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CFRP machining capability by a circular saw

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Highlights

- The particular characteristics of machined surface and tool failure on CFRP cutting by circular saw were investigated.
- Suppression of vibration of circular saw leads to good surface finish and to reduce tool wear.
- Finished surface quality was highly affected by the fiber orientation of carbon fiber.

Circular saws have the potential to be part of a high-efficiency machining method for carbon fiber-reinforced plastic (CFRP) compared to endmills and abrasive water jet cutting. This paper highlights the characteristics of machined surfaces and tool failure when CFRP was cut by circular saw. A circular saw is a thin, disk-shaped cutting tool; hence, the saw body often exhibits out-of-plane vibration during the machining process. This vibration affects the quality of the machined surface, as well as tool wear. In order to clarify the effect of vibration on machining characteristics, cutting tests were conducted with / without a pair of damping alloy sheets on either side of the circular saw body. Damping alloy sheets can suppress vibration amplitude. Characteristics of machined surface and tool wear were improved by damping. Surface roughness along the feed direction and laminated direction were 0.5 μm Ra and 1.1 μm Ra, respectively. In addition, we assessed the relationship between carbon fiber orientation and tool wear on CFRP cutting by circular saw. Four fiber orientations (0°, 45°, 90° and -45° against the feed direction) were tested. Cutting force, tool wear, and machined surface were measured after unidirectional CFRP cutting. Results showed that cutting force order was 0°> ±45° > 90°. Furthermore, finished surface quality was also affected by fiber orientation, with a good surface obtained for 0° fiber orientation, and smaller tool side-flank wear with -45°.

keywords：circular saw; CFRP; cutting tool; delamination; tool wear; vibration; surface roughness

1. Introduction

The demand for carbon fiber-reinforced plastic (CFRP) is increasing in the aerospace industry, due to its light weight and high specific strength and elastic modulus. With annual growth in the aerospace and defense market projected to be around 14%, the demand for CFRP is expected to total 23,000 tons by 2020 [1]. CFRP products usually must be machined during the trimming process. Abrasive water jet and milling are the trimming methods currently used, but these have disadvantages regarding cost and efficiency.

Abrasive water jet (AWJ) machining is suitable for CFRP cutting because it inflicts low thermal damage and imposes little mechanical stress on the workpiece. On the other hand, the disadvantages of AWJ machining include high equipment cost and the necessity of elaborate microfiltration before disposal of water. Moreover, conventional machining techniques do not work on composites like metals do, due to the composite structure, which consists of very strong fibers interwoven into a softer matrix [2]. Therefore, the effect of the AWJ process parameters on cut quality remains a target of study in engineering [3][4].

Milling is also commonly used for the trimming process, but is associated with a high cutting-tool wear rate and the potential for fiber delamination. Hanasaki et al. [5] studied the tool wear mechanism in CFRP machining. Although tool-wear characteristics are different for CFRP and GFRP due to the difference in fiber elastic modulus, the fundamental tool-wear mechanism is similar. In the case of cutting graphite or epoxy composite, the elastic energy of the deformed fibers is released after the fibers are severed, imparting a thrust force on the tool flank and providing a potent source of tool wear [6][7]. Moreover, Kaneeda et al. studied chip formation and reported that CFRP cutting results in three types of chip formation: delamination, fiber buckling, and fiber cutting type. They are determined by the fiber angles and tool-rake angles [8]. In terms of delamination as a defect of the machined surface, increased feed per tooth increases its likelihood [9].

On the other hand, laser cutting and electrical discharge machining (EDM) are studied as substitutes of these conventional machining processes. As both of the laser cutting and EDM are the thermal process, machining force doesn't act and then the delamination can be avoided and there is no tool wear. However, several problems are caused by the difference in thermal properties and light absorption characteristics between carbon fiber and matrix resin. For example, the matrix resin is excessively removed and a large heat affected zone (HAZ) is generated [10][11][12]. To solve these problems, Takahashi et.al.[13] reported that UV laser, which has higher absorption rate to the epoxy resin, can achieve high quality cutting. Wolynski etl.al. [14] similarly reported on HAZ using a high power picosecond pulsed laser system with varying laser wavelength. There is a trade-off relationship between machining efficiency and accuracy on laser cutting. As for the EDM, the delamination can be avoided because machining force doesn't act, but the machining efficiency for CFRP is much lower than that of milling and AWJ machining.

Against these conventional trimming processes, a proposal has been reported for using a circular saw to trim CFRP [10][11]. The amount of material removal with this saw is much smaller, and the machining efficiency would be higher than that of milling, because the thickness of the circular saw is several mms, and the cutter diameter is much larger than that of the endmill. Circular saws are commonly limited to straight cutting, it is the biggest disadvantage. Against this disadvantage, there have been methods proposed for applying them to curved-line cutting [15][16]. It is therefore expected that the circular saw could be applied to the high-efficiency cutting of CFRP. In our previous study, surface roughness along the feed direction with a circular saw was lower compared to milling. Although side-flank wear was small, chatter vibration was likely to occur, and led to tool wear [17]. Circular saw body should be deformed elastically to a bowl-like shape and the amount of its deformation should be controlled to suit the curvature of the cutting line. Then the low stiffness and the vibration was pointed as the second disadvantage. Machining accuracy was also worse when the vibration arose. In addition, a collection system of evacuated chips is necessary to keep environment clean as same as cases of the milling and grinding. Many points, however, remain to be clarified regarding the characteristics of machined surfaces and tool failure in CFRP cutting by circular saw.

In this study, CFRP material was straight cut with a circular saw under various conditions. First, we investigated the effect of vibration on machining characteristics, using a pair of damping alloy sheets on the sides of the circular saw body. In order to realize the curved-line cutting with controlling the circular saw body deflection, the damping capability was given with the damping alloy sheets assuming the future extension to the curves cutting with flexible circular saw. Also the other device to suppress the out of plane vibration was not used. Next, we clarified the effect of carbon fiber orientation on tool wear, cutting forces, and the machined surface quality in CFRP cut by circular saw. Finally, we demonstrated the advantages of machining CFRP with a circular saw by comparing results with those of milling.

2. Setup for the CFRP straight-cutting test

Figure 1 is a photograph of the developed CFRP straight-cutting machine. The setup had a moving table in the X direction and a main spindle to drive the circular saw rotation, which was numerically controlled. Maximum spindle speed was 3000 min^{-1}. Out-of-plane vibration of the circular saw during the cutting was measured by an eddy-current-type gap sensor set at the point where the cutting edge exited from the cutting point as shown in Fig.1. Cutting force was measured by a piezo-electric dynamometer on the table. Both sides of the machining part of the CFRP plate were fixed on the dynamometer with a jig so that unintended vibration was not generated in the workpiece. Measurement of surface roughness and observation of machined surface were made on the right side surface of the tool traveling direction. A safety cover was arranged around the system during the cutting test.

Specifications of the circular saw used for the cutting test are listed in Table 1; the circular saw's cutting edges are shown in Fig. 2. The saw had 50 cutting edges, and was made of cemented carbide. The cutting edge was brazed on the 1.7-mm thick saw body. Figure 3 shows the trapezoidal shape of the cutting edge. All cutting edges were the same shape. Rake angle was 10°, front and side-flank angles were 8°, side cutting edge angle was 1°, and cutting-edge roundness was 4 μm.

Mechanical properties of the CFRP plate are presented in Table 2. The material was a general-purpose CFRP used in aircraft and automobile parts. It was quasi-isotropic CFRP, in which carbon fiber orientation changes by 45º in each layer. Thickness of one layer is 0.25 mm, and the whole is a 16-layer accumulation with a total thickness of 4 mm.

