Evaluation of Machining Characteristics on CFRP Straight-Line Cutting Using Flexible Circular Saw

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Abstract:
Carbon-fiber-reinforced plastics (CFRP) are known as a difficult-to-cut material. We propose the use of a flexible circular saw in a novel machining process for CFRP plate cutting. Unlike a typical circular saw, it can cut curved lines by deflecting the saw body into a bowl-like shape to fit a target curved line. In this paper, we conducted a cutting test on CFRP plates using the flexible circular saw to evaluate its machining characteristics. As a result, the flexible circular saw showed excellent cutting properties compared with endmill cutting. Moreover, it was shown that the flexible circular saw could cut CFRP plates at a high feed rate of more than 3000 mm/min.

Keywords: Flexible Circular Saw, Circular Saw, CFRP, Cutting Tool, Trimming Process

1. Introduction
The demand for carbon fiber-reinforced plastic such as CFRP for industrial applications continues to increase. CFRP products usually need to be machined after the curing of laminated prepregs. Abrasive water-jet machining or endmill cutting is often used for the trimming process. However, these methods present problems regarding machining efficiency and cost [1-5]. Therefore, we propose the use of a flexible circular saw in a new process for CFRP plate cutting. A normal circular saw has a lot of cutting edges and rotates at a high rotational speed. Therefore, high-speed cutting with a feed rate (> 3000 mm/min) about three times higher than those of other machining methods can be achieved. However, a circular saw can generally only be used for straight-line cutting. Thus, it is difficult to cut curved lines without interference between the saw body and the machined surface. One of the ideas to avoid such interference is to deflect the circular saw to fit the target curved line. A flexible circular saw can be deflected into a bowl-like shape. This can be realized by circular forced displacement while the center is held. Then, the cross-section of the saw body becomes a circular arc. Therefore, a curved line can be cut without interference by the bowl-like deflection. In our previous study, we found that a flexible circular saw could cut curved lines at high speeds without interference [6]. However, the ability of the flexible circular saw to cut CFRP was not investigated.

In this research, in order to clarify the cutting properties of CFRP, we conducted a cutting test on CFRP plates using a flexible circular saw to evaluate surface roughness, cutting temperature and cutting force, and we compared the cutting properties of the flexible circular saw cutting with those of endmill cutting. The flexible circular saw showed better performance than the endmill; furthermore, it was shown that the flexible circular saw could cut the CFRP plate at a higher feed rate more than 3000 mm/min.

2. Setup for CFRP cutting test
A straight-line cutting test for a CFRP plate was conducted on a 4-axis control NC machine tool which had been specially developed for a flexible circular saw, as shown in Fig. 2. The C-axis is a swiveling axis for changing the sawing direction. The U-axis is a linear axis for changing the deflection of the saw body. The mechanism of the U-axis is also shown in Fig. 2. A draw bar is displaced in the axial direction by a servo motor. Therefore, the saw is deflected into a bowl-like shape by acting deflection rings. The deflection rings rotate synchronously with a spindle in order to avoid friction between the saw body and the deflection ring. Details of a flexible circular saw that was used for the cutting test are shown in Fig. 3 and Table 1. The saw has fifty circular arc slits to achieve easy deflection of the saw. In addition, the saw has sixty PCD cutting edges.

The cutting test setup is shown in Fig. 4. The CFRP plate was fixed on a dynamometer (KISTLER 9257B) and fifteen straight-line cuttings were conducted. The total cutting length was 2250 mm in this case. During the cutting, the surface temperature of the cutting edges was measured by infrared thermometer (FLIR SC640). The cutting conditions are shown in Table 2. Moreover, these results were compared with results of Kuroda et al. in which the same CFRP plate was machined using an TiAlN coated endmill [7]. The diameter was 8 mm. The number of flute was 2. The cutting conditions of the endmill cutting are shown in Table 2.
3. Machining characteristics on CFRP straight-line cutting using circular saw

3.1 Surface roughness

First, an observation of the machined surface was conducted. The machined surfaces of cutting lengths 500 mm and 2000 mm are shown in Fig. 5. On the endmill cutting, at the cutting length of 500 mm, the machined surface quality was good. However, at the cutting length of 2000 mm, the roughness of the machined surface increased, and uncut fiber was observed. Meanwhile, using the circular saw, both machined surfaces were smooth and no uncut fiber or delamination was observed.

