

EFFECT OF ULTRASONIC TORSIONAL MODE VIBRATION CUTTING ON DRILLING IN CFRP LAMINATES

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INTRODUCTION

Wide spread applications of composite material have been significantly growing in aerospace, naval, space and automotive industries. Especially, CFRP (carbon fiber reinforced plastics) laminates have a higher strength/weight ratio (about ten times larger tensile strength than advanced aluminum alloy in spite of about one half specific gravity) and high heat resistance. Therefore, recently most of wing, tail assembly and body of aircraft have been manufactured by assembling several parts made of CFRP laminates. Bolting and riveting are currently the preferred methods for fastening composite skins to the metal or other composite parts in assembly of aerospace and automotive composite structures [1]. Namely, drilling of CFRP laminates is indispensable for manufacturing aircraft and automotive composite structure and the quality of drilled holes strongly affects the fatigue strength of the structure besides the reliability of aircraft.

The particular objective of the present work was to conduct drilling experiments of CFRP laminates in order to investigate the cutting mechanism and the effects of ultrasonic torsional mode vibration cutting. Experimental work was performed to characterize major hole quality parameter and cutting mechanism encountered when drilling CFRP laminates and also to examine specific drilling assisted by ultrasonic torsional mode vibration. Inner surface texture of drilled hole, hole diameter and tool life were investigated and discussed by comparing the results of

conventional drilling with those of specific drilling assisted by ultrasonic torsional mode vibration [2].

EXPERIMENTAL SETUP AND PROCEDURE

Material Systems

CFRP was made from combining carbon fiber clusters with epoxy-resin matrix, to create a strong, high temperature composite. The CFRP laminates were made of 11 plies of CFRP oriented as follows: (0° , 90° , 0° , 90° , 0° , 90° , 0° , 90° , 0° , 90° , 0°), and both the upper and the lower two plies are thinner than mid 7 plies. The workpiece shown in Fig.1 was consolidated from laminates of one oriented carbon fiber prepreg using the autoclave method.

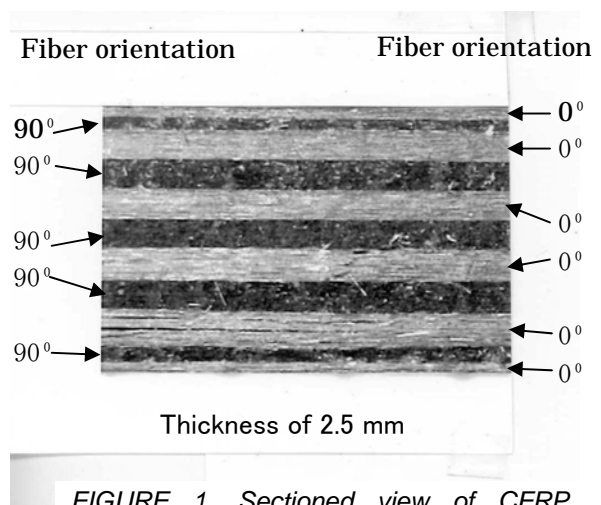


FIGURE 1. Sectioned view of CFRP laminates.

Drilling Experimental Method and Procedure

Drilling experimental setup assisted by ultrasonic torsional mode vibration consists of vibration unit, oscillation unit and display unit as shown in Fig. 2. The taper shank of vibration unit is attached rigidly to the main spindle of CNC milling machine. The electric control signal from oscillation unit oscillates torsionally at 27 kHz the twist drill attached to vibration unit, which are rotating as one body with the main spindle of the milling machine.