3. Effect of vibration on circular saw cutting

The circular saw is a thin, disk-shaped cutting tool. As a result, the machining process often produces out-of-plane vibration of the circular saw body, which can affect quality of the machined surface and tool wear. As we strongly intend to apply the new findings of this study to the curved line cutting with deflecting the saw body in the future, we did not adopt a technique that only improves rigidity. Then we examined the machining characteristics of CFRP machining with a circular saw with / without a pair of damping alloy sheets placed on either side of the circular saw body. The damping alloy sheets were made mainly of manganese, which can transduce the vibration energy to heat, enabling absorption of the vibration [18]. Table 3 shows the chemical composition of damping alloy D2052 (Daido Steel Co., Ltd). The machining conditions are listed in Table 4. Cutting speed and feed rate were the same as recommended conditions for the endmill, which was fabricated from the same material as the circular saw. A 2400-mm cutting test was conducted on a down cut under dry conditions.

3.1. Effect of damping alloy sheets

Figure 4 shows the results of FFT analyses of the saw body vibration measured on the side surface of saw body without and with the damping alloy sheets. Without damping, the 270-Hz frequency component was dominant. This frequency was in accord with that of intermittent cutting at tool edges. On the other hand, when the damping alloy sheets were inserted, the amplitude of vibration was suppressed at both the 270 Hz and high-harmonic component. Very low frequency vibrations of about 5.5Hz and higher harmonics resulted from a slight axial runout of circular saw body. We think it was because the damping alloy sheet had several microns of distortion.

3.2. Tool wear

Figure 5 shows the transition of tool wear at the side-flank face. On circular saw cutting, the side-cutting edge is important to the finish of the machined surface. Without the damping alloy, final side-flank wear was 68 μm. On the other hand, with the damping alloy, final side-flank wear was 56 μm at a cutting length of 2400 mm. Without damping, the amount of wear at the initial stage was larger, because the larger vibration induced a lot of minute chipping. In contrast, the wear rate during the steady wear period after 500 mm of cutting length was almost the same in both cases. After a certain level of chipping, the cutting edges are dulled, and dominant tool damage is considered to shift from chipping to abrasive wear.

Figure 6 contains photos of the side-cutting edge after 2400-mm cutting. Maximum flank wear width was 68 μm and 56 μm respectively as shown above. On the other hand, the length of the wear land is largely different. The length of the wear land was more than 1.4 mm and 0.6 mm along the side cutting edge in the cases of without and with the damping alloy sheets respectively. As a feed per tooth is 0.05 mm, length of the wear part on the side flank should be as same as 0.05 mm along the side cutting edge geometrically. It is related to the small side cutting edge angle of 1° and the out-of-plane vibration of the circular saw body. Contact with the machined surface occurred at a position away from the actual cutting point along the side cutting edge in both cases. As the vibration amplitude was large without damping alloy sheets, a wider area was worn. The damping alloy sheets improved stiffness and damping capacity, producing potentially lower frequency of unintended contact and less tool wear.

3.3. Surface roughness

Figure 7 compares surface roughness of machined surfaces with/without the damping alloy. With the damping alloy sheets, surface roughness along both the feed direction and laminated direction were better than without the damping. Moreover, maximum height roughness, *Rz*, along the laminated direction without damping alloy was 20.8 μm, much larger than the 9.5 μm with the damping alloy. This was because many small depressions arose on the machined surface in specific orientation to the fiber, as shown later.

Figure 8 contains images of the machined surface and height contour maps at a cutting length of 2400 mm taken by laser microscope. Without the damping alloy sheets, deep cutter marks and many deep depressions can be seen on the machined surface in the -45° fiber orientation. It is thought that the out-of-plane vibration of the circular saw body led to over cutting, deeper cutter marks, and some depression.

3.4. Comparison with milling

Transition of flank wear and machined surface roughness were examined in circular saw cutting with damping alloy sheet and conventional milling. Cutting conditions are shown in Table 4. It should be noted that the tool material is a non-coated tungsten carbide for both cases to enhance the effect of cutting manner, though the diamond coating tool is commonly used in the milling of CFRP. Cutting speed and feed per tooth were set same value in both cases. Number of cutting edges were 50 and 2 for circular saw and endmill respectively. Figure 9 shows the transition of flank wear. Wear rate in milling is higher than that in circular saw cutting. Since the number of cutting edge of circular saw is 25 times higher than that of endmill, tool wear was simply dispersed to the fifty cutting edges. Then, if the actual cutting length by one cutting edge of each tool is considered, wear rate is rather higher in circular saw. Figure 10 shows the transition of surface roughness. It can be seen that the roughness in milling rapidly increased and larger than 12 μm at 2400 mm of cutting length. On the other hand, the roughness in circular saw cutting stayed less than 3 μm until 7200 mm of cutting length. From the practical point of view, this surface roughness transition is preferable, and it means that circular saw can cut longer length until next tool change and it leads to less tool change and cost.

4. Effect of feed per tooth on cutting characteristics

In this experiment, cutting conditions were almost the same as those listed in Table 4; only the feed per tooth was varied. Damping alloy sheets were attached on both sides of the circular saw body in order to reduce unwanted vibration. The cutting test was conducted under three feed-per-tooth conditions: 0.025, 0.05, and 0.1 mm/tooth. A feed rate of 0.05 mm/tooth is recommended for the same tungsten carbide endmill cutting. As the cutting length was same for each test, number of interrupted cuts was different in three feed-per-tooth conditions.

4.1. Side-flank wear

Figure 11 shows the effect of feed per tooth on the width of side-flank wear at a cutting length of 2400 mm. The figure shows the average side-flank wear of three cutting edges. The larger the feed per tooth, the smaller the side-flank wear, because the actual cutting length of the cutting edge contacting the workpiece was decreased; as a result, the effect of abrasion by stiff carbon fiber also decreased. This shows the same tendency as that of endmills [7][19].

4.2. Machined surface

Figure 12 shows the machined surface and height contour maps at a cutting length of 2400 mm taken by laser microscope. Some depressions of approximately 30-μm depth can be seen on the -45° orientation layer at feed per tooth of both 0.025 mm and 0.05 mm. On the other hand, when the feed per tooth was 0.1 mm, a larger 250-μm depression was observed in the center of the -45° layer. No visible defects could be seen on the other fiber orientation layers.

Figure 13 is a schematic of the delamination occurring at the bottom surface of the CFRP plate. The bottom layer was 0° orientation, and this layer was easily peeled off during down cutting by the circular saw. Figure 14 compares the delamination on the bottom surface at a cutting length of 2400 mm for different feed rates. As feed rate increased, delamination widened. Figure 15 shows the transition of averaged cutting forces in the x-, y- and z-direction as a result of feed rate. It can be seen that the cutting forces increased with an increase of cutting length, which was the result of tool-wear progression. It also suggests that a larger normal force to the plate, namely Fz, leads to a larger amount of delamination.

5. Relationship between fiber orientation and cutting characteristics

As previous sections indicated that fiber orientation had a large effect on both the quality of the machined surface and tool damage, we investigated the relationship between fiber orientation and cutting characteristics using unidirectional CFRP. Unidirectional CFRP means that the orientation of all carbon fibers is in the same direction. Cutting conditions were approximately the same as in Table 4 except for the fiber orientation of the CFRP. Four different orientations against the feed direction were examined: 0°, 45°, 90° and -45° . Figure 16 illustrates carbon fiber orientation angle.

5.1. Relationship between cutting force and number of cutting fibers

Figure 17 shows how cutting force *Fxz* in the x- and z-directions was affected by fiber orientation at a cutting length of 1200 mm. Cutting force is the sum of the cutting forces acting on the front cutting edge, and right and left side cutting edges. In the figure, +45° and -45° are shown at the same point because, as shown in Fig. 18, the cases were mirror images. It means that when the fiber orientation on the right side is +45°, it is -45° on the left side. It can be seen that cutting force order was 0°> ±45° > 90°.

