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Cutting Characteristics of CFRP Boards Using Electroplated Diamond Wire Tools

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Abstract: CFRP (carbon fiber reinforced plastic), which is composed of carbon fibers in a resin matrix, is an extremely strong and light composite material that has found use in the aerospace and automotive industries. CFRP boards are very difficult to machine using common machining processes. Various machining artifacts, such as burrs and delamination, occur frequently when machining CFRP. Adequate techniques for machining CFRP have not yet been established. Recently, electroplated diamond wire machining technology has found use in cutting hard, brittle materials such as silicon and sapphire. In this study, we used an electroplated diamond wire saw to cut a CFRP workpiece. We quantified the cutting forces imposed on the workpiece and observed the surface state of the workpiece after cutting. We demonstrated that an electroplated diamond wire tool is suitable for the high-quality machining of CFRP boards.

Key words: CFRP, diamond wire, deflection, cutting force, cutting depth.

1. Introduction

Composite materials consisting of a fiber-reinforced polymeric matrix have received considerable attention as lightweight structural materials owing to their high strength-to-weight ratio, high stiffness, etc. These materials also have versatile applications as their properties can be tuned by combining different fibers and matrix resins in different proportions. CFRP (carbon fiber reinforced plastic) is an extremely strong and light composite material that has been utilized in aircraft, automobiles, and sporting goods, for example. However, it is difficult to achieve high-precision dimensional tolerances after laminating and curing the CFRP [1-3]. The dimensional accuracy around the edges of formed CFRP boards is the worst, and commonly manifests as unstable thicknesses, burrs, textured edges, and delamination. Therefore, a trimming process must be performed after forming CFRP boards.

Laser-based processes offer advantages over conventional techniques for the cutting, drilling, and surface preparation of composites. Because laser-based processes are non-contact techniques, they minimize the mechanical damage and avoid tool wear and surface contamination [4]. The first lasers used for processing polymer-matrix composites were CO_2 lasers. However, owing to the thermal nature of the radiation/material interaction for this type of laser, thermal and thermo-mechanical degradations of the material are likely to occur. Moreover, the carbon fibers in CFRP conduct heat to the bulk of the material leading to a large heat affected zone where the fiber/matrix interface is weakened by thermal degradation of the resin. Mechanical trimming processes, such as grit-blasting, are effective low-cost trimming methods, but they are liable to cause fiber fracture and fiber/matrix delamination, and a secondary cleaning operation is required to eliminate abrasive grits impressed in the CFRP during the blasting process.

In recent years, a fixed-abrasive diamond wire sawing technology has been developed and applied in slicing hard and brittle Si and sapphire ingots to wafers [5, 6]. The worn portion of the wire can be moved away from the machining area without

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interrupting the cutting operation. Further, compared to a circular saw and band saw, the diamond wire saw is more flexible and can cut parts with complicated geometry, such as a two-dimensional shape or a simple three-dimensional curved surface [7]. In this study, we focused on the stable machining characteristics of electroplated diamond wire sawing technology in machining CFRP boards. We evaluated the cutting force, specific cutting energy, and cutting depth of the abrasive on the diamond wire, as well as the machined surfaces and swarf of the CFRP work-piece in various machining conditions.

2. Experimental Procedure

In this experiment, a single wire saw, seen in Fig. 1, was employed for cutting CFRP boards. Fig. 2 shows the detailed schematic of the wire saw cutting a CFRP board. The machining was performed as follows. A diamond wire was wrapped alternately around a feed reel and a take-up reel. The reciprocating movement of the wire was achieved by changing the direction of movement of the wrapping reels. The wire was wrapped around the feed reel, auxiliary pulleys, two tension pulleys, and the take-up reel. The wire tension was adjusted to stable values using the left and right tension pulleys. The axis distance of the work rollers was set to one of three possible values: 190 mm, 250 mm, or 310 mm. A 5-mm-thick CFRP board, fixed on a dynamometer, was fed perpendicular to the wire movement direction for cutting. The cutting forces were recorded by the dynamometer. The CFRP board was cut along the vertical direction of the carbon fibers.

