STUDY ON APPLICATION OF ABRASIVE WATER JET CUTTING TO THICK CFRP PLATE

H. Hira 1*, T. Okado1, T. Suzuki2
1 School of Engineering, Daido University, Nagoya, Japan
2 Aichi Science & Technology Foundation, Toyota, Japan
* (hira-h@daido-it.ac.jp)

Keywords: CFRP, cutting, water jet, surface roughness, drag line

1 Introduction
Rapid cutting process is required for the production of CFRP panel, and new cutting processes, fiber laser cutting and abrasive water jet cutting are considered as new generation cutting methods. Authors showed the application studies of fiber laser cutting to CFRP in the 18th ICCM[1]. In this study, application of abrasive water jet cutting to same CFRP plates as the previous study was examined. And then tilt effect on cut quality was studied. Then water jet cutting and fiber laser cutting were compared.

2 Experimental Procedures

2.1 Materials
Prepared CFRP plates were flat panels as follows.
- Material: Resin-Epoxy#135, Fiber-UTS50 12K,
- Resin content: 35%
- Layup sequence pattern: (+45/0/-45/90)
- Quasi-isotropic lamination
- Thickness: 4 kinds of thickness as follows.
  1.5mm(8ply), 3.1mm(16ply), 4.6mm(24ply), 9.1mm(48ply)

2.2 Water jet cutting method
Water jet equipment, Mash3 was applied. Equipment is shown in Fig.1. Its maximum water pressure was 414MPa. Garnet particle #80 was included as abrasive material. Nozzle diameter was 1.2mm. Cutting speed and water pressure and amount of garnet were controlled as cutting parameter. Most of cut was applied perpendicular to the top surface of panel. Experiment of the tilt effect on cutting quality was carried out using the plate of 9.1mm thickness as shown in Fig.2. 60°tilt cut depth is same as perpendicular cut of 2 plates, so two plates cut was also conducted.

2.3 Measurements
Following measurements were conducted.
- Geometry of the material removed area by water jet
- Roughness of cut surface
- Macroscopic observation cut surface appearance
- Microscopic observation of cut surface by laser microscope or optical microscope
Effect of cutting parameters on these results was considered.

Fig.1 Water jet cutting equipment used

![Fig.1 Water jet cutting equipment used](image1)

Fig.2 Tilt cut test, and two plates cut test to compare 60° cut at same cut depth

![Fig.2 Tilt cut test, and two plates cut test to compare 60° cut at same cut depth](image2)
3 Results and Discussions

3.1 Effect of plate thickness on cut results

Plates were cut under various conditions, and results were organized in each plate thickness. Fig.3 shows the example of the macro section of cut area and roughness of cut surface. Water jet was ejected perpendicular to the plate. Thickness of this plate is 3.1mm(16ply). Water pressure is 414MPa and amount of garnet is 330g/min, effect of cutting speed on them was compared.

When water jet was passed, material was grinded and removed at jet erupted area. Width of material removed area was called as cutting width in this report. When cutting speed was sufficiently low, cutting width at top side(side facing the water jet) was nearly same as water jet nozzle size. Cutting width of the top side and width of bottom side was almost same when cutting speed was low. However cutting speed increased, cutting width became narrow and width of bottom side became narrower than that of top side. As a result, cut surface became tilted from the right angle. Roughness of cut surface increased with increase of cutting speed.

Fig.4 shows the effect of cutting speed on the plane angle between top surface and cut surface. Water pressure 414MPa and amount of garnet is 330g/min. When cutting speed was low, plane angle was nearly right angle. Cut plane angle decreased with increase of cutting speed. When plate was thin, angle did not decrease from a certain speed. However thickness was over 3.1mm (16ply), angle continuously decreased with cutting speed and did not depend on plate thickness.

Fig.5 shows the effect of cutting speed on the roughness of cut surface.
When cutting speed was under 1000mm/min, surface roughness was small and did not depend on thickness. However, the cut surface became rougher with increase of speed and with increase of plate thickness over 1000mm/min. Then drag line was caused when too fast cutting speed was applied. Fig.6 shows the macro section of cut area and cut surface of 9.1 mm thick plate (48ply). The water jet moved to the right direction. When cutting speed was 200mm/min, cut surface was very smooth. Then cutting speed was 2000mm/min., cut surface became rough and line of water flow was curved and that of back side was little delayed compared with front side. Curvature was severe and interlaminar crack was occurred when cutting speed was 4000mm/min.

