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# Ultrafast Feed Drilling of Carbon Fiber-Reinforced Thermoplastics

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**Abstract**

Carbon fiber-reinforced thermoplastics (CFRTP) are just beginning to be utilized for various applications such as aerospace, automobiles, and sporting goods in place of CFRPs, and the demand for through-hole drilling of CFRTPs is increasing. In this study, the machinability in drilling of CFRTPs under various conditions was experimentally analyzed in terms of the material properties, and a feasibility study of ultrafast feed drilling was conducted. The results showed that delamination at the outlet surface can be significantly suppressed during high rotational drilling when the feed rate is set to more than 3000 mm/min. By providing appropriate drilling conditions to prevent polymers in CFRTPs from softening, ultra-fast drilling of CFRTPs was successfully achieved under dry conditions.

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*Keywords:* Drilling; CFRTP; High-performance drilling

## 1. Introduction

Recently, carbon-fiber-reinforced polymers (CFRPs), which require high strength-to-weight ratio and rigidity, have been widely applied to mechanical parts in aerospace and automobile industries. In terms of aerospace and automobile parts, CFRPs are primarily applicable as replacements for metal alloys in structural components for weight reduction. The structural parts of CFRPs must be drilled after the forming process to connect with other components, and bolt-joining efficiency and quality depend critically on the accuracy of the machined holes [1]. Thus, not only highly efficient but also highly precise drilling of CFRPs is required. In terms of a machined hole's quality, drilling should suppress delamination and the formation of burrs at the inlet and outlet, which easily occurs because of their material characteristics, which tend to be anisotropic and inhomogeneous [2].

The binding polymer used in CFRPs is mainly a thermoset resin such as epoxy because it provides high heat residence and chemical resistance. However, the cost of epoxy is relatively high, and a typical production process of resin transfer molding has a longer takt time than injection molding and press molding [3]. Hence, carbon fiber-reinforced thermoplastics (CFRTPs) have attracted attention, although the issue of lower heat resistance remains. CFRTPs are just beginning to be utilized for various applications, especially in automobiles, and the demand for through-hole drilling of CFRTPs is increasing. In this study, machinability in drilling of CFRTPs under various conditions was experimentally analyzed in terms of the material properties, and the feasibility of ultrafast feed drilling as compared to ultrasonic vibration-assisted drilling and abrasive water jet machining was investigated.

## 2. Carbon fiber-reinforced thermoplastics (CFRTPs)

CFRTPs have received considerable attention from the automobile industry in recent years. Conventional CFRPs use a thermosetting resin, which hardens when heated. To shape the CFRP, the resin transfer molding process is typically employed. Requiring several minutes or hours to mold the desired shape, it is not suitable for mass-produced automobiles. On the other hand, a thermoplastic resin, which softens when heated and hardens when cooled, has a significant advantage in terms of mass production. CFRTPs can be press-molded in a much

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shorter time [4]. The Japanese company Teijin reported that mass-production technology capable of molding a CFRTP structural part in less than a minute was realized. CFRTPs have a further advantage in that the shape of the part can be modified after molding, which facilitates recycling through reuse or reforming [5].

In this study, cross-ply laminated CFRTP plates, shown in Fig. 1, were prepared as workpieces. The material properties are listed in Table 1. The CFRTP plates consisted of thermoplastic Nylon PA66 and 14 layers of cross-ply laminated carbon fibers. The tensile strength and density of the plates are 785 MPa and 1.4 g/cm$^3$, respectively.

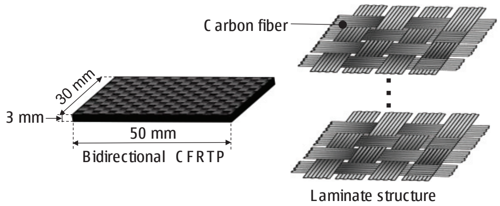


Fig. 1 Laminate structure of CFRTPs

Table 1 Material properties

| | |
|---|---|
| Fiber | Carbon |
| Resin | PA66 |
| The number of layers | 14 |
| Fiber content % | 45 |

