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Rotary Ultrasonic Machining of CFRP: A Comparison with Twist Drilling

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Keywords:

Carbon fiber reinforced plastic composite, Cutting force, Rotary ultrasonic machining, Surface roughness, Tool wear, Twist drilling.

Abstract:

Drilling is involved in many applications of carbon fiber reinforced plastic (CFRP) composite. Twist drilling is widely used in industry. Rotary ultrasonic machining (RUM) has been successfully tested to drill holes in CFRP. However, there are no reports on comparisons between RUM and twist drilling of CFRP. This paper compares RUM and twist drilling of CFRP in six aspects (cutting force, torque, surface roughness, delamination, tool life, and material remove rate). Experimental results show that RUM is superior in almost all these aspects.

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1. Introduction

Many applications of carbon fiber reinforced plastic CFRP composite require drilling of holes [Enemuoh et al., 2001; Tsao and Hocheng, 2005; Sprow, 1987; Chung, 2010; Gay et al., 2003]. Twist drilling and its derivate methods are widely used to produce holes in composites [Ramulu et al. 2001; Tsao and Hocheng, 2005a; Tsao and Hocheng, 2004; Campos Rubio et al., 2008; Davim and Reis, 2003b]. These methods have such shortcomings as short tool life and poor hole quality [Wong et al. 1982]. Since holes are often drilled in finished products, part rejections due to poor hole quality are very costly [Tsao and Hocheng, 2005b, Abrate and Walton, 1992].

Rotary ultrasonic machining (RUM) has been used in drilling of CFRP [Li et al., 2007, Cong et al., 2011]. RUM is a hybrid machining process that combines material removal mechanisms of diamond grinding and ultrasonic machining. Figure 1(a) illustrates the RUM process. The cutting tool is a core drill with metal-bonded diamond abrasives. During drilling, the rotating tool vibrates axially at an ultrasonic frequency and moves along its axial direction towards the workpiece. Coolant pumped through the core of the drill washes away the swarf and prevents the tool from jamming and overheating. The literature does not have any reports on comparisons between RUM and twist drilling of CFRP. Such comparisons will be useful when deciding which process should be selected to drill holes in CFRP. This paper compares RUM and twist drilling (as illustrated in Figure 1(b)) of CFRP in six aspects (cutting force, torque, surface roughness, delamination, tool life, and material removal rate).

There are four sections in this paper. Following this introduction section, Section 2 describes experimental conditions and measurement procedures. Section 3 presents and discusses experimental results. Finally, Section 4 provides conclusions.

2. Experimental conditions and measurement procedures

2.1 Properties of workpiece material

The CFRP workpiece was composed of carbon fibers and epoxy resin. Plain woven fabric of carbon fibers had an orientation of 0/90 degrees, as illustrated in Figure 2. The carbon fiber yarn in the woven fabric had a thickness of 0.2 mm and a width of 2.5 mm. The workpiece contained 42 layers of carbon fibers. The size of workpiece was 200 mm × 150 mm × 16 mm. Workpiece material properties are listed in Table 1.

2.2 Experimental set-up

Twist drilling was performed on a machining center (Model VF-E, Haas Automation Inc., Oxnard, CA, USA). RUM was performed on a rotary ultrasonic machine (Series 10, Sonic-Mill, Albuquerque, New Mexico, USA). The RUM experimental set-up is schematically illustrated in Figure 3. It consisted of an ultrasonic spindle system, a data acquisition system, and a cooling system. The ultrasonic spindle system was mainly comprised of an ultrasonic spindle, a power supply, and a motor speed controller. The power supply converted (60 Hz) electrical supply to high-frequency (20 kHz) AC output. This high frequency electrical energy was provided to a piezoelectric converter (located inside the ultrasonic spindle) that converted electrical energy into mechanical vibration. The ultrasonic vibration from the converter was amplified and transmitted to the rotary tool attached to the spindle. The amplitude of ultrasonic vibration was adjusted by changing the setting of output control of the power supply. The motor attached atop the ultrasonic spindle supplied the rotational motion of the tool and different speeds were obtained by adjusting the motor speed controller. The cooling system was comprised of pump, coolant tank, pressure regulator, flow rate and pressure gauges, and valves. The cooling system provided coolant to the spindle and the interface of machining.