Effect of another cutting parameter was examined. Fig.7 shows the relation between water pressure and the angle between bottom surface and cut surface, another parameter was fixed shown in the figure title. Angle closed to right angle as the water pressure
increased. So high power machine might be desirable, and the machine we used was one of the highest power machines in the world. And 414 MPa which was the maximum power of the machine used was selected as standard condition.

Fig.8 shows the relation between the amount of garnet and the angle between bottom surface and cut surface. Peak was shown at 500g/min, however effect of the amount of garnet was relatively small within the scope of this experiment. Amount of garnet affects cost directly, small amount might be better if the degradation of performance is small. So, 330g/min was selected as standard condition of the amount of garnet.

### 3.2 Tilt effect on cut quality

Taper cut of CFRP plate is often applied in order to smoothly transmit the load. Plate of 9.1mm thickness (48ply) was cut as shown in Fig.2.

Example of the results is shown Fig.9. Cutting parameter was constant and macro sections of cut area and cut surface appearances where those were cut at various angles were shown.

When cut angle was 15° and 30°, cut surface was smooth. 45° caused surface rough a little. When cut angle was 60°, cut surface became rough and drag line was appeared.

Cut depth became long if cut angle was increased, and when cut depth became large roughness of cut surface was increased from the results of Fig.5. Trend of the results in Fig.9 might be consistent with the result of Fig.5. However right angle cut results of the plate of 18.2mm thickness(48 ply 2plates) showed rather smooth cut surface and drag line was very weak compared with the 60° cut results of the plate of 9.1mm thickness. These two cases have same cut depth length, however results were different and cut result of tilt case was worse. Then cut path of 60° was not straight, curved toward top surface at the back side a little.

Table 1 show the effect of cutting speed and cut angle on the cut surface observation results where another cutting parameters fixed constant. When cut angle was 0°, this means cut was conducted perpendicular to CFRP panel, cut surface was very smooth if cutting speed was 800mm/min. Smooth cut became difficult with increase of cut angle and cutting speed. When cut angle was 45°,
smooth cut surface might be obtained in the cutting speed 200mm/min below. And When cut angle was 60°, smooth cut surface might be obtained in the cutting speed 100mm/min below. From the result of 2 plates cut, smooth surface cut was obtained in the cutting speed 200mm/min below. So taper cutting was not easy compared with right angle cutting. Microscopic observation of cut surface was conducted by laser microscope in order to explain above tilt cut effect. Some observation results by laser microscope were shown in Fig.10. CFRP panel used made quasi isotropic lay-up of uni directional pre-preg. Perpendicular axis layer to cutting direction was mainly observed. Observed area was about the center of the plate thickness. Fig.10(a) shows the cut surface that was cut tilted 15°. This surface was macroscopically smooth. This surface was also smooth by the observation of laser microscope, and cut surface of carbon fiber of the circular shape could be seen. Fig.10(b) shows the cut surface that was cut tilted 45°. This surface macroscopically became rough. This surface was rough by the observation of laser microscope, cut situation of carbon fiber was mixed, one was shown cut surface of the elliptical shape and another in which carbon fiber protruded a little and was broken. Fig.10(c) shows the cut surface that was cut tilted 60°. Drag line appeared in this cut surface macroscopically. Long cylindrical surface of carbon fiber was revealed.

Carbon fiber of perpendicular axis of cut direction in the CFRP was considered to be almost cut along the panel cut surface of panel when tilted angle was 15°, however cut angle was increased carbon fiber was not cut along the panel cut surface. This might be because breaking energy of carbon fiber was low compared with the tilt grinding of carbon fiber over certain angle. Mode change of fiber cutting from grinding to breaking seemed to cause the resistance of the cutting to proceed in the direction of the jet stream. So, cylindrical surface was revealed and cut path was curved when 60° tilted cut was conducted.
3.3 Cut results by water jet compared with the results by fiber laser cutting

Cut results by water jet was compared with that by fiber laser[1] and conventional mechanical cut using endmill.
Fiber laser equipment, YLR-5000C2 was applied. Its maxim power was 5kW. Wave length was 1.07 μm. Beam diameter was about 1mm.
Energy concentration was very high, and cutting speed was very first. However certain area of heat affected zone was generated around the cut path. Size of heat affected zone was very small when laser cutting was applied to thin plate, then became larger with increase of plate thickness[1]. Heat affected zone degraded the mechanical properties, so heat affected zone must be grinded if CFRP panel was used as important structure.
Water jet was also fast cutting method. Problems of water jet cutting were not so good surface roughness and cut surface was tilted, however it was easier to be corrected than fiber laser cutting.