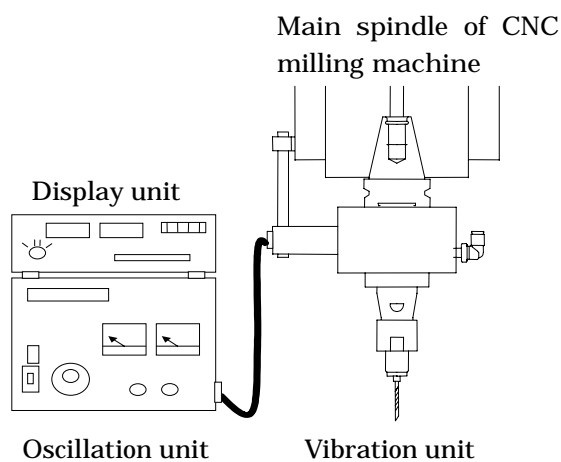


FIGURE 2. Schematic drilling experimental setup assisted by ultrasonic torsional mode vibration.

Display unit expresses resonant frequency, tip amplitude of twist drill constantly, and supplied voltage, ampere and electric power selectively during running of the drilling system.

Coated cemented carbide fiber drills of 3 mm diameter, which have a pair of special cutting edge shown in Fig.3, were used for all experiments. As shown in Fig.3, thinning is applied to the chisel edge but margin does not exist being different from a conventional twist drill. The summary of experimental conditions for CFRP laminates is listed in Table 1.

RESULTS AND DISCUSSION

Cutting Mechanism

The variation of relative angle between fiber orientation and cutting direction is shown in

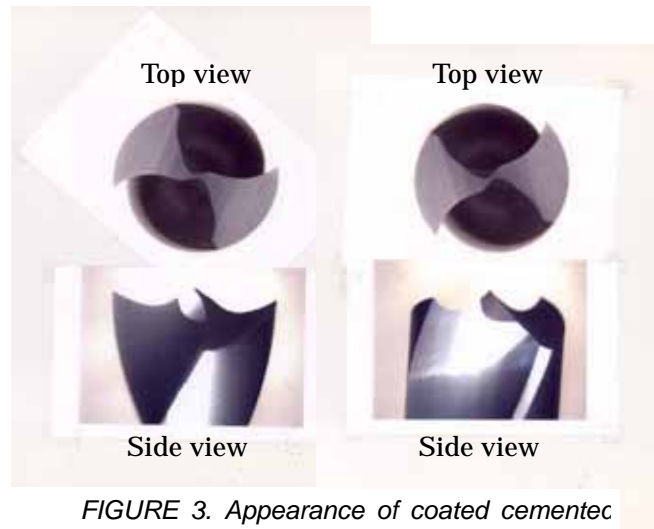


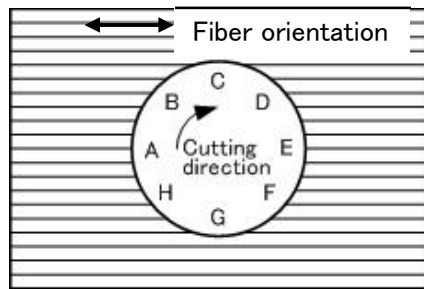
FIGURE 3. Appearance of coated cemented carbide fiber drill used.

TABLE 1. The summary of experimental conditions for CFRP laminates.

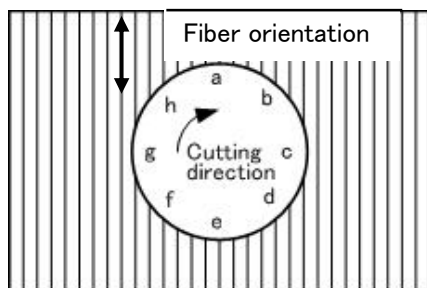
Drilling of CFRP laminates	
Machine tool	Vertical milling machine with CNC control
Workpiece material / Shape	CFRP laminates of 11 plies / Plate of 2.5mm thickness
Tools / Diameter / Length	Coated cemented carbide fiber drill / 3mm in diameter / 36mm in length
Drilling conditions (Dry cutting)	Rotational speed 1480rpm (Cutting speed 13.9m/min) Feed 0.04 mm/rev (Feed rate 59.2 mm/min)
Ultrasonic torsional mode vibration cutting	Frequency 27 kHz Amplitude 12.5 μ m Max. vibrational speed 127 m/min Max. power 50 W

Fig.4(a)(b). (a) and (b) in Fig. 4 show the ply of fiber orientation 0° and 90° respectively. In these figures, the relative angle at A, E in (a) and a, e in (b) is 90° , and the angle at C, G and c, g is 0° , and the angle at B, F and b, f is -45° , and the angle at D, H and d, h is $+45^\circ$ respectively.