The fact that cutting force and tool wear differ depending on fiber orientation is well known in milling or drilling [20][21]. Murakami et al. reported that cutting force and tool wear also depended on number of cutting fibers [19]. We therefore examined the relationship between the number of cutting fibers, cutting force, and tool wear on CFRP cutting with a circular saw.

With a circular saw, there are two kinds of cutting area, the front-cutting edge, and the side-cutting edge, as shown in Fig. 19. The number of cutting fibers N_{cf} was defined as follows.

$$N_{cf} = A_c/r^2, \quad (1)$$

where r is the mean fiber radius (7 μm) and A_c is defined as follows. For the cutting area by the front cutting edge, A_c is the projection of the cutting area to the plane vertical to the feed direction as shown in the green area of the Fig.19. On the other hand, for the cutting area by the side cutting edge, A_c is the machined cross section by one cutting edge as shown in blue region in Fig.19. A_c was calculated to be 14 mm^2 and 0.2 mm^2 for the front-cutting and side-cutting edges, respectively, under the conditions tested.

Figure 20 shows the number of cutting fibers affected by the fiber orientation at the front and side cutting edges. The number of cutting fibers by the side-cutting edge was much smaller than by the front-cutting edge. It is thus understood that the total number of cutting fibers depends mainly on the front cutting edge. If we refer to the cutting forces shown in Fig. 17, the higher the number of cutting fibers, the higher the cutting force. As the number of cutting fibers becomes very small, cutting force depends on the strength of the bonding resin, because the end cutting edge passes along the interface of the carbon fiber. The strength of the resin is much lower than that of the carbon fiber.

5.2. The relationship between side-flank wear and fiber orientation

Figure 21 shows the effect of fiber orientation on side-flank wear at a cutting length of 2400 mm. Compared to Fig. 20(b), it may be seen that number of cutting fibers does not have a strong influence on side-flank wear.

Figure 22 presents SEM images of the machined surface by the side-cutting edge for different fiber orientations. In the case of 0°, the number of cutting carbon fibers is very small, but the width of side-flank wear was not small. It was thought that this was because the side of fibers rubbed with an abrasive action on the side-cutting edge.

In the case of 45°, the outline of the carbon fibers can be clearly observed, and some are protruding from the surface. In the case of 90°, however, the machined surface is almost flat. Because protruding fibers could brush on the side-cutting edge with abrasive action, side-flank wear becomes large in the case of 45° orientation.

Finally, in the case of -45°, the machined surface appears very rough. It seems that the carbon fibers were not cut off sharply, but rather the carbon fibers ruptured by bending or shearing after elastic deformation on the inside of the machined surface. In this case, the abrasive action to the cutting edge by the carbon fiber became smaller than in other cases.

6. Conclusions

In this paper, we investigated the particular characteristics of machined surface and tool failure in CFRP cutting by circular saw, and demonstrated the machining capability of the circular saw for CFRP. Our findings can be summarized as follows.

1) In order to improve the low stiffness and damping capacity, a pair of damping alloy sheets was positioned on either side of the circular saw body. The amplitude of frequency at which the cutting edge cut the CFRP was then smaller compared to without damping. Moreover, with damping alloy sheets, side-flank wear and surface roughness were also improved.
2) As feed rate became high, cutting force increased and machined surface quality worsened. Meanwhile, amount of tool wear for the same cutting length decreased, because the frequency of the abrasion becomes lower with the increase of feed rate.
3) Unidirectional CFRP plates with different fiber orientations were machined with a circular saw. Cutting force was largest in the case of 0° fiber orientation, followed by ±45° and 90° cases. This corresponds to the number of cutting fibers. In addition, the finished surface quality was also affected by the fiber orientation; a good surface was obtained in the case of the 0° fiber orientation, and tool side-flank wear was smallest in the case of -45° fiber orientation.

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Figures

(b) With damping alloy sheets

Figure 9 Comparison of flank wear on circular saw cutting and milling

Figure 10 Comparison of surface roughness on circular saw cutting and milling

Figure 11 Comparison of average side-flank wear affected by feed per tooth

Figure 12 Difference of machined surface for each feed per tooth
(a) Feed per tooth: 0.025 mm
(b) Feed per tooth: 0.05 mm
(c) Feed per tooth: 0.1 mm

Figure 13 Delamination area in cutting CFRP by circular saw

Figure 14 Relationship between delamination width and feed per tooth
(a) Feed per tooth: 0.025 mm
(b) Feed per tooth: 0.05 mm
(c) Feed per tooth: 0.1 mm

Figure 15 Effect of feed per tooth on cutting force *Fz*

Figure 16 Definition of carbon fiber orientation

Figure 17 Effect of fiber orientation on cutting force

Figure 18 Schematic of circular saw cutting when 45° and -45° carbon fiber is cut

Figure 19 Cutting area by front-cutting edge and side-cutting edge

Figure 20 Number of cutting fibers

(a) Using front-cutting edge and side-cutting edge (b) Using only side-cutting edge