High speed steel twist drills (Kennametal Inc., Latrobe, PA, USA) were used in twist drilling experiments of this study. High speed steel twist drills were used in numerous reported studies on drilling CFRP [Chen, 1997; Ramulu et al., 2001; Davim and Reis, 2003; Zhang et al., 2003; Hocheng and Tsao, 2003; 2006; Kim and Ramulu, 2004; Wang et al., 2004; Tsao and Hocheng, 2004; 2005b; 2007], and would serve well as the base for comparison with RUM. A metal-bonded diamond core drill (NBR Diamond tool corp., LaGrangeville, NY, USA), as illustrated in Figure 4, was used in RUM experiments. Table 2 contains more information on tool parameters.

2.3 Experimental conditions

Based on experience from preliminary experiments and due to the limitations of the experimental set-ups (for example, vibration frequency was fixed at 20 kHz on the RUM machine and maximum tool rotation speed on the machining center was 4000 rpm), only two machining variables (tool rotation speed and feedrate) were changed when comparing RUM and twist drilling. Their values are shown in Table 3. Four holes were drilled under each machining condition.

2.4 Measurement procedures for output variables

A dynamometer (Model 9272, Kistler Inc., Switzerland) was used to measure the cutting force in the axial direction and torque. The electrical signals from the dynamometer were amplified by a charge amplifier (Model 5070A, Kistler Inc., Switzerland) and then transformed into digital signals by an A/D converter. After being processed by a signal conditioner, the digital signals were collected by a data acquisition card (PC-CARD-DAS16/16, Measurement Computing Corporation, Norton, MA, USA) on a computer with the help of Dynoware software

(Type 2815A, Kistler Inc., Switzerland). The sampling rate was 20 Hz.

The measured cutting force fluctuated with time within a certain range. Figure 5 shows a typical curve of measured cutting force versus time. The maximum cutting force (Fz) on each force curve was used to represent the cutting force for drilling of each hole. Similarly, the maximum torque on the torque curve was used for drilling of each hole.

Surface roughness was measured on the surface of each machined hole. A surface profilometer (Surftest-402, Mitutoyo Corporation, Kanagawa, Japan) was used with the tested range being set at 4 mm and the cut-off length being set at 0.8 mm. The surface roughness reported in this paper was Ra (average surface roughness). As shown in Figure 6, roughness was measured at a location near the hole entrence and along the axial direction of the hole. Four measurements were performed with 90° between two adjacent measurements. Each measurement was repeated twice. So for each hole, there were eight Ra values. The average of these eight values was used as the Ra value for each hole.

Delamination was observed sometimes on the hole drilled in composite materials. Delamination factor [Tsao and Hocheng, 2004] was used to describe the degree of delamination. It was determined by D_d/D. Figure 7 illustrates both D_d and D. D is the hole diameter. D_d is the diameter of the smallest circle that encloses all the delamination area around the hole. D_d and D were measured by a vernier caliper (model IP-65, Mitutoyo Corp., Kanagawa, Japan).

Material removal rate (MRR) was calculated as the volume of material removed divided by machining time. It can be expressed by following equations:

$$\mathrm{MRR} = \frac{\pi \cdot [(D/2)^2 - (D_\mathrm{r}/2)^2] \cdot h}{T} \qquad \text{(for RUM)} \tag{1}$$

$$\mathrm{MRR} = \frac{\pi \cdot (D/2)^2 \cdot h}{T} \qquad \text{(for twsit drilling)} \tag{2}$$

where, D is the diameter of machined hole, h is the thickness of workpiece, T is the time it takes to drill the hole, and D_r is the diameter of machined rod (only applicable to RUM). Figure 8 illustrates the machined hole and rod in RUM. D_r was also measured by a vernier caliper (model IP-65, Mitutoyo Corp., Kanagawa, Japan).

3. Experimental results

3.1 Cutting force

Figure 9 shows a comparison of cutting force between RUM and twist drilling when tool rotation speed changed. In Figure 9 (as well as Figures 10 − 16), the data points are the average values from four holes drilled under the same condition. Error bars represent the maximum and minimum values from all four holes. For both RUM and twist drilling, cutting force decreased with the increase of tool rotation speed. However, cutting forces in RUM were much lower. When tool rotation speed was 2000 rpm, cutting force in twist drilling was nearly five times of that in RUM. The change of cutting force in RUM was very small when tool rotation speed increased from 1000 to 5000 rpm.