Inner surface textures, which are measured



(a) Ply of fiber orientation 0°



(b) Ply of fiber orientation 90°

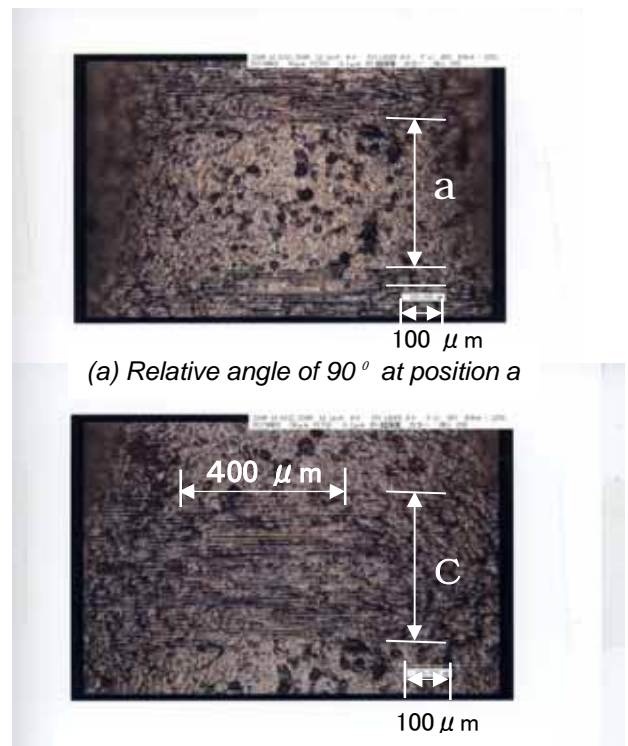
FIGURE 4. Relative angle between fiber orientation and cutting direction.

using a laser beam scanning microscope, at relative angle of 90° , 0° and $\pm 45^\circ$ are shown in Fig.5(a)(b)(c). (a) at relative angle of 90° shows the almost smooth surface but several dark dots like a circle are found. On the other hand, (b) at relative angle of 0° shows the scratched traces of about $400\mu\text{m}$ width, which would be caused by rubbing of cutting edges. In (c) at relative angle of $\pm 45^\circ$, two dark areas are seen at D of the angle $+45^\circ$. From more detailed observations it is confirmed that the dark areas form the craters of $50\sim 70\mu\text{m}$ depth.

Hole Quality Assessment

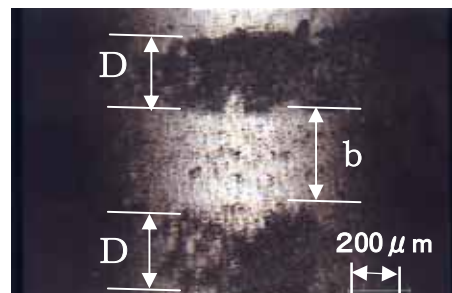
As applicable CFRP laminates, hole quality consists of material integrity, hole diameter and roundness, inner surface texture, and hole exit damage of drilled holes. The present work focuses the subject on inner surface texture, hole diameter and tool life.