Figure 21 Effect of fiber orientation on side-flank wear

Figure 22 SEM images of machined surface on circular saw cutting

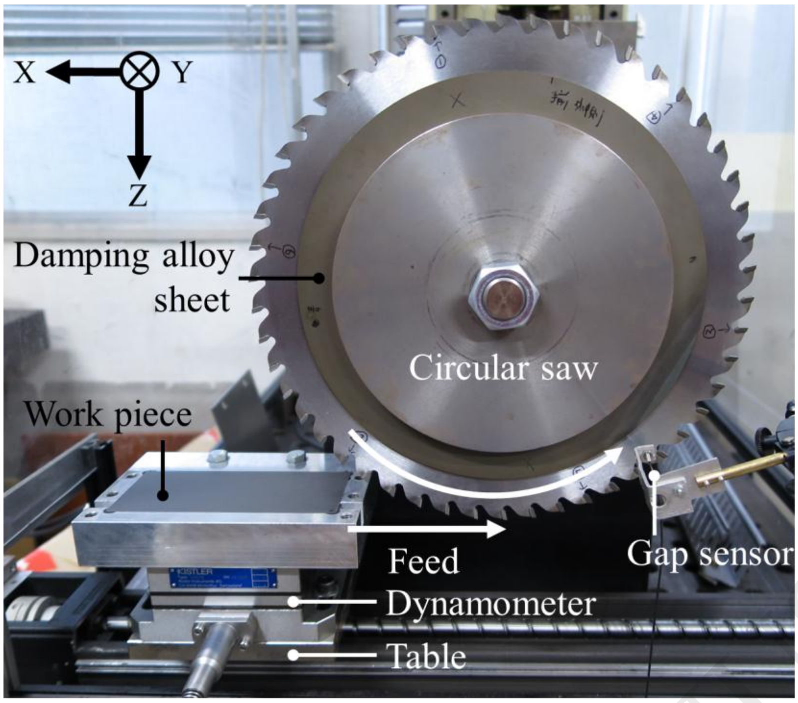


Figure 1 CFRP straight cutting machine using circular saw

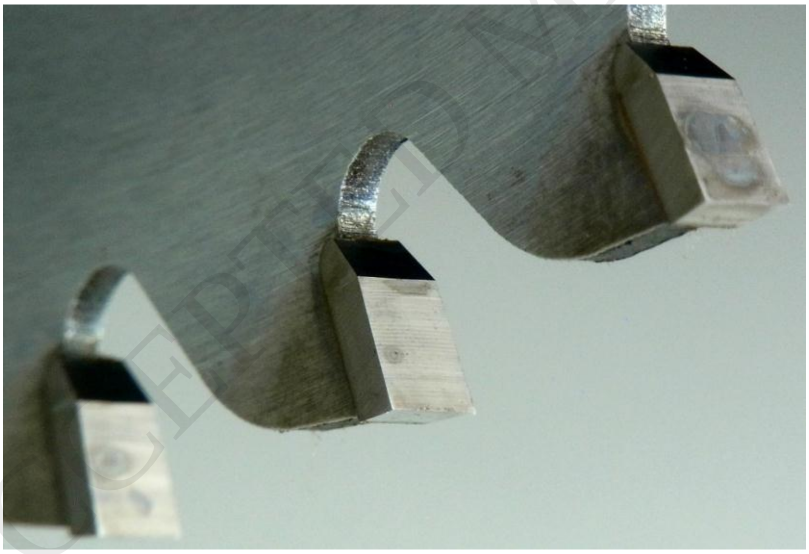


Figure 2 Circular saw cutting edges

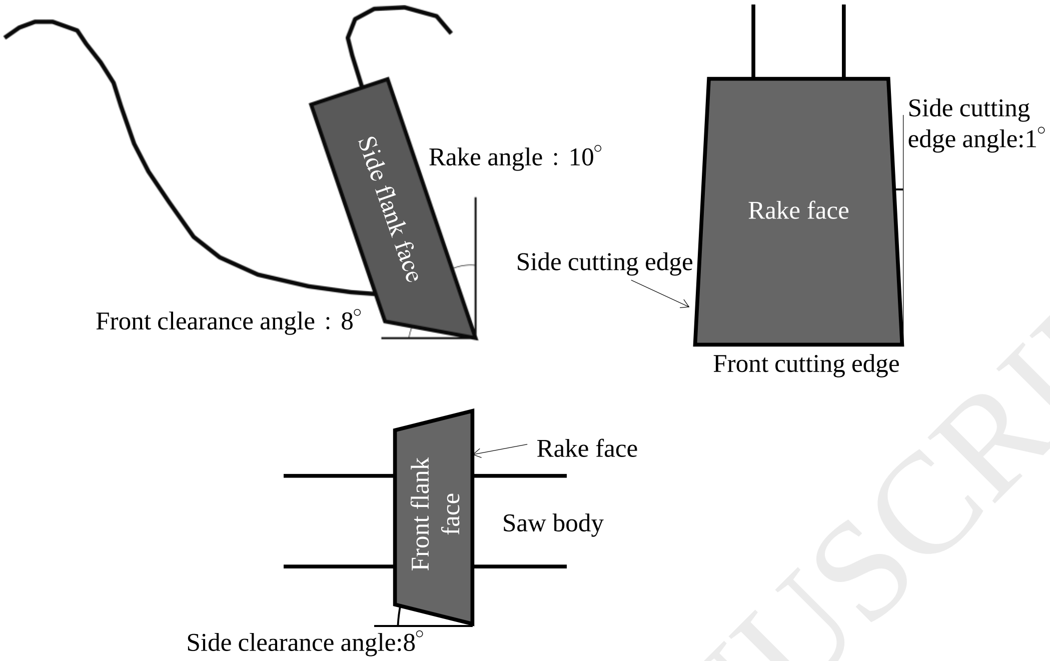
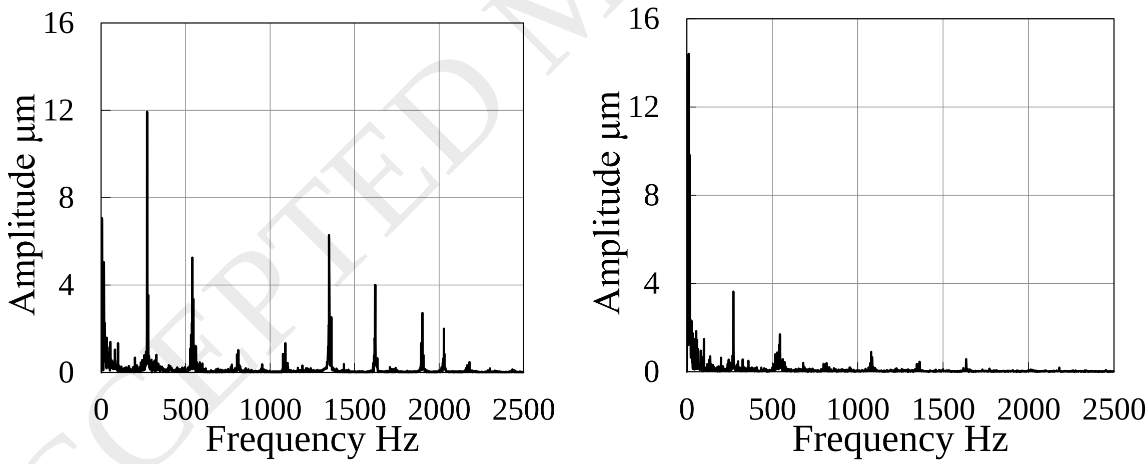


Figure 3 Cutting edge shape



(a) Without damping alloy sheets

(b) With damping alloy sheets

Figure 4 Effect of damping alloy sheet on vibration of circular saw body during cutting

