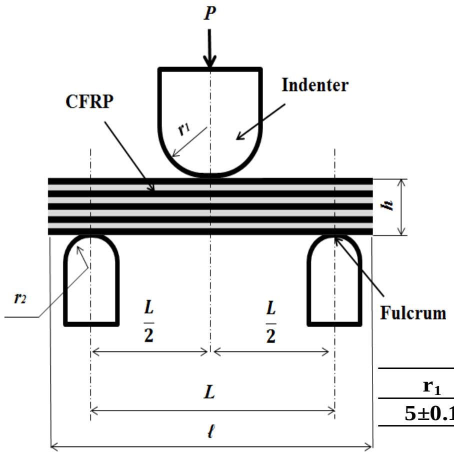


Fig. 3 Interlaminar shear strength



r_1	r_2	L
5±0.1	2±0.2	5h±0.2

Fig. 4 Three-point bending test

3. Experimental Results

Figure 5 shows the straightness of the machined surface measured using a contact type contour measuring instrument. Comparing the results of the trim cutter, the straightness at a rotational speed of 1800 min^{-1} is not much different from that at a rotational speed of 8000 min^{-1}. On the other hand, comparing the results of the end mill, the straightness at a rotational speed of 1800 min^{-1} is considerably larger than that at a rotational speed of 8000 min^{-1}. Furthermore, the straightness at a rotational speed of 1800 min^{-1} using the end mill is considerably larger than the other results.

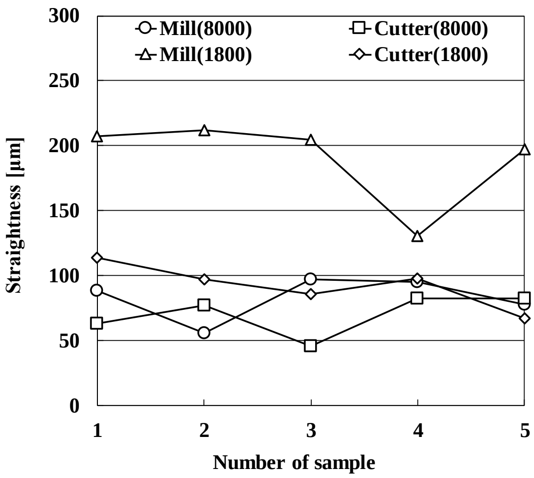
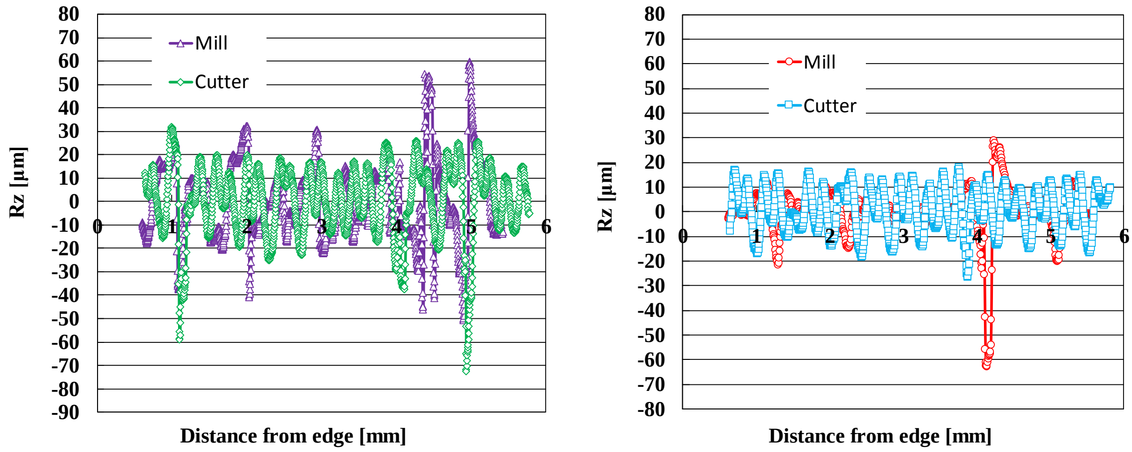


Fig. 5 Straightness of machined surface (*f*=0.065mm/rev, *b*=0.6mm)