Effects of Ultrasonic Torsional Mode Vibration Cutting on Inner Surface Texture



(a) Relative angle of 90° at position a

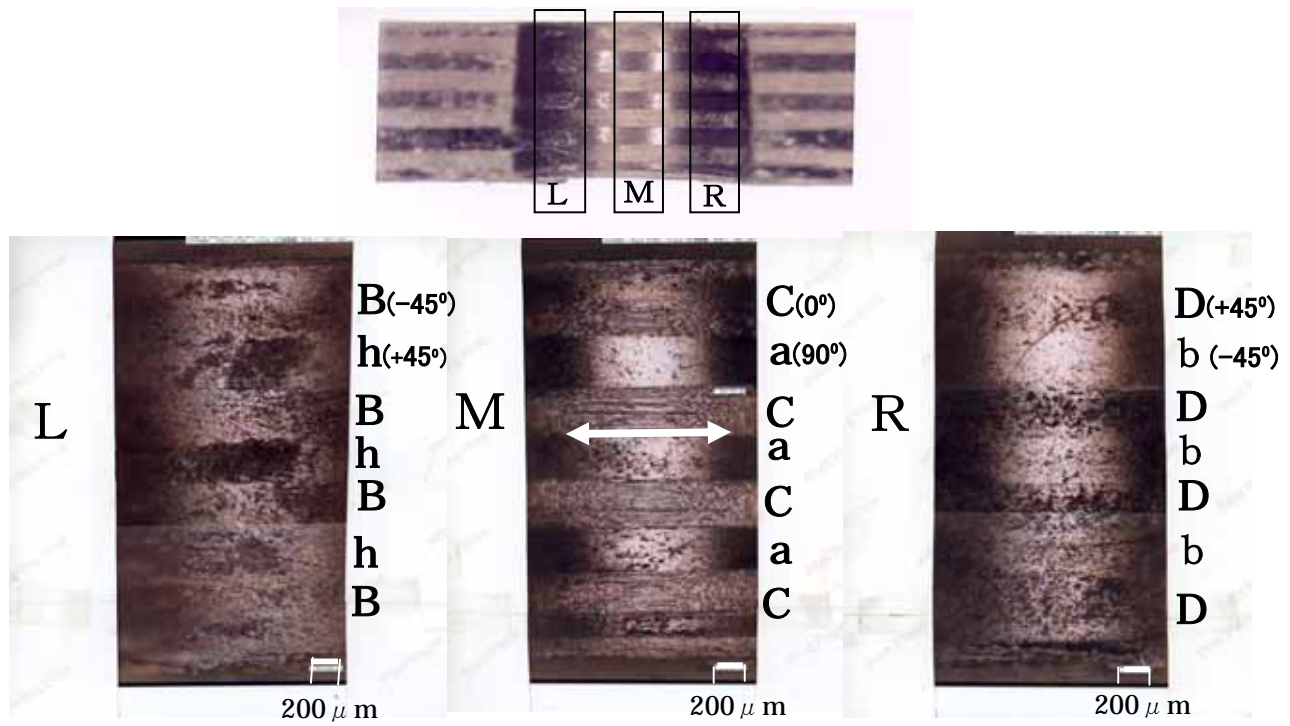
(b) Relative angle of 0° at position C



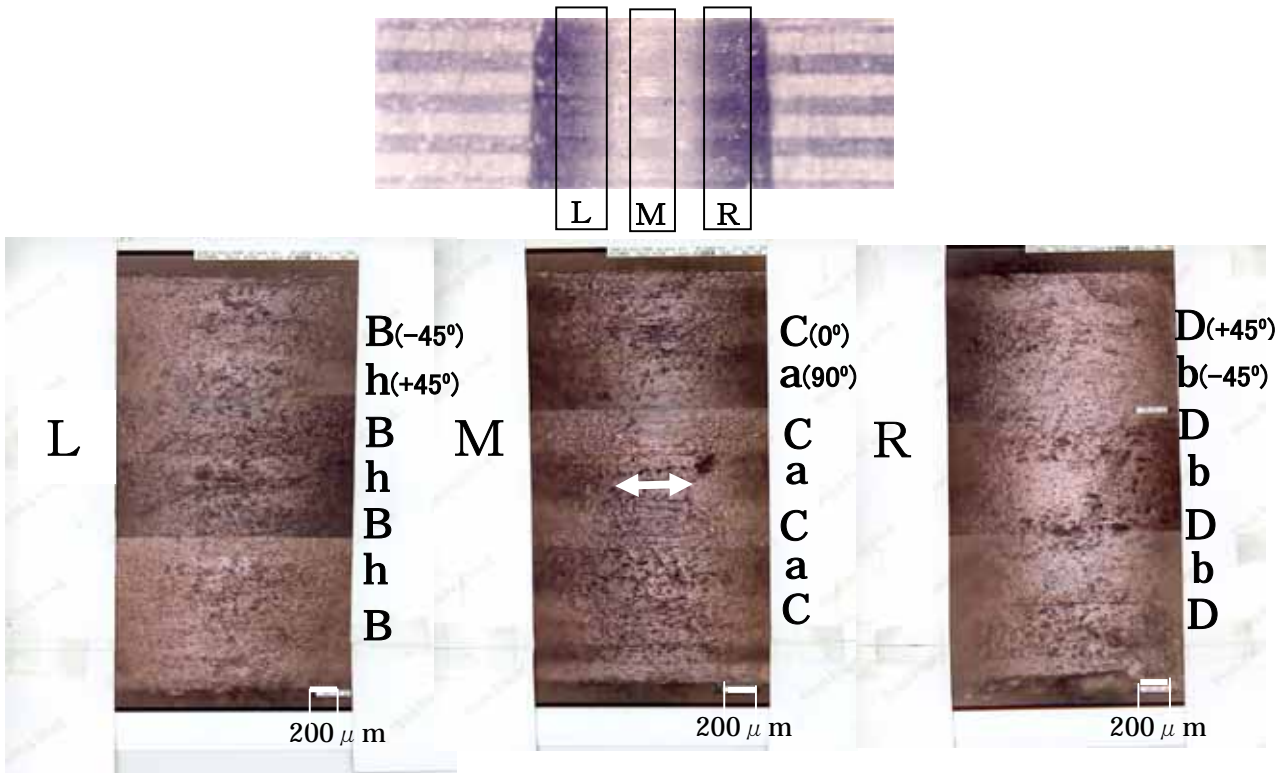
(c) Relative angle of $+45^\circ$ at position D and -45° at position b.

FIGURE 5. Inner surface texture at relative angle of 90° , 0° and $\pm 45^\circ$.

To examine the effect of ultrasonic torsional mode vibration cutting on the inner surface texture of drilled hole, the texture was observed using a laser beam scanning microscope after being cut at the center of hole with an abrasive water jet cutting. Figure 6 (a) and (b) show the inner surface texture of half hole at 19th hole by conventional drilling and that by specific drilling assisted by ultrasonic torsional mode vibration respectively. In Fig. 6 (a), at only position of h and D of the



(a) 19th hole by conventional drilling



(b) 19th hole assisted by ultrasonic torsional mode vibration

FIGURE 6. Comparison between inner surface texture of 19th hole by conventional drilling and that assisted by ultrasonic torsional mode vibration.

relative angle of $+45^\circ$, the dark areas are found remarkably. From the similar observations for the inner surface opposite half hole to that in Fig. 6(a) the dark areas are found at the position of d and H. Based on the more detailed observations using a laser beam scanning microscope, the fact that the dark areas form shallow craters of $50 \sim 70 \mu\text{m}$ depth is ascertained. However, in Fig. 6(b) assisted by ultrasonic torsional mode vibration, they are not found scarcely at the same positions of h and D.