Figure 10 shows a comparison of cutting force between RUM and twist drilling when feedrate changed. At all levels of feedrate, cutting forces in twist drilling were much higher than those in RUM. With the increase of feedrate, cutting force increased for both RUM and twist drilling. However, when feedrate increased from 0.1 to 0.8 mm/s, the change of cutting force in RUM was very small, less than 100 N. In contrast, the change of cutting force in twist drilling was much larger.

3.2 Torque

Figure 11 shows a comparison of torque between RUM and twist drilling when tool rotation speed changed. When tool rotation speed increased, torque in both RUM and twist drilling decreased. Torques in twist drilling were larger than those in RUM when tool rotation speeds were 2000, 3000, and 4000 rpm. Tool rotation speed had larger effects on torque in twist drilling than in RUM. In RUM, the change of torque was very small (about 0.2 N·m) when tool rotation speed increased from 1000 to 5000 rpm. In twist drilling, the change of torque was 0.6 N·m when tool rotation speed increased from 2000 to 4000 rpm.

Figure 12 shows a comparison of torque between RUM and twist drilling when feedrate changed. With the increase of feedrate, torque increased in both RUM and twist drilling. At all levels of feedrate, torques in twist drilling were larger than those in RUM. When feedrate increased from 0.1 to 0.7 mm/s, torque in twist drilling increased almost linearly from 0.6 to 1.0 N·m. In contrast, the change of torque in RUM was only 0.2 N·m when feedrate changed from 0.1 to 0.8 mm/s.

3.3 Surface roughness

A comparison of surface roughness between RUM and twist drilling when tool rotation speed changed is shown in Figure 13. Surface roughness in twist drilling was higher than that in RUM. When tool rotation speed increased, surface roughness decreased in both RUM and twist drilling, but the change of surface roughness in RUM was smaller.

A comparison of surface roughness between RUM and twist drilling when feedrate changed is shown in Figure 14. In both RUM and twist drilling, surface roughness of drilled holes increased with the increase of feedrate. However, the magnitudes of changes were different. In twist drilling, surface roughness increased remarkably with the increase of feedrate. In contrast, surface roughness in RUM increased moderately. At all levels of feedrate, surface roughness in twist drilling was higher than that in RUM.

3.4 Delamination

No delamination could be observed in RUM of CFRP under all the conditions tested.

The change of delamination in twist drilling when tool rotation speed changed is shown in Figure 15. When tool rotation speed changed from 2000 to 3000 rpm, delamination factor decreased from about 1.4 to 1.3. However, delamination factor did not change much with further increase of tool rotation speed (from 3000 to 4000 rpm).

The change of delamination in twist drilling when feedrate changed is shown in Figure 16. When feedrate changed from 0.1 to 0.7 mm/s, delamination factor increased almost linearly from about 1.2 to 1.4.

3.5 Tool life

Figure 17 shows pictures of a brand new tool and a used tool in RUM. It can be seen that the used tool was shorter than the new one. The used tool had been used to drill more than 200 holes and its abrasive portion decreased by 0.9 mm in length. At this wear rate, one tool with 7 mm length of abrasive portion can drill more than 1400 holes.

Figure 18 shows pictures of a brand new tool and a used tool in twist drilling. Cutting edges of the twist drill were worn out after drilling only five holes.

3.6 Material removal rate (MRR)

Figure 19 shows a comparison of MRR between RUM and twist drilling when tool rotation speed changed. It can be seen that tool rotation speed had no effects on MRR. At all levels of tool rotation speed, MRR remained constant for both RUM and twist drilling. However, MRR in twist drilling was higher than that in RUM.

A comparison of MRR between RUM and twist drilling when feedrate changed is shown in Figure 20. In both RUM and twist drilling, MRR increased linearly with the increase of feedrate. However, the rates of increasing were not the same. When feedrate changed from 0.1 to 0.7 mm/s, MRR in twist drilling increased by 18 mm^3/s (from 3 to 21 mm^3/s), but MRR in RUM increased by only 3.5 mm^3/s. In addition, the values of MRR in twist drilling were higher than those in RUM. This is because the machined rod was not included when calculating MRR in RUM. It is noted that holes with the same diameter (9.6 mm) were produced in both RUM and twist drilling, although MRR values were very different. However, if the rod is included in its calculation, MRR in RUM will be the same as that in twist drilling.

4. Conclusions

This paper reported a comparison study on twist drilling and rotary ultrasonic machining RUM of CFRP. Cutting force, torque, surface roughness, delamination, tool life, and material removal rate were compared. The following conclusions are drawn from this study:

(a) Cutting force and torque in twist drilling were higher than those in RUM.