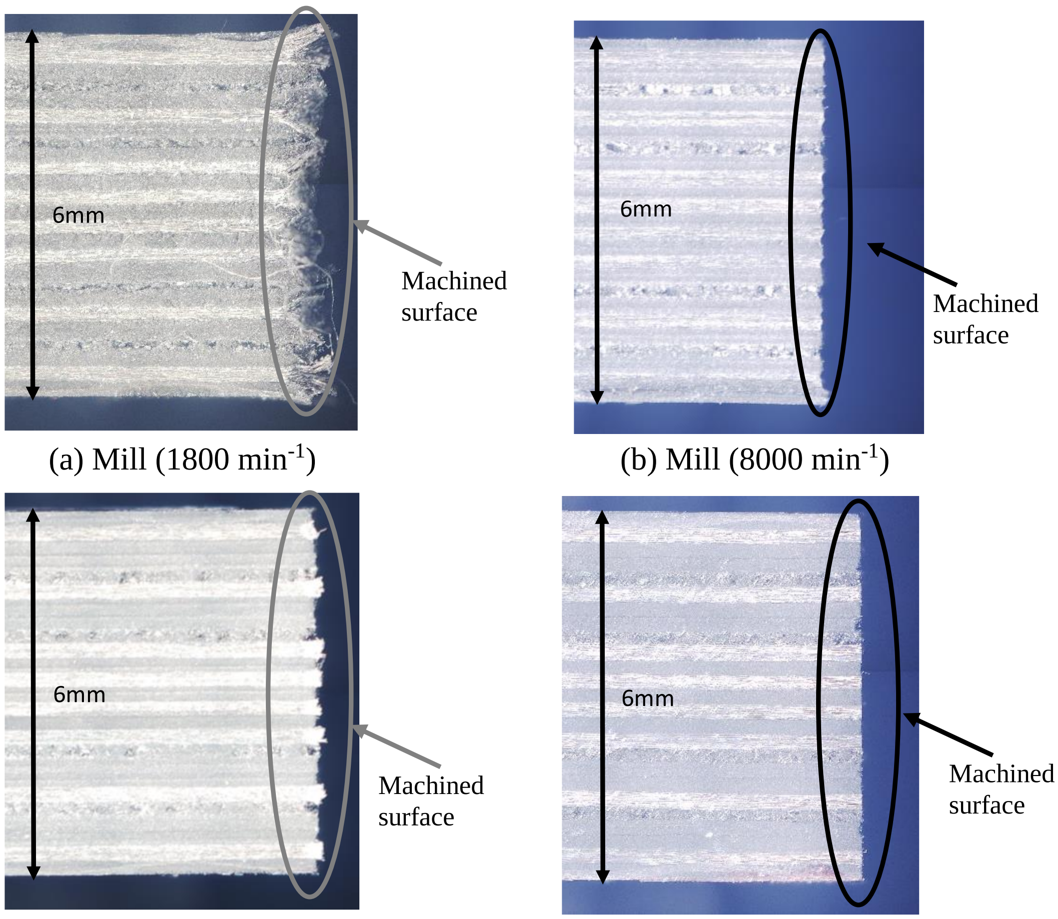
Figure 6 shows the maximum height roughness of the machined surface, *Rz*, measured using a non-contact optical 3D surface measurement system. Comparing the results of the trim cutter in Fig. 5, the straightness at a rotational speed of 1800 min^{-1} is not much different from that at a rotational speed of 8000 min^{-1}. However, comparing the results of the trim cutter in Fig. 6, the maximum height roughness at a rotational speed of 1800 min^{-1} is larger than that at a rotational speed of 8000 min^{-1}. Furthermore, it is found that the maximum height roughness is quite large at the edge of the CFRP plate at a rotational speed of 1800 min^{-1} using both tools. Figure 7 shows the photograph of the machined surface after cutting tests. It was observed that delamination tended to occur as the cutting speed decreased. Consequently, it was found that the maximum height roughness at a rotational speed of 8000 min^{-1} is smaller than that at a rotational speed of 1800 min^{-1} using both tools.

Figure 8 shows the cutting force *Fx*, *Fy*, *Fz* in cutting tests. The principal force *Fx* is larger than the other forces *Fy*, *Fz* in both tools. The principal force *Fx* with an end mill is more than twice as large as that with a trim cutter. This is because the trim cutter seems to be good for discharging chips. Furthermore, reduction of cutting force leads to extension of tool life. The principal force *Fx* is almost constant with increase in cutting speed using an end mill. On the other hand, the principal force *Fx* decreases with increase in cutting speed using a trim cutter.