The cutting force is the sum of the reaction force, Fz, in the feeding direction of work-piece, and the frictional force, Fx, in the running direction of the wire as the angle owing to the deflection of the diamond wire was determined to be negligible. The flexible diamond wire deflects because of the cutting force in the feed direction of the work-piece during the cutting process. Two types of diamond wire were used to determine the relationship between the deflection of the diamond wire and the normal cutting force. The diamond wire was immobilized under a constant tension, and the work-piece was fed to the wire in increments of 1 mm. As shown in Fig. 3, the cutting force, Fz, increases commensurately with the deflection distance and tension of the wire. Further, for a given tension force, differences in the cutting force, Fz, are small between

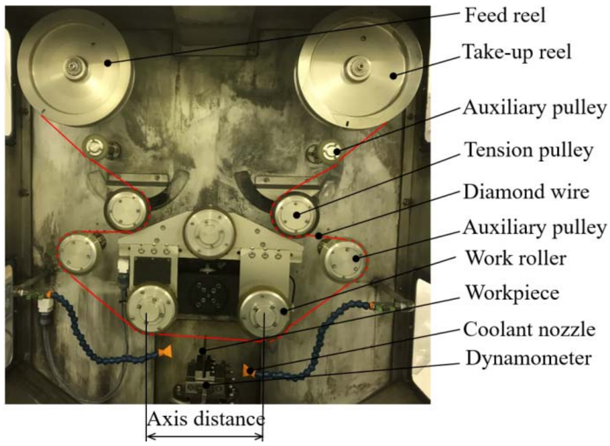


Fig. 1 Apparatus of a diamond wire saw.

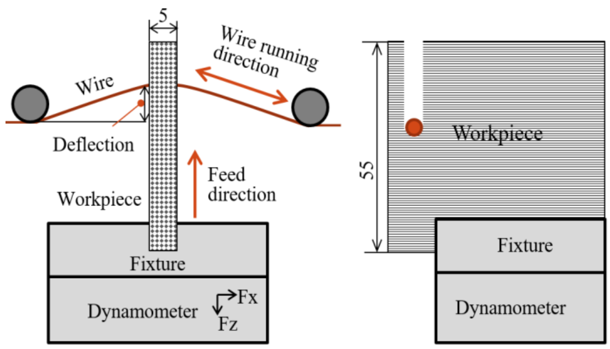


Fig. 2 Schematic of the wire saw.

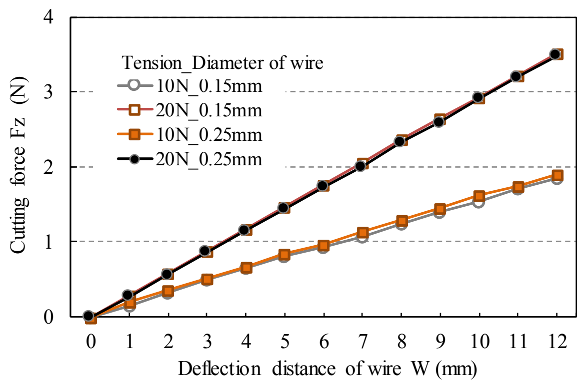


Fig. 3 Relationship between deflection of diamond wire and cutting force *Fz*.

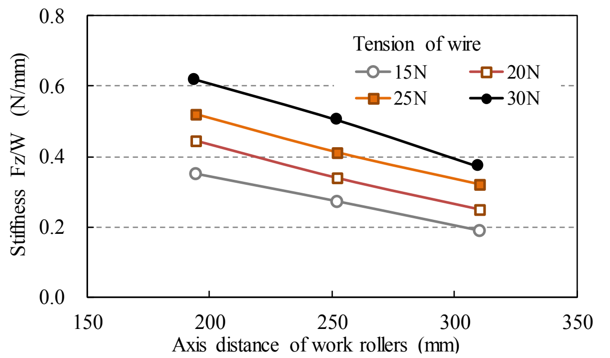


Fig. 4 Effect of axis distance of work rollers on deflection of diamond wire.