The occurrence of the shallow craters at only the relative angle of $+45^\circ$ for conventional drilling is considered as follows. Comparing the surface texture at the position C of relative angle 0° in Fig. 9(a) with the same that in Fig. 9(b), the width of scratched traces of cutting edges is clearly different. Namely, in Fig. 9(b) assisted by ultrasonic torsional mode vibration, because instantaneous cutting is repeated 27000 times during one second, the ability for cutting edge to cut carbon fiber cluster would be significantly improved. As a result the width of scratched traces caused by rubbing of cutting edges against carbon fiber cluster and epoxy-resin is narrowed as shown by the white arrow \Leftrightarrow in the Figures M of Fig. 9(a) and (b). Since shortening the rubbing duration contributes to decrease heat generation by friction, the temperature increase of cutting edges, carbon fiber cluster and epoxy-resin is restrained. As shown in Table 2, the thermal conductivity of epoxy-resin is much smaller than carbon fiber and also the carbon fiber cluster has better thermal conductivity in the fiber

TABLE 2. Comparison of coefficient of thermal conductivity.

Material	Coefficient of thermal conductivity [cal/cm·s·°C]
Carbon fiber	5.7×10^{-2}
Epoxy-resin	$4 \sim 5 \times 10^{-4}$

orientation than that in other direction. Therefore, during conventional drilling the heat generated by rubbing at position C is conducted to the following position D through carbon fiber cluster and the temperature of position D will be risen. It is well-known that epoxy-resin becomes brittle at the temperature over about 180°C of glass transition temperature.

From the above-mentioned consideration, it is revealed that the heat generation by rubbing and the characteristics of thermal conductivity of carbon fiber and epoxy-resin would be the prime cause of shallow crater's generation at the positions h, D, d and H of the relative angle $+45^\circ$.

Figure 7 (a) and (b) show the relationship between number of crater, which are found on the inner surface of half hole, and number of machined hole, and (a) is the relationship during

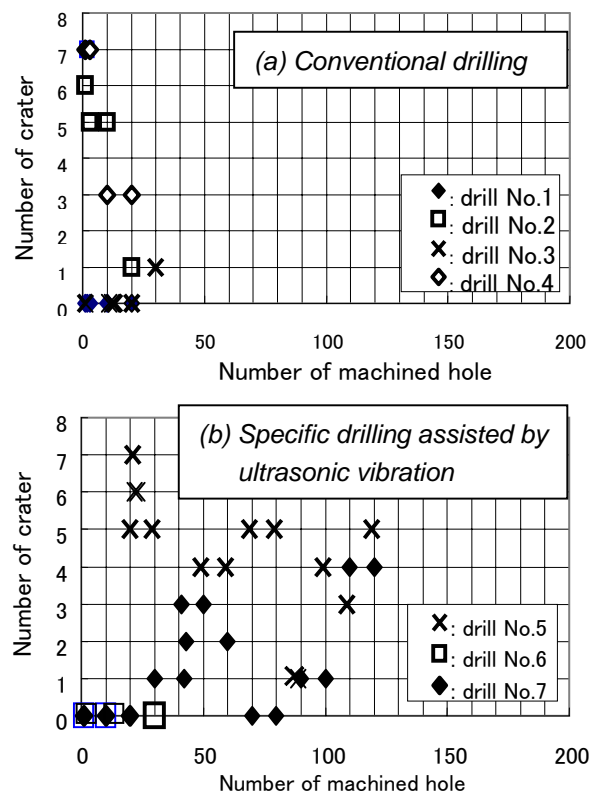


FIGURE 7. Relationship between number of crater on half hole and number of machined hole.

conventional drilling and (b) is that during specific drilling assisted by ultrasonic torsional mode vibration, respectively. From (a) and (b) in Fig. 7, the crater was generated from first hole during conventional drilling, nevertheless it was found after 30th hole during specific drilling assisted by ultrasonic torsional mode vibration.