(b) Surface roughness in twist drilling was higher than that in RUM.

(c) The holes machined by RUM did not show any delamination. In twist drilling, delamination decreased as tool rotation speed increased or feedrate decreased.

(d) Tool life in RUM was much longer than in twist drilling. A new RUM tool could drill more than 1400 holes while a new twist drill could drill only five holes before wearing out.

(e) Twist drilling had higher material removal rate than RUM under the same conditions when holes with the same diameter were produced.

RUM is a diamond grinding process assisted with ultrasonic vibration. Since the cutting tool is metal-bonded diamond abrasives, it is much more effective in machining CFRP, especially the carbon fiber inside CFRP. Therefore, in comparison with twist drilling of CFRP (for the same size hole within and the same duration of time), RUM has lower cutting force and torque, better surface roughness, no delamination, and longer tool life.

Acknowledgements

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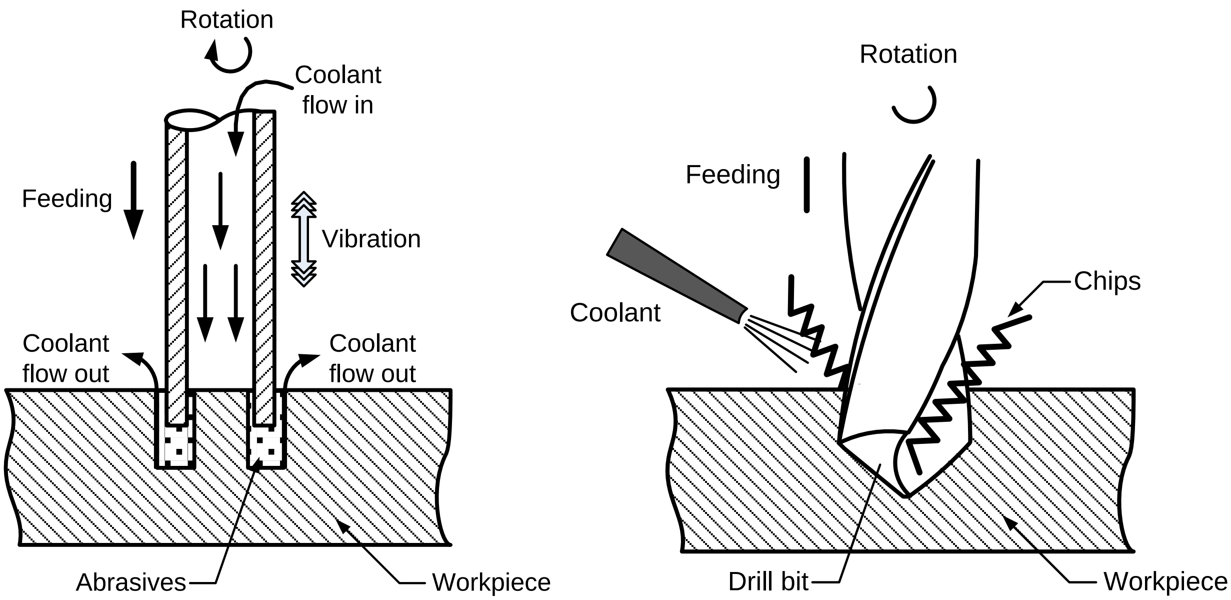

(a) Rotary ultrasonic machining (b) Twist drilling

Figure 1 Illustration of two CFRP drilling processes.

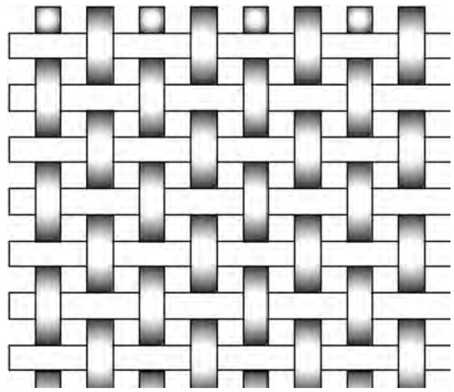

Figure 2 Illustration of woven fabric in CFRP.