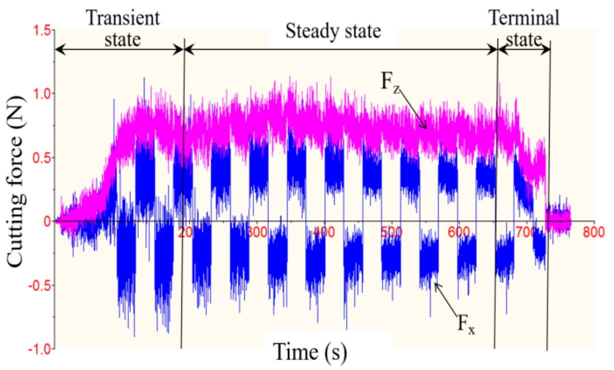


Fig. 5 Example of measured cutting force during a whole cutting process.

wires of different diameters. Fig. 4 shows the effect of the axis distance between the two work rollers on the bending stiffness of the diamond wire. It was found that the smaller the axis distance of the work rollers, the larger the cutting force, *F*z. The axis distance of the work rollers affects the bending stiffness of the wire to a much greater extent than the diameter of the wire because the diamond wires are very thin compared to the axis distance of the work rollers. The cutting accuracy could be improved by reducing the deflection distance of the diamond wire. The deflection distance could be reduced by raising the tension of the wire or shortening the axis distance of the work rollers. The cutting force could be reduced by using a thinner diamond wire; however, the tension a thinner wire that can sustain is limited.

Fig. 5 shows a typical change of cutting forces (*F*x and *F*z) during the whole cutting process using the diamond wire saw. An accumulation phenomenon caused a transient state in the initial cutting process in which the normal force, *F*z, increased rapidly. The cutting force, *F*z, gradually levelled and stabilized to a small range of values, and the cutting process entered its steady state. A balance between the cutting speed and feeding speed was established and no external adjustments were required. Even when the cutting speed became smaller than the feeding speed of the work-piece, the cutting force, *F*z, would quickly increase, causing the cutting speed to increase in turn and approach the feeding speed. The vector of the cutting force, *F*x, changed alternately because the running direction of the diamond wire had a reciprocating action. The absolute value of *F*x increased gradually in the transient state because the cutting speed and material removal rate both increased gradually. Thus, *F*x represents the frictional forces between the wire and the work-piece, while *F*z represents the deflection of the wire and the force of the abrasives acting on the work-piece. The steady state cutting forces were used to evaluate the cutting characteristics.

3. Cutting Experiments

Table 1 presents the key cutting parameters in cutting a CFRP board by wire saw. The cutting test was conducted on a 50-mm-long CFRP board. The carbon fibers in the CFRP board were arranged unidirectionally. The cutting parameters (wire speed, feeding speed, tension of wire) reflect the cutting ability of the wire tool and affect the cutting force

Table 1 Cutting conditions.

Machine	Single wire saw, WSD-K2, Takatori Corporation, Japan
Diamond wire	Diameter: Φ 0.15 mm Grain size: 15 μm
Workpiece	Unidirectional CFRP board Fiber content: 67 vol% Thickness: 5 mm, Length: 50 mm
Wire speed	600 m/min
Cycle time	60 s (acceleration time is 3 s.)
Tension of wire	20 N
Feed speed	5 mm/min

considerably. Fig. 6 shows the relationship between the cutting forces (average horizontal and normal cutting forces) and the wire speed. The normal force and the horizontal force decrease linearly as wire speed increases. At low wire speeds, average amount of material removed by per abrasive is larger in the cutting process, which explains the high cutting forces.