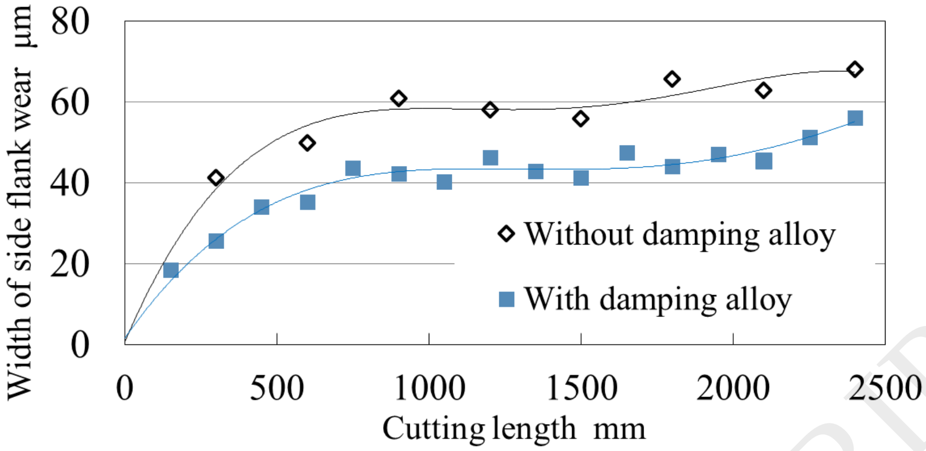


Figure 5 Transition of side flank wear affected by with/without damping alloy

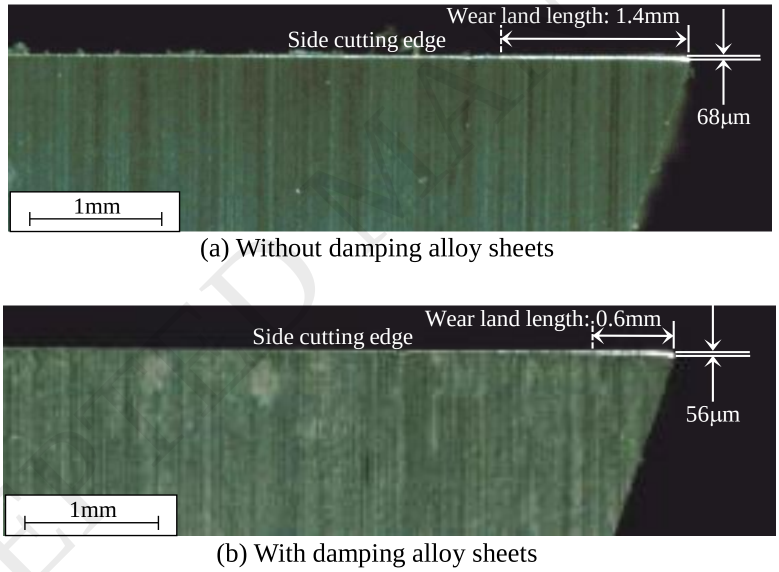
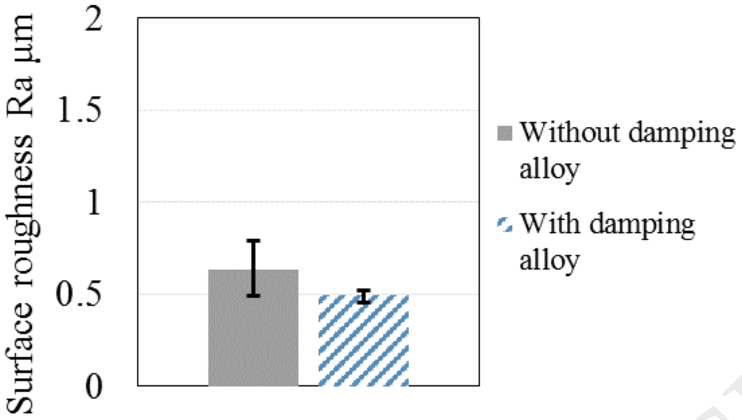
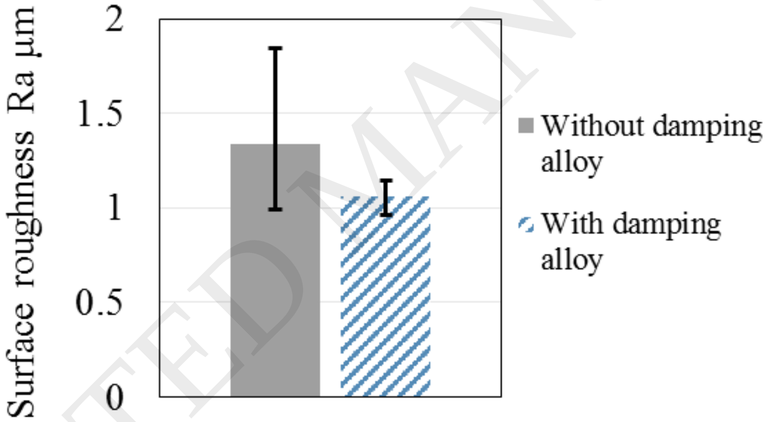


Figure 6 Side cutting edge after 2400mm cutting

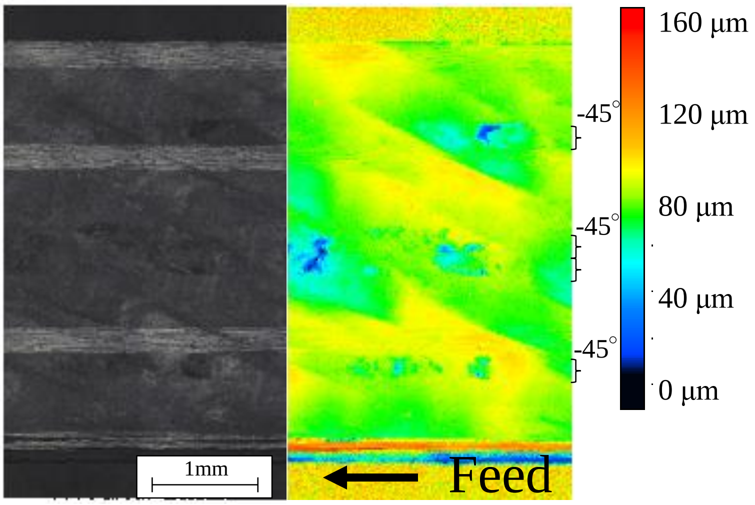


(a) Along feed direction

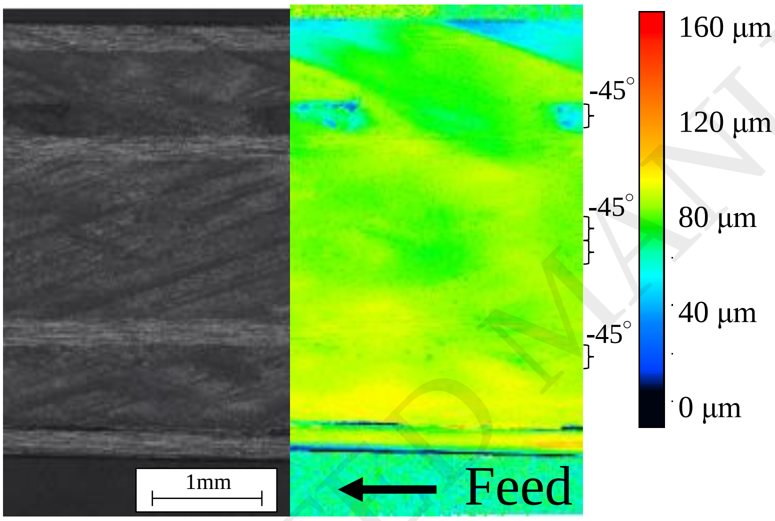


(b) Along laminated direction

Figure 7 Effect of damping sheet alloy on surface roughness at cutting length 2400mm