Table 2 Suitable cutting condition of new cutting processes and conventional endmill cutting
(CFRP panel of 4.6mm thick (24ply) )

<table>
<thead>
<tr>
<th>Process</th>
<th>Suitable Cutting Speed (mm/min)</th>
<th>Reserve for cutting(mm)</th>
<th>Grinding required(mm)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Laser</td>
<td>4000</td>
<td>0.2</td>
<td>2.5</td>
<td>5kW</td>
</tr>
<tr>
<td>Water Jet</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High quality</td>
<td>1500</td>
<td>1.2</td>
<td>0~0.2</td>
<td>414 MPa</td>
</tr>
<tr>
<td>High velocity</td>
<td>6000</td>
<td>1.2</td>
<td>0.5</td>
<td>414 MPa</td>
</tr>
<tr>
<td>Endmill</td>
<td>260</td>
<td>10</td>
<td>0</td>
<td>10mmΦ</td>
</tr>
</tbody>
</table>
Recently precise control of the angle of water jet nozzle in order to remove correct process was developed. When cut speed was under 1000 mm/min, cut surface might be acceptable to be used as cut condition. However additional grinding process was required when plate is thick and cutting speed was over 1000 mm/min. Cutting speed of 1000 mm/min was lower than by fiber laser however it is sufficiently faster than the cutting speed by endmill.

Conventional endmill cutting was very slow, however cut surface was very smooth and angle of cut surface was right angle. Cutting process of 4.6mm thick plate (24ply) was examined to compare among 3 processes, water jet, fiber laser cutting and conventional endmill cutting in order to check above. Table 2 shows the proper suitable cutting speed of each process. And reserve width for cutting and width of grinding required were shown when these cutting conditions were applied.

For the water jet, two type application concepts were considered. One was that relatively slow cutting speed and precise nozzle axis control was applied in order to remove or reduce post process. It was called quality cut condition. Another was the high speed rough cutting without drag line formation. Drag line was considered to relate the generation of interlaminar crack. It was called high velocity condition.

Fig.11 shows the each macro section of cut area and Fig.12 shows the observation results of each cut surface by optical microscope. Heat affected zone where it was distinguished by the change of color was found at the cut area of fiber laser, width of it was about 2mm. This area must be removed because void was generated and fiber orientation became irregular as shown in Fig.12. Grinding speed of this area was rather first compared with endmill cutting speed. In the case of water jet cutting, tilted cut surface was appeared. The effect of the presence of this area on mechanical properties was very small or not if there was no interlaminar crack. So removal of this area depends on the situation. If high velocity cut was applied angle of cut surface was left from right angle compared with high quality cut. And step like pattern at surface was revealed shown in Fig.12. This might be because each ply had another characteristic of water jet grinding.
Proper application field of two new fast cutting processes are considered.

Problem of fiber laser cutting is heat affected zone, which becomes wide with increase of thickness. However it is negligibly small while plate is thin. Strong point is the controllability of beam path. Three dimensional complex beam path will be realized. Fixture is easy because load durability is not required and fiber laser source is light. So, proper application field of fiber laser cutting may be for the thin complex shape large or small thin structure.

Water jet is also fast cutting process, and applicable speed might be restricted to not so fast level because of rigid fixture in order to resist the reaction force of water jet. And post process of the treatment of water and garnet is the problem. However, quality of cut is good and high potential of thick plate cutting is clearly demonstrated. So, proper application field of water jet cutting may be for large scale and not complex thick structure.

4 Conclusions
Application of abrasive water jet cutting to CFRP plates was examined. And then tilt effect on cut quality was studied. Then water jet cutting and fiber laser cutting were compared and proper application field was considered. Main results were as follows;
1) When fast cutting speed was applied, cut surface of water jet became rougher and cut angle left from right angle. As cut surface might be acceptable if cutting speed was under 1000mm/min.
2) High angle tilt cut was difficult, it caused rougher cut surface compared with perpendicular cut at same cut depth. This is because of the difficulty of the high angle cut of each carbon fiber in CFRP.
3) Applicable cutting speed was lower than that of fiber laser; however problem of the quality was easier to be recovered. Proper application field of water jet cutting is for large scale and not complex thick structure.

Acknowledgement
This work was supported by “The Knowledge Hub of AICHI, The priority Research Project”. Authors are thanks to Kawasaki Heavy Industries Ltd for for providing CFRP panels.

References