## 3. Experimental setup for CFRTP drilling

### 3.1. Ultrafast feed drilling (UFFD)

Unlike a thermosetting polymer, a thermoplastic weakens rapidly with increasing temperature, resulting in a viscous liquid. From this viewpoint, it is presumed that the cutting heat and friction heat would be dominant factors in determining the quality of a machined hole in drilling. The cutting heat is rapidly transferred from the cutting point to the inside of the CFRTP because of high thermal conduction. As a result, the thermoplastic binding carbon fibers at the cutting area are melted before completion of the cutting process. To avoid melting the thermoplastic binder during cutting, ultrafast feed drilling was proposed in this study, and its validity was verified through drilling tests and comparing the results with those obtained through ultrasonic vibration-assisted drilling and abrasive water jet machining.

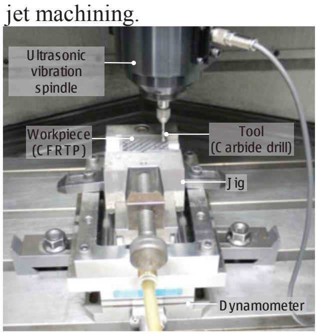


Fig. 2 Experimental setup for UFFD and UVD

Figure 2 shows the experimental setup, i.e., a three-axis vertical machining center (V33, Makino Milling Machine Co., Ltd.). A three-component dynamometer (9257B, KISTLER Co., Ltd.) was set on the machine table in order to measure the cutting forces. The CFRTP sample was fixed by the jig. The cutting tests were carried out using a carbide drill 3.0 mm in diameter. The cutting conditions are shown in Table 2. To investigate the influence of the fast feed rate, feed rates of 3000, 5000, and 7000 mm/min were used in the tests.

Table 2 Cutting conditions for UFFD and UVD

| | |
|---|---|
| Drill diameter mm | 3 |
| Hole depth mm | 3 (penetrate) |
| Feed rate mm/min | 3000, 5000, 7000 |
| Spindle speed min$^{-1}$ | 13000, 16000, 20000 |
| Ultrasonic amplitude µm | 6.0～10 |
| Ultrasonic frequency kHz | 70 |
| Cutting method | Dry |
| Machining time s | 3 (F=3000 mm/min) |

### 3.2. Ultrasonic vibration drilling (UVD)

In this study, axial ultrasonic vibration was adopted for the drilling of CFRTP. To apply ultrasonic vibration to the cutting tool, a piezoelectric crystal oscillator was fitted in and mounted properly between the chuck and the collet. The specially designed spindle was controlled by the ultrasonic vibration controller (Sonic Impulse SD-100, Taga Electric Co., Ltd.). The frequency was constant at 70 kHz and the amplitude was adjustable from 6 to 10 µm. Intermittent cutting according to the ultrasonic vibration reduces the friction between the tool and the workpiece, which could suppress heat generation at the cutting point [6].

### 3.3. Abrasive water jet machining (AWJ)

In recent years, abrasive water jet machining has become the main process for the cutting of CFRPs bound with thermosetting resin. Abrasive water jet machining is a method of cutting materials using only water pressure and abrasives. It is usually used as trimming machining [7]. Figure 3 shows the experimental setup for the abrasive water jet machining. The CFRTP sample was fixed by double-sided tape on the plywood and the plywood was fixed by the jig. The abrasive supply tube was connected to the water supply tube. The diameter of the water jet nozzle was 0.84 mm. The process of machining a 3-mm-diameter hole is shown in Fig. 4.

- First step: water is shot through the nozzle and an initial 0.84 mm hole is produced.
- Second step: the water jet nozzle moves with a circular motion and machines a 3-mm-diameter hole

The machining conditions are shown in Table 3. When much higher water pressure is applied, the high pressure results in widespread damage to the CFRTP. Therefore, the water pressure was regulated in order to prevent damage.