(a) Without damping alloy sheets



(b) With damping alloy sheets

Figure 8 Machined surface and height contour maps taken by laser microscope

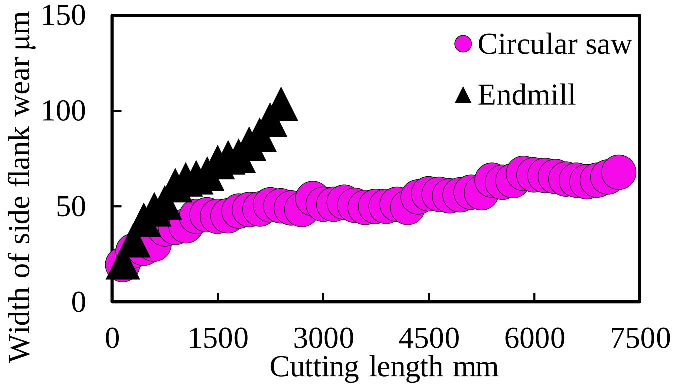


Figure 9 Comparison of flank wear on circular saw cutting and milling

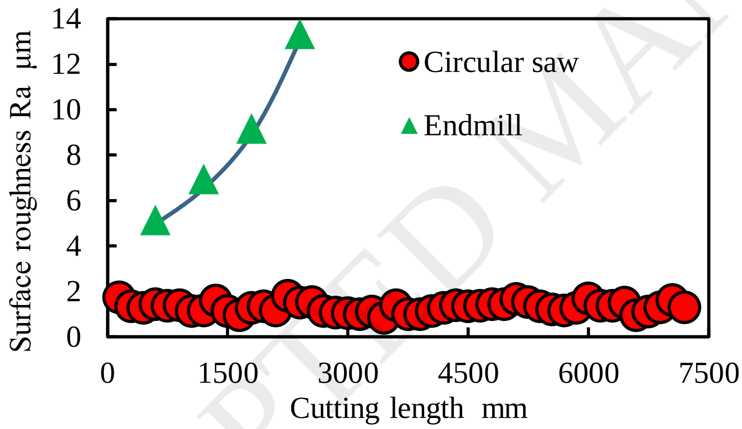


Figure 10 Comparison of surface roughness on circular saw cutting and milling

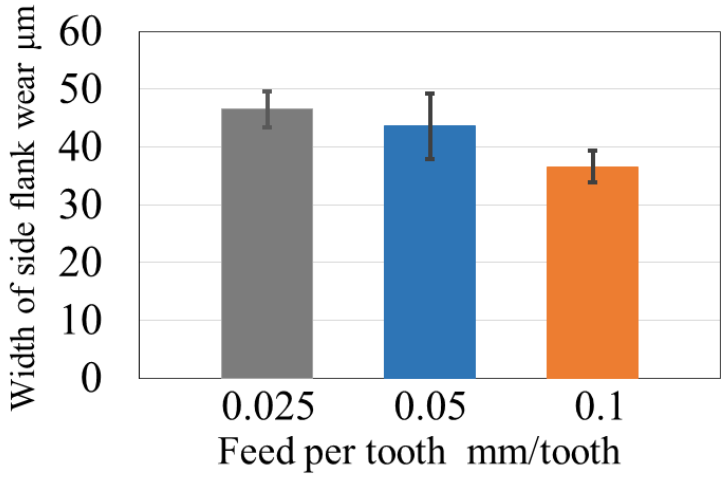
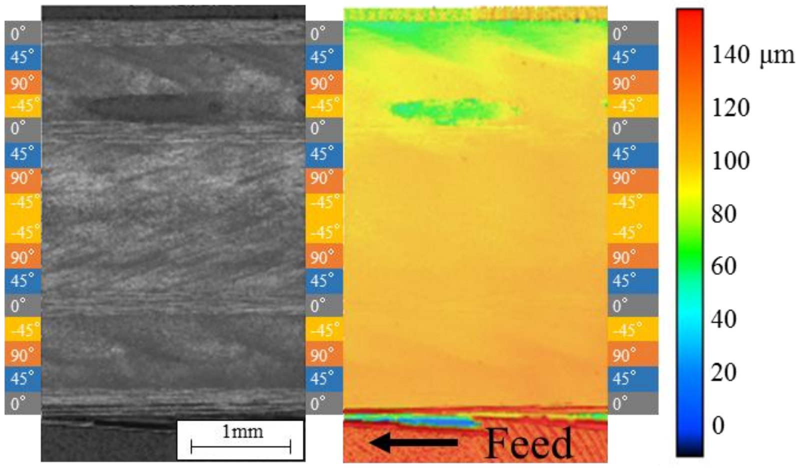
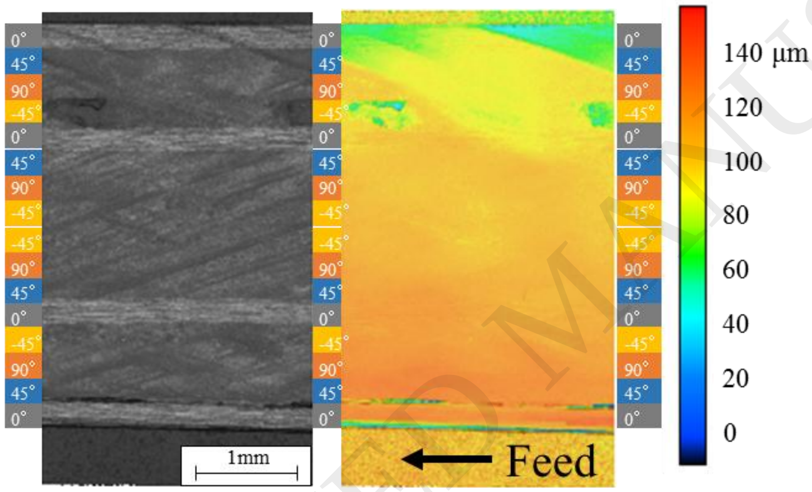


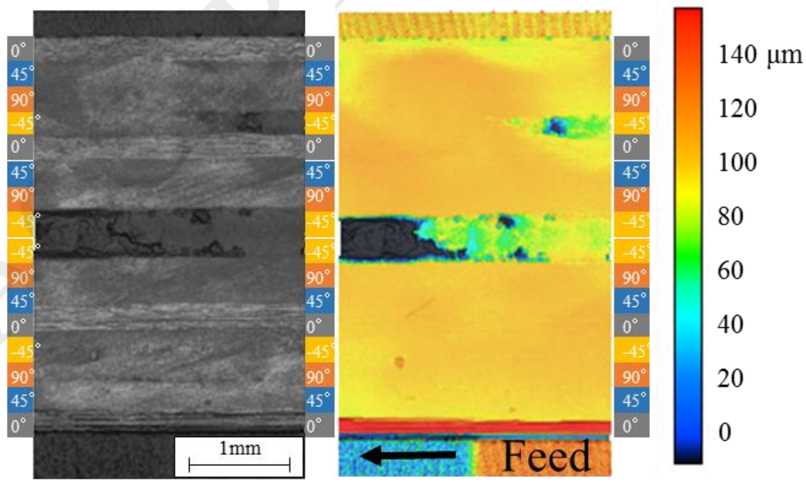
Figure 11 Comparison of average side flank wear affected by feed per tooth



(a) Feed per tooth: 0.025mm



(b) Feed per tooth: 0.05mm



(c) Feed per tooth: 0.1mm

Figure 12 Difference of machined surface between each feed per tooth

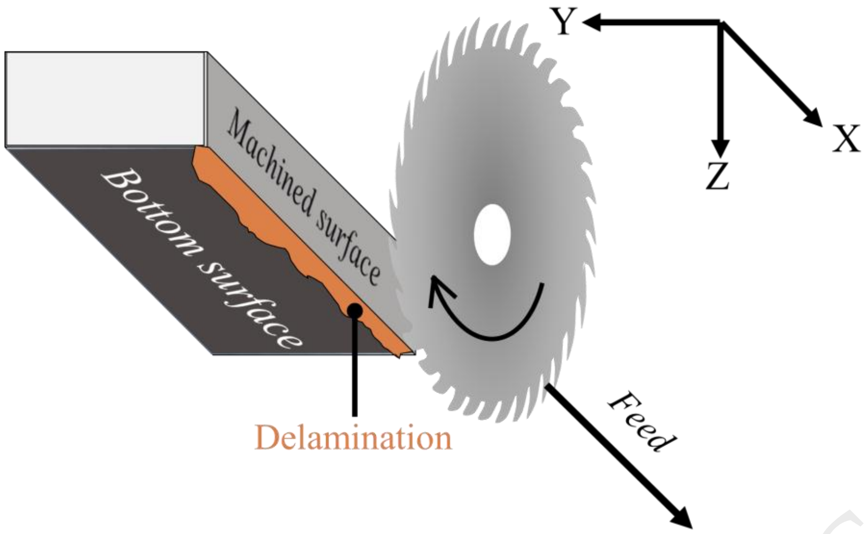
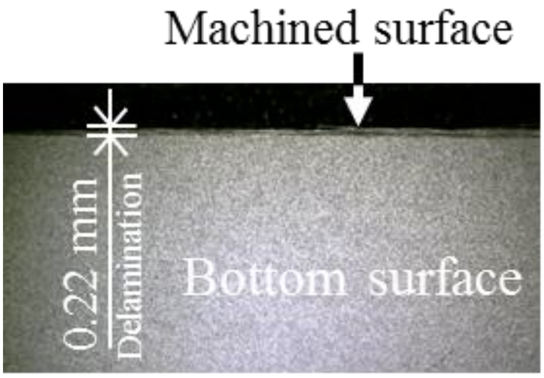
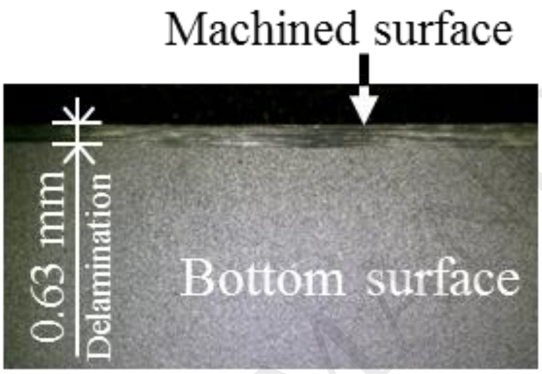


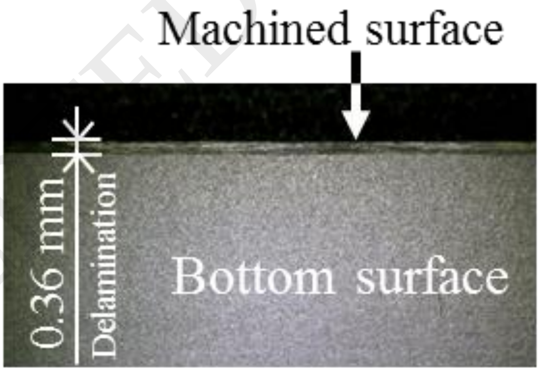
Figure 13 Delamination area on cutting CFRP by circular saw