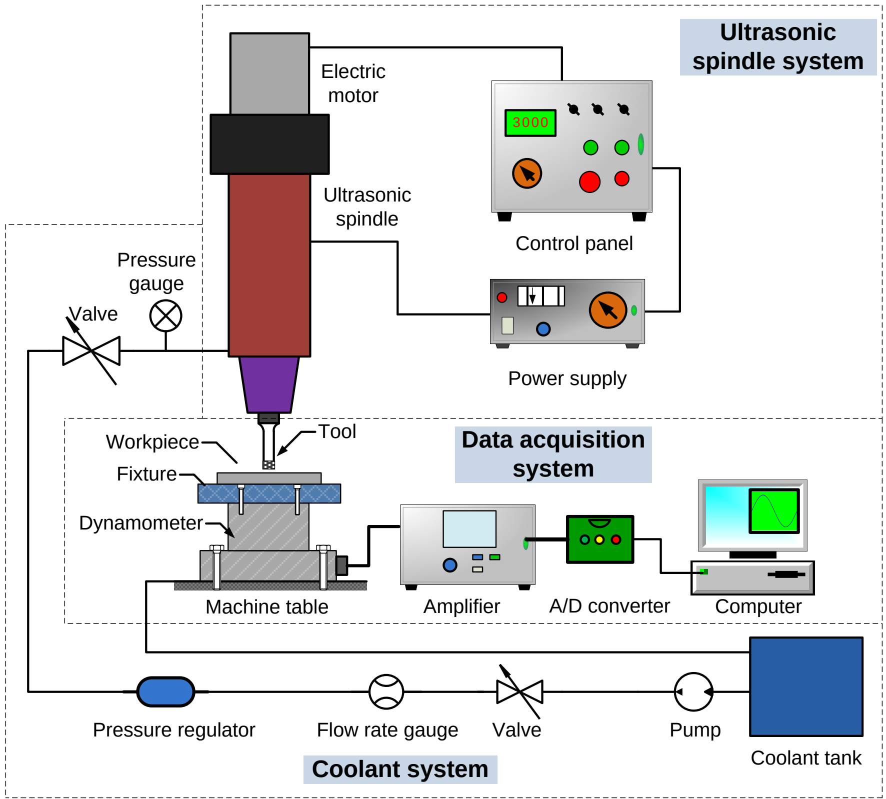

Figure 3 RUM experimental set-up.

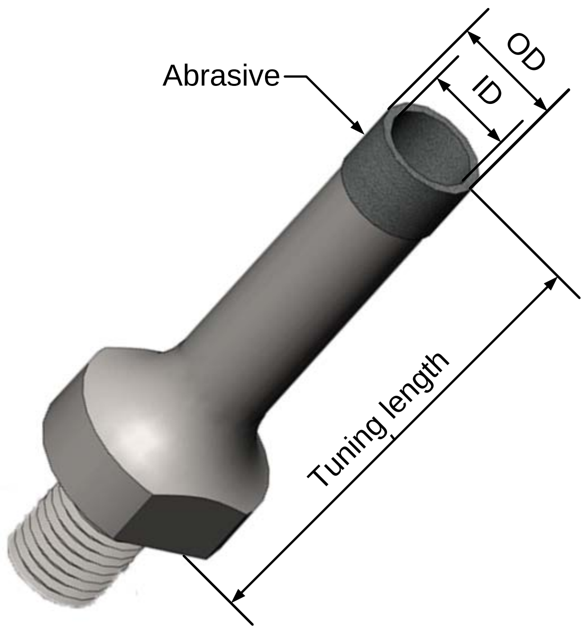

Figure 4 Illustration of RUM tool.

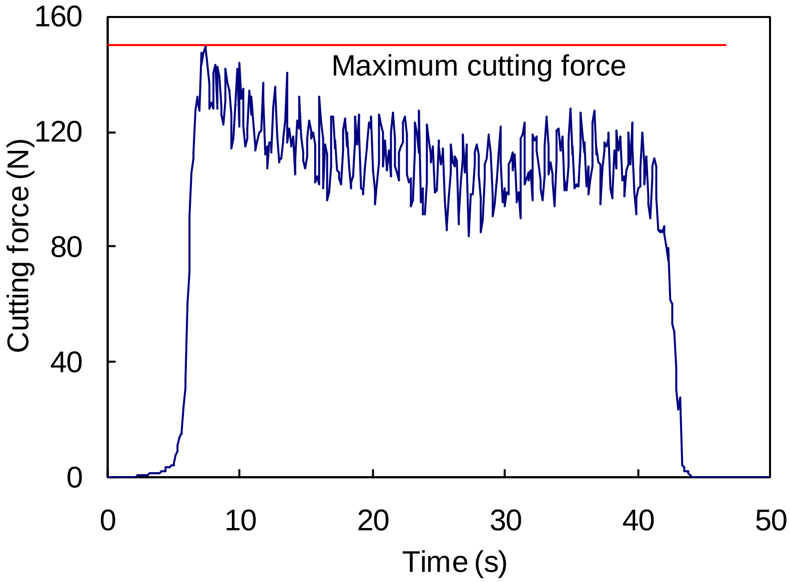

Figure 5 Typical relationship between cutting force and time (in RUM).