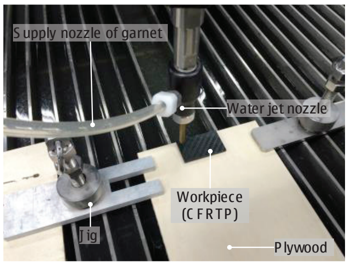


Fig. 3 Experimental setup for abrasive water jet machining (AWJ)

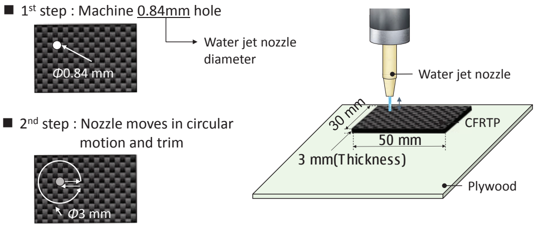


Fig. 4 Procedure of abrasive water jet machining

Table 3 AWJ machining conditions

| | |
|---|---|
| Hole diameter mm | 3 |
| Nozzle diameter mm | 0.84 |
| Water pressure MPa | 50 (1st step)<br>300 (2nd step) |
| Abrasives | Garnet |
| Amount of abrasives g/min | 50 (1st step)<br>150 (2nd step) |
| Feed rate mm/min | 100 |
| Machining time s | 14 |

## 4. Cutting performance evaluation of UFFD

### *4.1. Cutting phenomena*

To investigate the influence of feed rate on the quality of a machined hole, the cutting phenomena was observed at the outlet of the hole. Figure 5 shows the difference in cutting behavior between the ultrafast feed drilling at 3000 mm/min and a lower feed drilling at 50 mm/min. In the ultrafast feed drilling, the cutting process worked effectively and cut chips of an appropriate size were evacuated. Consequently, almost no burrs remained at the outlet of the hole. On the other hand, at a low feed rate of 50 mm/min, the CFRTP was gradually deformed along the tool shape just before drill penetration. The hat-shaped chips were not perfectly removed, and crown-shaped burrs were generated around the edge of the hole. It is suggested that nylon softened by cutting heat and frictional heat causes large burr generation, as expected.

Figure 6 shows the thrust force in drilling at each feed rate. Even though the peak value of the thrust force at 3000 mm/min is 6 times higher than at 50 mm/min and approaches 22 N, the machining time at 3000 mm/min is approximately 1/60 of the time at 50 mm/min. The proposed UFFD realized highly efficient drilling while maintaining the fine quality of the machined hole. Comparing total impulse, which is the product of force and time, the total impulse at 3000 mm/min was less than 1/10 that at 50 mm/min. Hence, UFFD has a significant advantage in terms of reducing the machining energy.

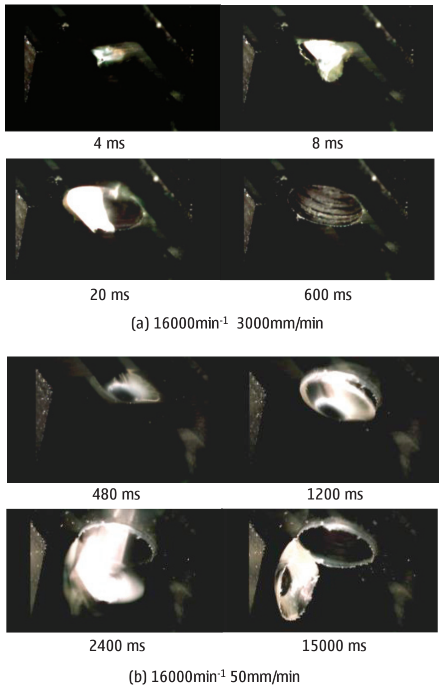


Fig. 5 High-speed microscope images at the outlet of the machined holes as a result of (a) ultrafast feed drilling and (b) low feed drilling