Then, the arithmetic mean roughness (Ra) of the machined surface was measured on the surface roughness tester (Mitsutoyo Surftest SJ-210). In the measurement, the surface roughness along the feed direction was evaluated. The results are shown in Fig. 6. It is clear that the surface roughness from the circular saw was smaller than that from the endmill. With the endmill, the surface roughness became larger as the cutting length increased. However, on the circular saw, a surface roughness less than 2 μm Ra was maintained even as the cutting length increased. From these results, it was clear that the circular saw could cut the CFRP plate with high quality.

In order to cut a CFRP plate without uncut fibers and delamination, very sharp edges are required. It appears, then, that the circular saw cutting was able to maintain sharp cutting edges because the tool wear was small.
3.2 Tool wear

To confirm the tool wear of the circular saw, tool wear at the cutting length 2250 mm on the circular saw was observed by microscope. No face wear or front flank wear were observed, as shown in Fig. 7(a). However, side flank wear was observed. The results of the measurements are shown in Fig. 7(b). The maximum width of the side flank wear was 0.182 mm. A circular saw often generates transverse vibration because the lateral stiffness of the circular saw is low during cutting. Therefore, it is considered that the side flank face contacted the machined surface through vibration, and the side flank faces wore by the interaction with the hard carbon fibers.

This result was compared with the width of the side flank wear on the endmill. The comparison is shown in Fig. 8. On the endmill cutting, the width of side flank wear at the cutting length 2500 mm was 0.600 mm, which is the same as the width of flute land of the endmill. From this result, it is clear that the tool wear on the circular saw was less than that of the endmill. Taken together, circular saw cutting is more effective for CFRP plate cutting. It is thought that the reason why the circular saw was able to cut CFRP plate with less tool wear despite its far greater (> six times higher) feed rate is that the cutting edge is made from PCD, which has high resistance to wear. In addition, the tool wear was distributed along a longer cutting edge. Circular saw cutting has the potential to cut even longer if its side-flank wear is improved.

3.3 Surface temperature of cutting edge

In the trimming process of a CFRP plate, melting of the matrix resin by cutting heat is a potential problem. In addition, thermal buckling of the circular saw by thermal stress is also a potential problem. Therefore, the surface temperature of the cutting edge while cutting a CFRP plate was measured on an infrared thermometer. The measurement point was located near the cutting point in order to avoid the effect of scattering chips. The result of the measurement is shown in Fig. 9. The maximum temperature of the endmill was 389 °C. On the other hand, the maximum temperature of the circular saw was 82 °C. It was thought that the surface temperature of the cutting edge of a circular saw was so much lower because the non-cutting time is long. Therefore, the cutting heat diffuses into the saw body and the atmosphere. Furthermore, the cutting volume was small because the narrow cutting edge width contributes to the low temperature elevation.

Moreover, the temperature of the endmill becomes high as the cutting length becomes longer. This is because the abrasive action between the tool and the workpiece became large as the tool wear increased. On the other hand, the temperature of the circular saw was stable around 70 °C because the tool wear was small.

From this result, it is shown that the melting of the matrix resin and thermal buckling during the CFRP cutting using the circular saw was small because the cutting temperature of the circular saw remained low.

3.4 Cutting force

In circular saw cutting, the vibration of the saw is also one of the major potential problems. Circular saws often
cause chatter vibration because the saw body is thin [8-10]. The chatter vibration worsens machining accuracy and surface quality, increases tool wear and leads to tool breakage. Therefore, the influence of the vibration during the CFRP plate cutting was studied. The average cutting forces at the cutting lengths of 500 mm and 2250 mm were measured. The sampling frequency of the measurement was 20 μs (50 kHz). The result of the measurement is shown in Fig. 10. When each cutting force was compared, it was found that the wave shape of the overall cutting force at both cutting lengths was almost the same. From this result, it was found that the influence of the tool wear that was shown in the previous section is small in relation to the cutting forces.

On the straight-line cutting using a circular saw, the cutting force component $F_x$ is generally minute because the cutting edge has no inclined angle. However, the result demonstrates the size of the cutting force component $F_x$, caused by a chatter vibration. Then the average values for the cutting force component $F_x$ were measured in the case of distances from the end face of the dynamometer to the end face of workpieces of 10 mm, 18.5 mm, 27.5 mm, 35.5 mm and 44 mm. The results are shown in Fig. 11. It is clear that the wave shapes of the cutting force differed at different distances. In particular, the wave shapes of the distance 18.5 mm (Fig. 11(b)) and 35.5 mm (Fig. 11(d)) fluctuated widely. The maximum cutting forces are also higher than those machined at other conditions. It is shown that in these two cases the transverse vibration was close to the natural frequency of the CFRP plate. In these cases, the cutting edges contact the machined surface.