(a) Feed per tooth: 0.025 mm



(b) Feed per tooth: 0.05 mm



(c) Feed per tooth: 0.1 mm

Figure 14 Relationship between delamination width and feed per tooth

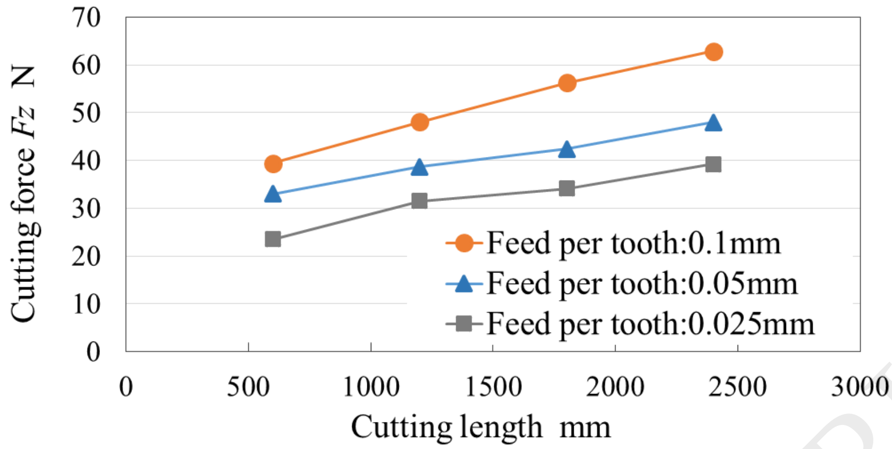


Figure 15 Effect of feed per tooth on cutting force Fz

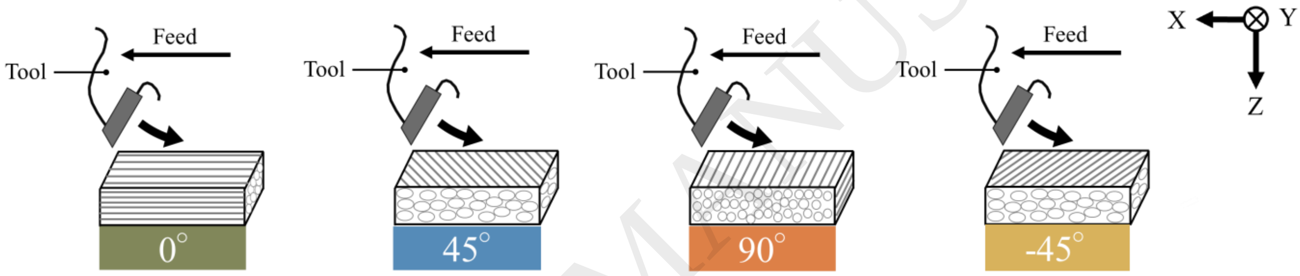


Figure 16 Definition of carbon fiber orientation

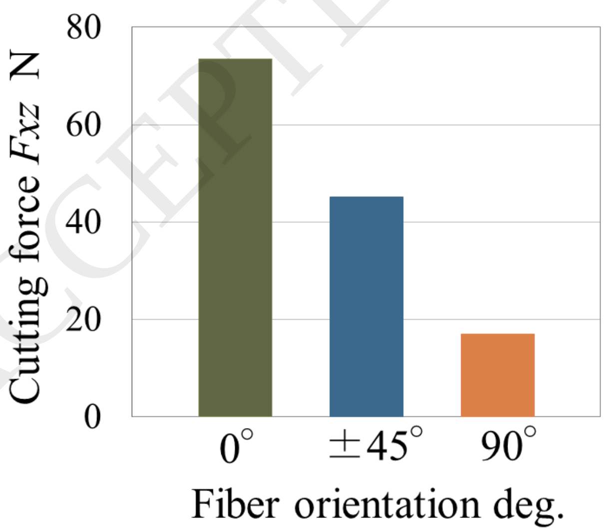


Figure 17 Effect of fiber orientation on cutting force

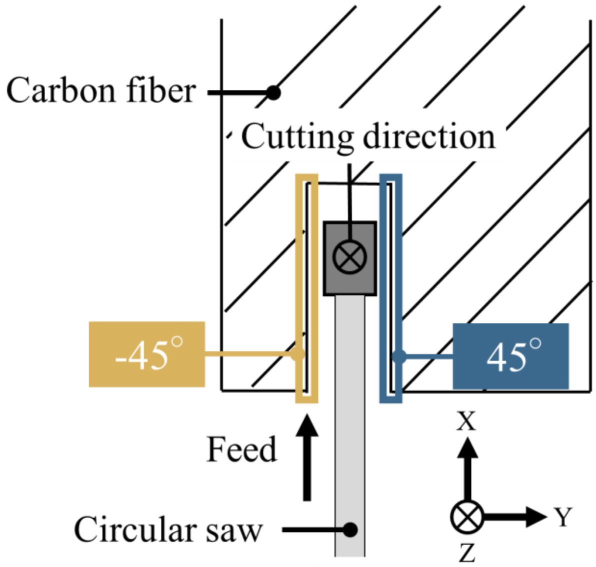


Figure 18 Schematic of circular saw cutting when 45° and -45° carbon fiber is cut

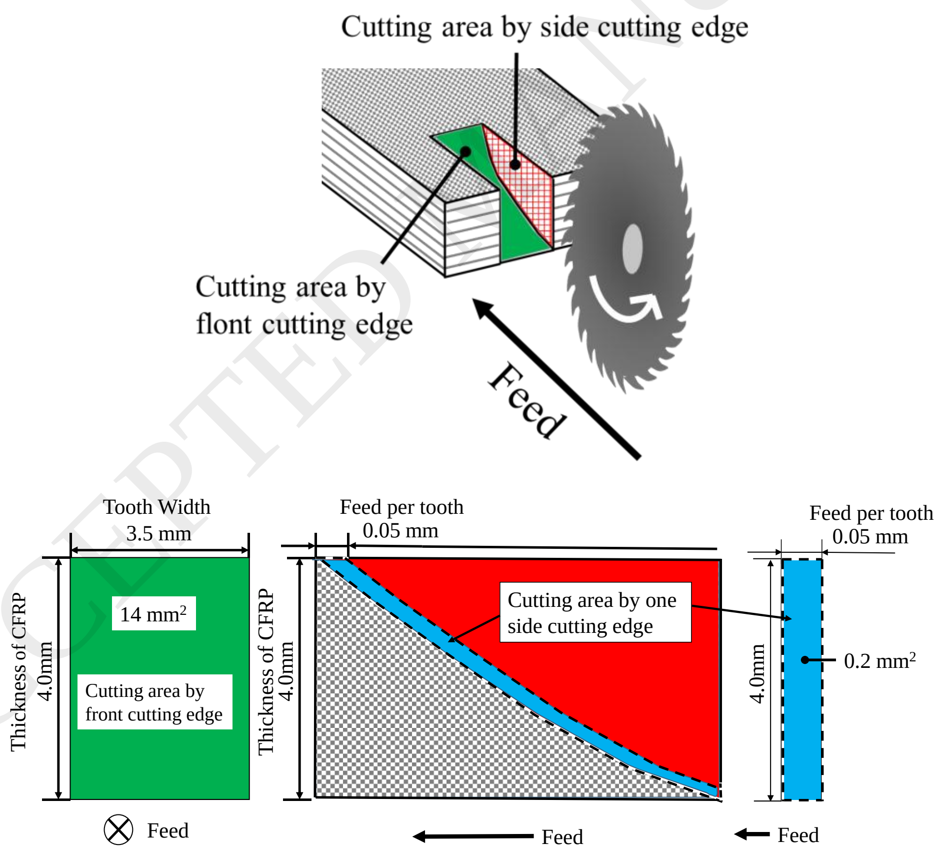
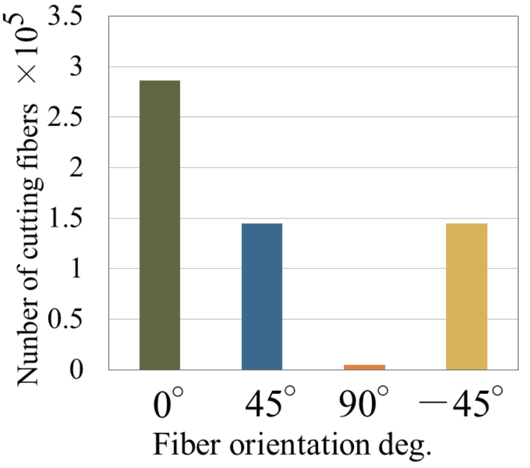
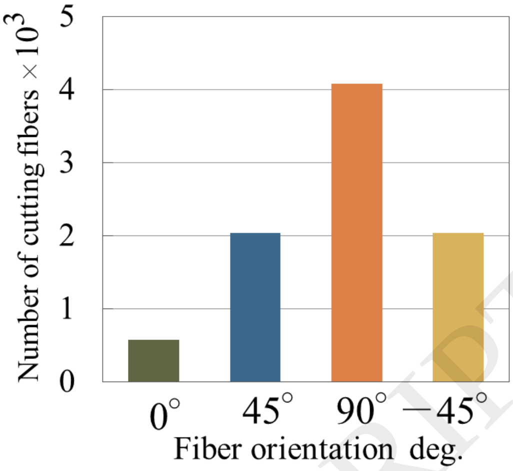