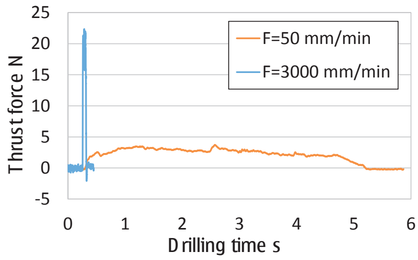


Fig. 6 Cutting forces at ultrafast feed and low feed

### *4.2. Evaluation of delamination and burr*

To evaluate the cutting performance of UFFD, the influence of feed rate and spindle rotation on delamination volume and burr volume was investigated. Delamination volume and burr volume can be measured by a three-dimensional (3D) measuring microscope (VR-3000, Keyence Co., Ltd.). Figure 7 shows the 3D profile data of the inlet of the hole. From the results of preliminary drilling tests, it is clear that delamination and the formation of burrs take place at the inlet rather than the outlet of the hole. Therefore, delamination and burr formation at the inlet were evaluated. In this study, the delamination area and burr area were defined as the area 20 μm below and the area 20 μm above from average height of the surface, respectively. Figure 8 shows the delamination volume for each cutting condition. When the feed rate was set to 3000 mm/min, no delamination was observed regardless of spindle speed. At feed rates greater than 3000 mm/min, the delamination volume increased with increasing feed rate at spindle speeds up to 20,000 min$^{-1}$. This may be because excessive thrust force or impact force at feed rates of 5000 mm/min and 7000 mm/min caused expansion of the delamination area. It is confirmed that the 3000 mm/min feed rate was optimum for suppressing the delamination area.

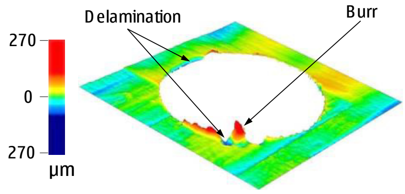


Fig. 7 3D profile of a machined hole at inlet

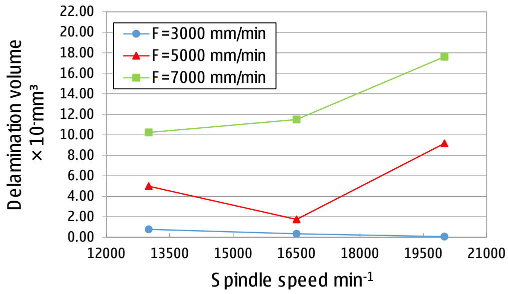


Fig. 8 Delamination volume for each cutting condition

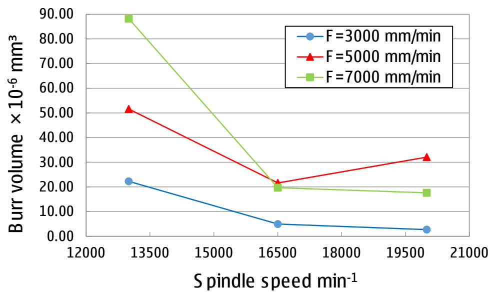


Fig. 9 Burr volume for each cutting condition

Figure 9 shows burr volume for each cutting condition. The burr volume tends to decrease with increasing spindle speed. Burr volume can be considerably suppressed at a feed rate of 3000 mm/min and a spindle speed of 20,000 min$^{-1}$. As shown in Fig. 10, the hole quality at 3000 mm/min is better than those at 5000 mm/min and 7000 mm/min.

Both results indicate that the appropriate cutting conditions to minimize delamination and burr formation is a feed rate of 3000 min/mm and a maximum spindle speed of 20,000 min$^{-1}$.