Effect of Ultrasonic Torsional Mode Vibration Cutting on Hole Diameter

Figure 8 shows the relationship between deviation of hole diameter from 3 mm and number of machined hole. As shown in Fig. 8, it is seen that scattering of deviation of hole diameter from 3 mm can be reduced from 16 μm to 8 μm by assist of ultrasonic torsional mode vibration. The large scattering of hole diameter during conventional drilling would be induced by the occurrence of crater on the inner surface of hole.

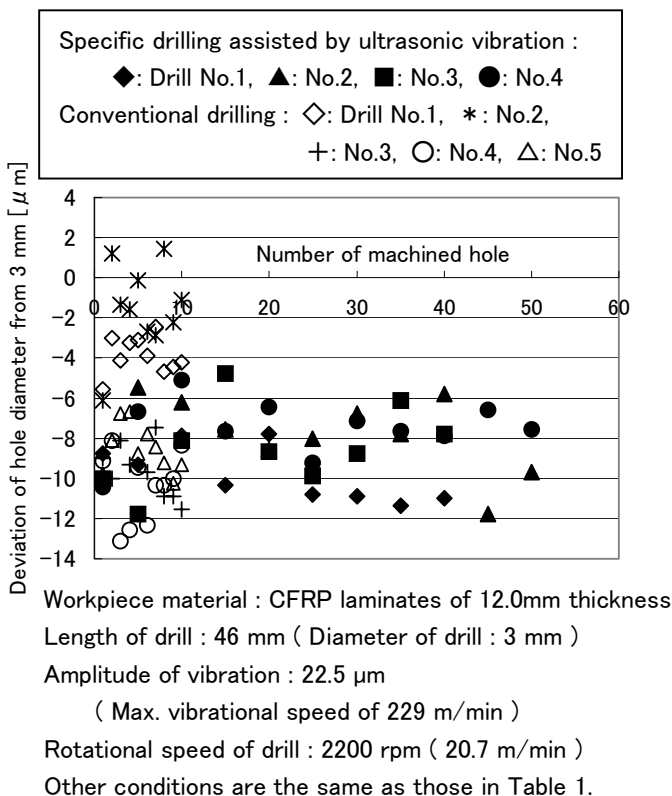


FIGURE 8. Relationship between deviation of hole diameter and number of machined hole.

Effect of Ultrasonic Torsional Mode Vibration Cutting on Tool Life

Based on the criteria of tool life when the wear width of circumferential cutting edge reaches to 0.07mm, effect of ultrasonic torsional mode vibration cutting on tool life of drill was examined. Since tool life is affected by the occurrence of micro-chipping, drilling tests were executed five times in conventional drilling and also in specific one assisted by ultrasonic torsional mode vibration respectively. As shown in Fig. 9, the assist of

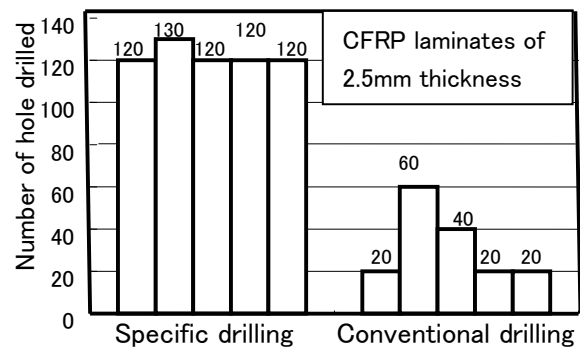


FIGURE 9. Comparison of tool life between conventional drilling and specific one.

ultrasonic torsional mode vibration to drilling CFRP laminates is significantly effective to extend the tool life of cemented carbide fiber drill. It can be understood thoroughly that the extension of tool life is caused by temperature increase being restrained at cutting edge due to decrease of rubbing duration between cutting edge and carbon fiber cluster.

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- [2] Yagishita H. Cutting Mechanism of Drilling CFRP Laminates and Effect of Ultrasonic Torsional Mode Vibration Cutting. Transactions of the North American Manufacturing Research Institution of SME. 2006; 34: 213-220.