Figure 19 Cutting area by front cutting edge and side cutting edge



(a) Using front cutting edge and side cutting edge



(b) Using only side cutting edge

Figure 20 Number of cutting fibers

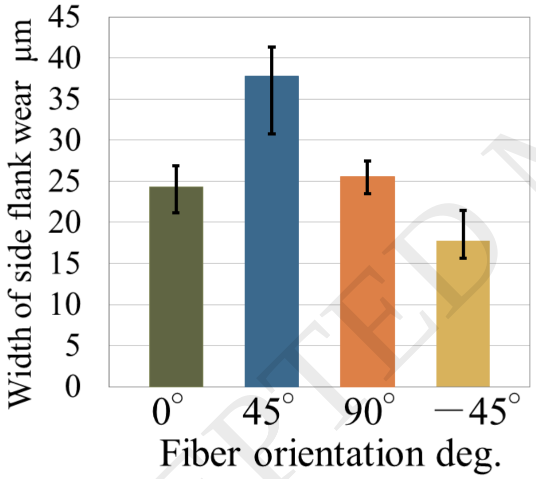


Figure 21 Effect of fiber orientation on side-flank wear

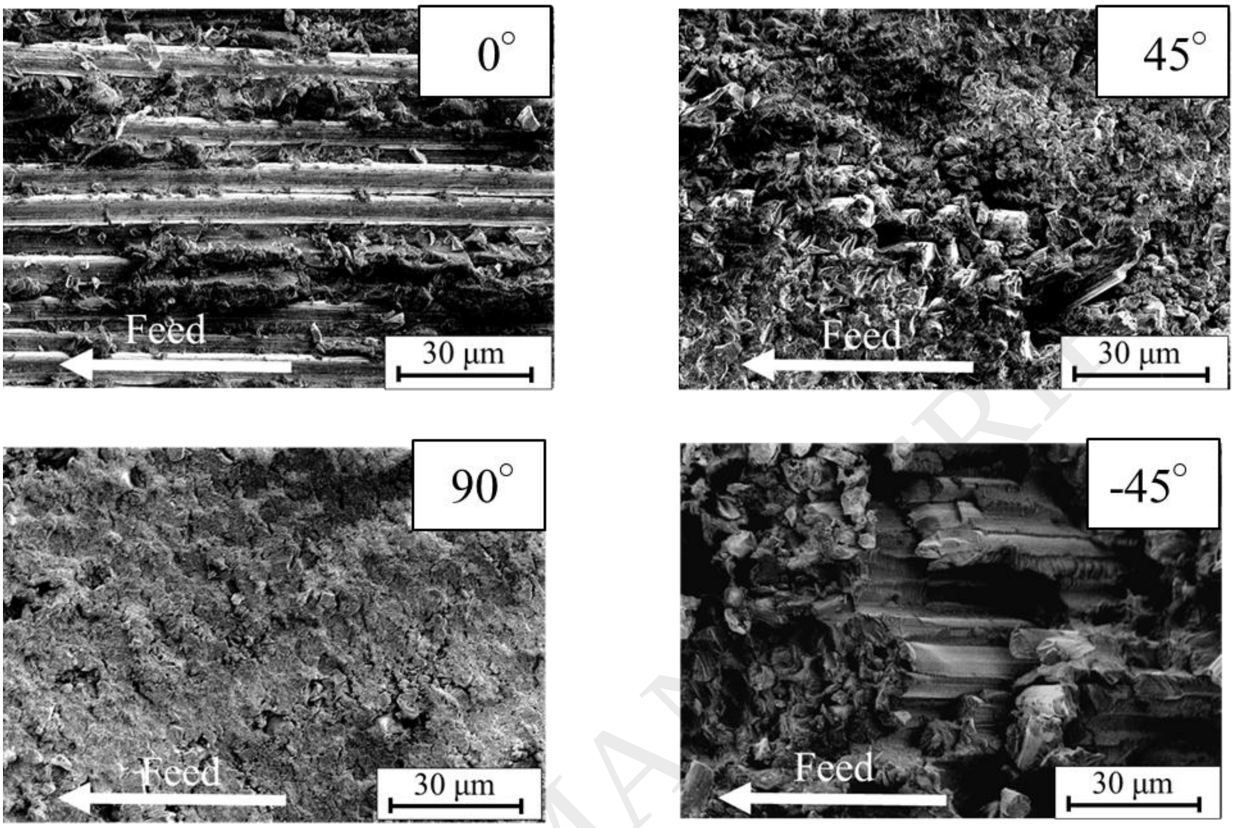


Figure 22 SEM images of machined surface on circular saw cutting

Table 1 Specifications of the circular saw

Tool tip material	Cemented Carbide
Coated material	Non coated
Number of cutting edges	50
Diameter (mm)	305
Saw body thickness (mm)	1.7
Cutting edge width (mm)	3.5
Rake angle (deg)	10
Clearance angle (deg)	8
Side cutting edge angle (deg)	1

Table 2 Mechanical properties of CFRP

Carbon fiber	Mitsubishi Rayon TR380G250S
Fiber areal weight (g/m^2)	250
Resin content (wt%)	33

Total areal weight (g/m^2)	373
Ply thickness (mm)	0.25
Number of layers	16

Table 3 Chemical composition of damping alloy D2052 [18]

	Mn	Cu	Ni	Fe	
D2052	Ba1.	22.4	5.2	2.0	wt%

Table 4 Machining conditions

Tool	Circular saw		Endmill
Tool material	Cemented carbide		
Workpiece	CFRP		
Workpiece thickness (mm)	4		
Damping alloy sheets	With	Without	-
Number of cutting edges	50		2
Diameter (mm)	305		10
Helix angle (deg)	-		30
Feed rate (mm/min)	818		1000
Spindle speed (min^{-1})	327		10000
Cutting speed (m/min)	314		314
Feed per tooth (mm/tooth)	0.05		0.05
Cutting direction	Down cut		Down cut
Coolant supply	Dry		Dry