The relationship between the average cutting forces and the feeding speed of the work-piece is shown in Fig. 7. The cutting forces increase as the feeding speed of the work-piece increases. The total amount of material removed is greater at higher feeding speeds for a constant machining time. The loads on the diamond wire increase with feeding speed as shown by the increased cutting forces. Fig. 8 shows the relationship between the average cutting forces and the tension of the diamond wire. Increased wire tension appears to slightly decrease the cutting forces, but the effect is smaller in magnitude compared to the effect caused by changing the wire speed or the feeding speed.

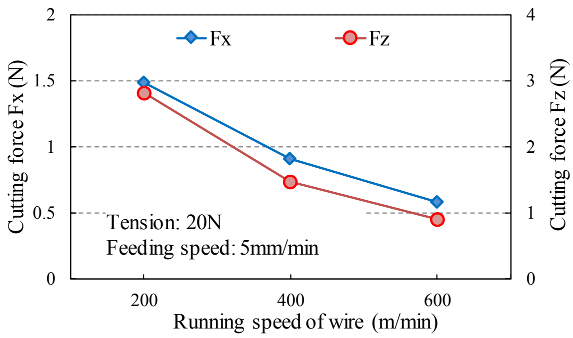


Fig. 6 Effect of wire speed on cutting forces.

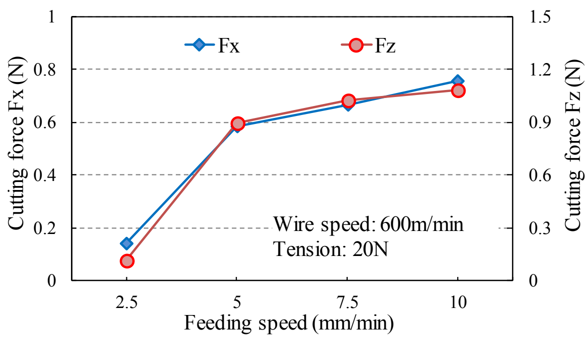


Fig. 7 Effect of feeding speed on cutting forces.

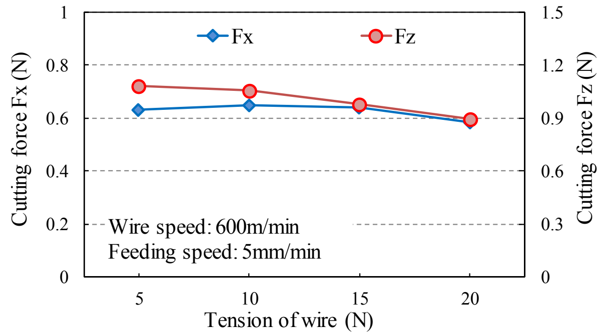


Fig. 8 Effect of tension of wire on cutting forces.

4. Analysis of Material Removal Method

We assumed values for some parameters in the analytical model. The cross section of the diamond abrasive was assumed to be hexagonal and the tip angle of the abrasives was assumed to be 120°. We also assumed that the abrasives were uniformly distributed on the diamond wire and that half of the abrasives on the diamond wire act on the work-piece. Fig. 9 shows the schematics involved in determining the average cutting depth of the abrasives and the specific cutting energy [8]. ΔV, which is the stock removal material by abrasives, is calculated as the following function:

$$\Delta V = V_0 \cdot \Sigma n = \frac{\sqrt{3}}{2} \cdot B \cdot v \cdot d_0^2 \cdot \Delta t \cdot \sigma \qquad (1)$$

The volume of removed material ΔD can also be calculated from cutting conditions by the following function:

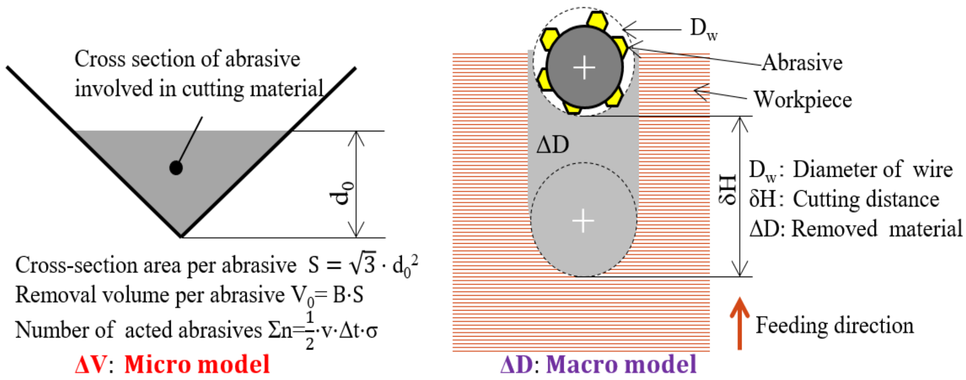
$$\Delta D = B \cdot \Delta H \cdot Dw = B \cdot f \cdot \Delta t \cdot Dw \qquad (2)$$

The total volume of stock cut material per abrasive ΔV is equal to the removal material by a diamond wire ΔD. Thus, the average cutting depth of abrasives d_0 and the specific cutting energy k_s are calculated as the following calculation formula:

$$d0 = \sqrt{\frac{2 \cdot f \cdot Dw}{\sqrt{3} v \cdot \sigma}} \qquad (3)$$

$$ks = \frac{Fx \cdot v \cdot \Delta t}{\Delta D} = \frac{Fx \cdot v}{B \cdot Dw \cdot f} \qquad (4)$$

The specific cutting energy and average abrasive cutting depth at various cutting conditions, was calculated by Eqs. (3) and (4). Fig. 10a shows the relationship between the specific cutting energy and



B	Thickness of CFRP
σ	Abrasive density
v	Wire running speed
f	Feeding speed
F_x, F_z	Cutting force

Fig. 9 Cutting model for analysis.

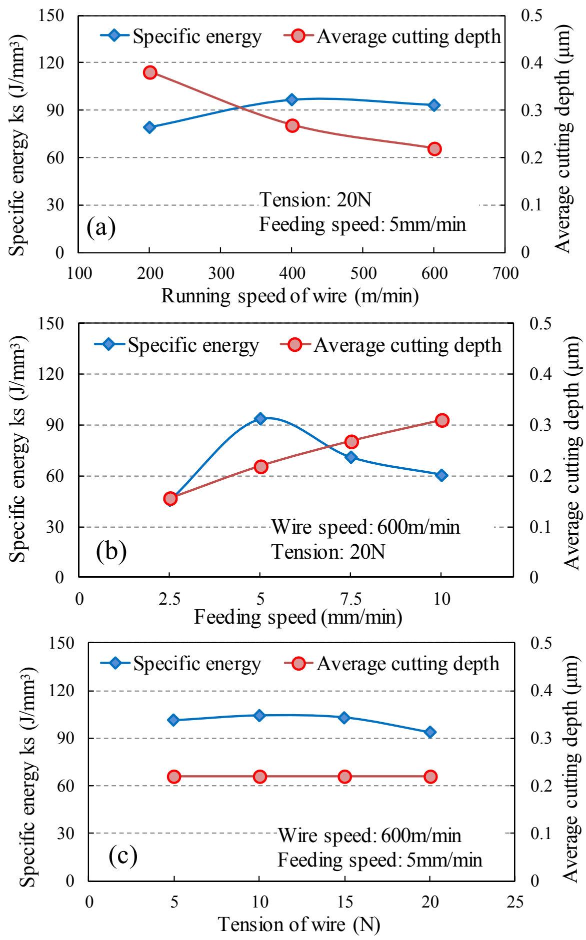
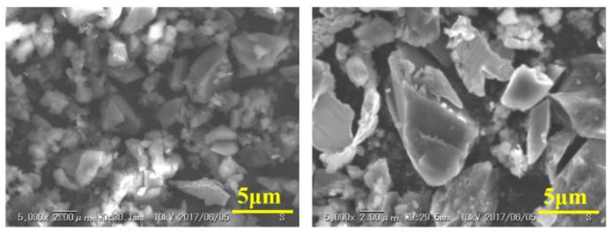


Fig. 10 Effect of cutting conditions on specific energy and average cutting depth of abrasives.