(a) 1800 min^{-1} (b) 8000 min^{-1}

Fig. 6 Maximum height roughness of machined surface *Rz* (*f*=0.065mm/rev, *b*=0.6mm)



(a) Mill (1800 min^{-1}) (b) Mill (8000 min^{-1})

(a) Cutter (1800 min^{-1}) (b) Cutter (8000 min^{-1})

Fig. 7 Photograph of machined surface (*f*=0.065mm/rev, *b*=0.6mm)

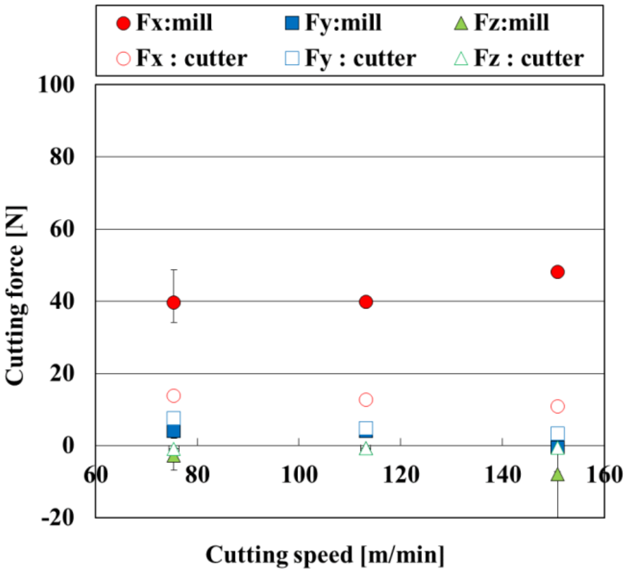
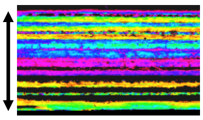
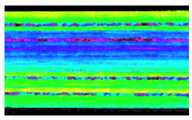
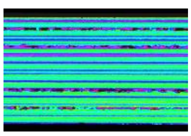
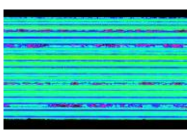


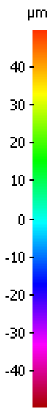
Fig. 8 Cutting forces *Fx*, *Fy*, *Fz* (*f*=0.065mm/rev, *b*=0.6mm)

Table 2 shows the surface profile of machined surface measured using a non-contact optical 3D surface measurement system. The machined surface with an end mill leaves more deep scratches than that with a trim cutter. It is considered that chips are not discharged well at both twisted portions of the flute using an end mill. Furthermore, in both tools, the machined surface at a rotational speed of 1800 min^{-1} leaves more deep scratches than that at a rotational speed of 8000 min^{-1}

Figure 9 shows the relationship between the straightness of machined surface and the interlaminar shear strength obtained from three-point bending tests. It is found that the interlaminar shear strength with an end mill is smaller than that with a trim cutter. Furthermore, in both tools, the interlaminar shear strength at a rotational speed of 1800 min^{-1} is smaller than that at a rotational speed of 1800 min^{-1}. It is shown in three-point bending tests that scratches remaining on the machined surface reduce interlaminar shear strength.

Table 2 Surface profile of machined surface
(*f*=0.065mm/rev, *b*=0.6mm)

	Rotational speed[min^{-1}]	
	1800	8000
Mill	6mm 	
Cutter		



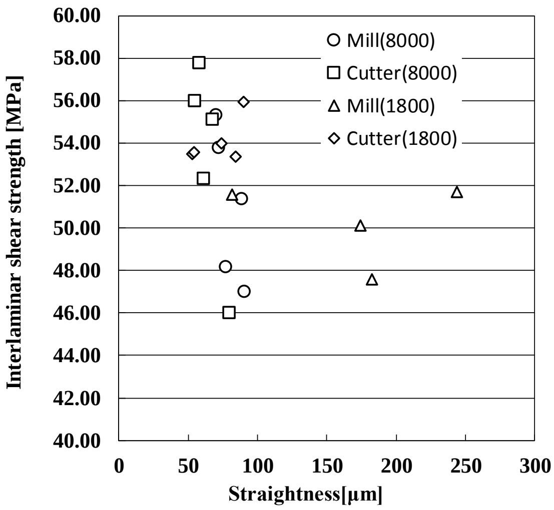


Fig. 9 Interlaminar shear strength
(*f*=0.065mm/rev, *b*=0.6mm)

4. Conclusions

The results obtained by the end milling experiments of CFRP can be summarized as follows.

1) The trim cutter was superior to the end mill for the surface integrity in sideway cutting of CFRP. Many flutes lead to reduction of cutting force. Reduction of cutting force leads to extension of tool life. Therefore, it is considered that extension of tool life lead to improvement of surface integrity.
2) The accumulation of chips and cutting at low cutting speed lead to deterioration of surface integrity. It was shown in three-point bending tests that scratches remaining on the machined surface reduce interlaminar shear strength.

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