In order to solve the problem, it is necessary to consider the stiffness of the circular saw and the workpiece. Tensioning and slotting can prevent the lowering of the critical speed by thermal stress [11][12]. Guiding can damp the vibration of the saw body [13]. In addition, measuring the natural frequencies of the saw and the workpiece can help to find a critical speed at which chatter vibration can be avoided.

Next, the cutting forces were compared. The results are shown in Fig. 12. The levels of cutting force component $F_y$ of the 4000 mm/min and 3000 mm/min feeds were almost same. However, the cutting force component $F_x$ and $F_z$ differed: The wave shape of $F_x$ showed the occurrence of chatter vibration at 4000 mm/min, and the cutting force for $F_z$ was higher at 4000 mm/min than at 3000 mm/min. It is thought that this also shows the occurrence of chatter vibration.

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Next, the surface roughness of the feed direction and the laminating direction (perpendicular to the feed in the depth direction) were evaluated, and the surface roughness for the 4000 and 3000 mm/min feeds were compared. Results are shown in Fig. 13. There was no difference in surface roughness between the two feed rates in the feed direction. However, in the laminating
In the direction, the surface roughness at the 4000 mm/min was larger than the surface roughness at the 3000 mm/min. This difference was caused by the transverse vibration of the saw. In order to investigate the reason, the machined surfaces were observed on a laser micro scope (KEYENCE VK-X100). Fig. 14 shows surfaces machined at 4000 mm/min and 3000 mm/min, respectively, and the height of the surface shape by three-dimensional display. In this figure, cut marks from the saw are observed. The heights of the cut marks at 4000 mm/min are higher than those at 3000 mm/min. This is because the depth of cut increased by occurring transverse vibration. Therefore, it is thought that the surface roughness at 4000 mm/min in the laminating direction is worsening.

Finally, the surface temperatures of the cutting edges at 4000 mm/min and 3000 mm/min were compared, as shown in Fig. 15. It is shown that the temperature at 4000 mm/min was higher than that at 3000 mm/min. However, the difference is slight. It is found that the influence of increasing the cutting speed and the feed rate on the cutting temperature is small.

From these results, high-speed cutting using a circular saw does not influence the surface temperature of the cutting edge. This shows that circular saw cutting has the potential to cut CFRP plates at speeds even higher than 4000 mm/min.

**Table 3: Cutting conditions of high feed rate cutting**

<table>
<thead>
<tr>
<th>Material</th>
<th>CFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material thickness mm</td>
<td>8</td>
</tr>
<tr>
<td>Feed rate mm/min</td>
<td>3000 4000</td>
</tr>
<tr>
<td>Spindle speed min⁻¹</td>
<td>3000 4000</td>
</tr>
<tr>
<td>Cutting speed m/min</td>
<td>2875 3833</td>
</tr>
<tr>
<td>Feed per tooth mm/tooth</td>
<td>0.017</td>
</tr>
<tr>
<td>Cutting direction</td>
<td>Down cut</td>
</tr>
<tr>
<td>Coolant supply</td>
<td>dry</td>
</tr>
</tbody>
</table>

**Conclusions**

In order to realize the high-speed cutting of a CFRP plate using a flexible circular saw, a straight-line cutting test was conducted. Then, the machining characteristics were researched. The results are summarized as shown below.

1. The surface roughness of the machined surface on the circular saw cutting is small. The circular saw can cut the carbon fibers completely with sharp cutting edges even if the cutting length is long.
2. On circular saw cutting, tool wear occurs at the side flank face by chatter vibration. However, the tool wear is small compared with endmill cutting. This method can cut CFRP plate with high efficiency.
3. The surface temperature of the cutting edges on the circular saw is low compared with endmill cutting. The circular saw has longer non-cutting time during the course of one rotation, and thus it can cut a CFRP plate with much less tool wear.

4. It was found that chatter vibration possibly occurs during the circular saw cutting depending on the cutting conditions. It is necessary to consider the cutting conditions and the machining setup.

5. High-speed cutting using the circular saw did not affect surface roughness, cutting temperature or cutting force. These results suggest that this method has the potential to cut CFRP plates at feed speeds even higher than 4000 mm/min, which was the highest speed tested here.

References