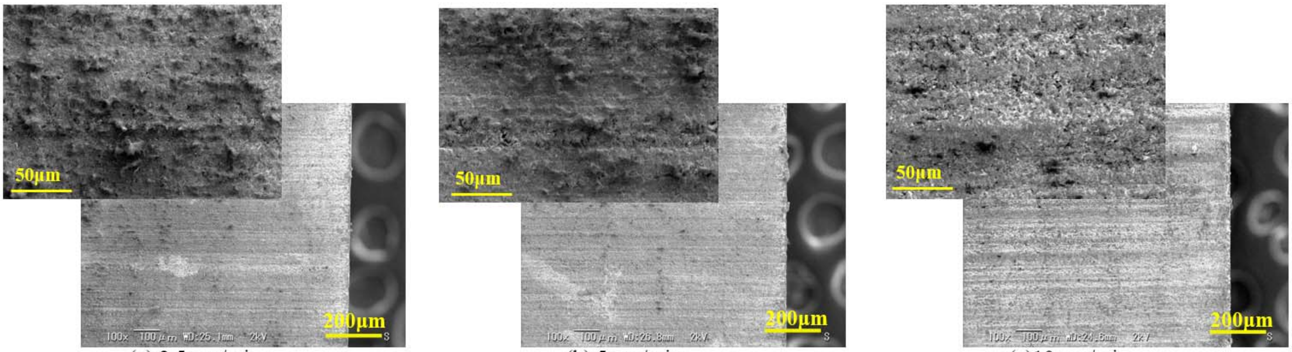
the wire speed. The average cutting depth of the abrasive decreases and the specific cutting energy increases as the wire speed increases. The CFRP material can be removed effectively by the abrasive at low wire speeds. The relationship between the specific cutting energy and the feeding speed of the work-piece is shown in Fig. 10b. The average cutting depth of the abrasive increases linearly with the feeding speed, while the specific cutting energy shows a peak at a feeding speed of 5 mm/min. We suspect that the mechanism of machining carbon fiber composites is different depending on the average cutting depth. At shallow average cutting depths (less than approximately 0.25 μm), the carbon fibers are worn away by the abrasives. However, at higher average cutting depths, the fibers are crushed by the abrasives, and this "crush energy" is advantageous in cutting the fibers and leads to a low specific cutting energy. The specific cutting energy and the average cutting depth of abrasives show no appreciable variation, due to the tension of diamond wire, as shown in Fig. 10c. In other words, the tension of diamond wire has a negligible effect on cutting characteristics.

The SEM micrographs of swarf generated at different feeding speeds are shown in Fig. 11. A large piece of swarf cut at a high feeding speed can be seen in Fig. 11b. Swarf size tends to increase with increasing feeding speed. The surface states of the CFRP board machined by the diamond wire are shown



(a) 2.5mm/min (b) 10mm/min

Fig. 11 Observation of swarf.



(a) 2.5mm/min (b) 5mm/min (c)10mm/min

Fig. 12 Observation of cut surface state.

in Fig. 12. No burrs and lamination are observed. Therefore, we conclude that the diamond wire saw is suitable for the high-quality machining of CFRP boards. The surface roughness of cut surface was measured by a contact type surface roughness meter. It was confirmed that the value of surface roughness tends to increase with increasing the feeding speed.

5. Conclusions

Experiments utilizing a diamond wire saw to cut CFRP boards are presented in this study. The influences of the cutting parameters on the cutting forces and the cutting quality were investigated. The following results are obtained.

The deflection of diamond wire is proportional to a normal cutting force. The bending stiffness of diamond wire is affected by the axis distance of work rollers and the wire tension.

CFRP board can be cut by diamond wires at high cutting speeds to achieve superior cutting quality.

The average cutting depth of the abrasives increases as the wire speed decreases and the feeding speed of workpiece increases. The material removal behavior changes to the average cutting depth of abrasives.

The specific cutting energy trends change depending upon the wire speed, feeding speed.

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