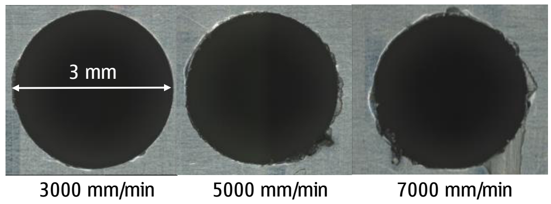


Fig. 10 Microscope images at the inlet of the machined holes

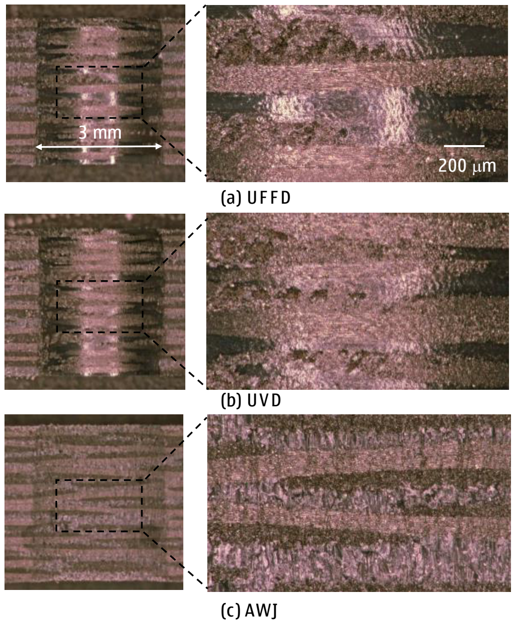


Fig. 11 Microscopic images of wall surface in each machined hole

## 5. Comparison of UFFD to UVD and AWJ

In order to verify the validity of UFFD, comparison tests were conducted with UVD and AWJ in terms of hole quality and form accuracy. Figure 11 shows the microscopic images of the wall surfaces of each machined hole. Each carbon fiber layer is clearly observed at the hole wall in UFFD, whereas each layer is blurry due to covering by molten nylon in UVD and AWJ. The magnified images of the hole edges, shown in Fig. 12, showed that fuzzy and tiny molten nylon threads spread in AWJ. Even though the edge of the hole machined by UVD has better quality than the one by AWJ, the quality of the hole edge was much better with UFFD. The results of the comparison between UFFD and AWJ are listed at Table 4. In UFFD, the difference in hole diameter between the inlet and outlet is less than 2.5 μm. On the other hand, AWJ produced a difference of hole diameter that was 20 times higher. With respect to the surface roughness of the hole wall and machining time, UFFD provided a finer surface in a shorter time than AWJ. In terms of surface quality, form accuracy, and machining time, it can be said that the proposed UFFD is a promising process for drilling of CFRTPs.

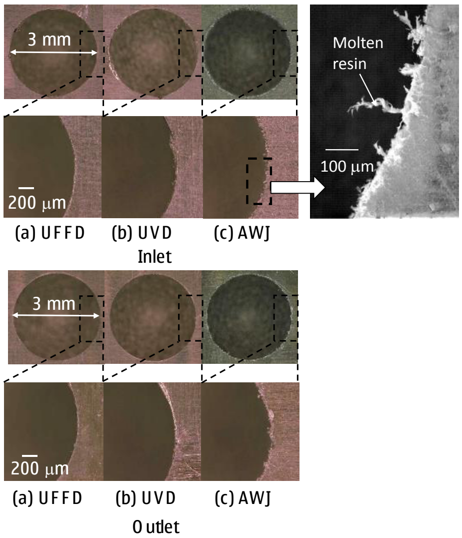

Fig. 12 Magnified images of hole edge for each machining method

Table 4 Comparison of UFFD and AWJ results

| | Edge of machined hole | Difference in diameter μm | Ra μm | Machining time s |
|---|---|---|---|---|
| UFFD | High precision | 2.43 | 1.59 | 3 |
| AWJ | Molten resin | 55.5 | 2.25 | 14 |

## 6. Conclusion

In this study, ultrafast feed drilling (UFFD) for making holes in CFRTP plates with thermoplastic binding was proposed, and the validity was experimentally verified by comparing it to ultrasonic vibration-assisted drilling (UVD) and abrasive water jet machining (AWJ). The obtained results are as follows:

1) Even though the hat-shaped chip was not perfectly removed and crown-shaped burrs were generated around the edge of the hole in conventional low feed drilling, there were no burrs at either the inlet or the outlet of the hole in UFFD.
2) Setting the feed rate at 3000 min/mm and the spindle speed 20,000 $min^{-1}$ can minimize delamination and burr volume in this experiment.
3) Each carbon fiber layer is clearly observed at the hole wall in UFFD, whereas each layer becomes blurry due to the molten nylon in UVD and AWJ. Compared to UVD and AWJ, UFFD enhances both the machined hole quality and efficiency in the drilling of CFRTPs.

In future work, we plan to measure the cutting temperature in each drilling process. The validity of the proposed UFFD will be clarified in terms of temperature during drilling.

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