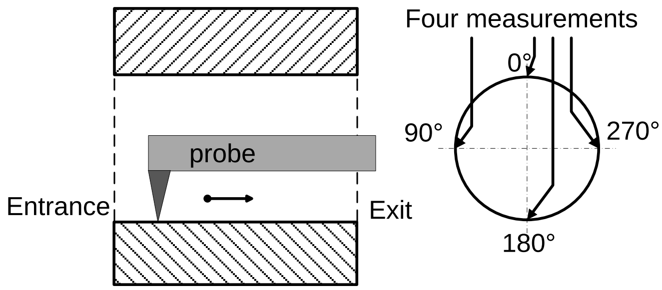

Figure 6 Illustration of surface roughness measurement.

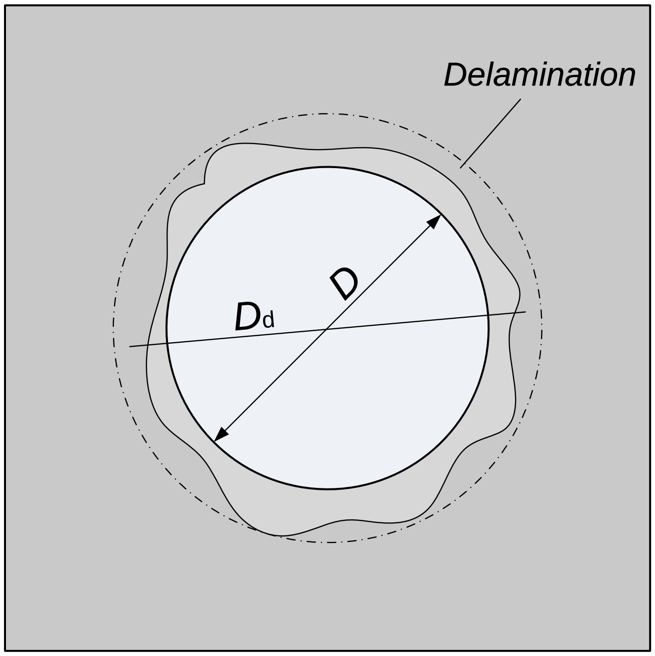

Figure 7 Measurement of delamination factor.

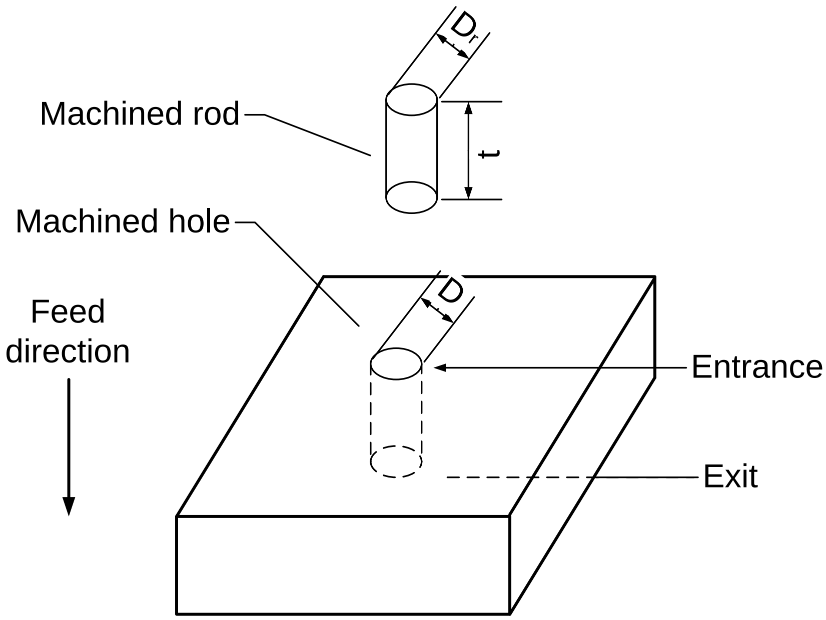

Figure 8 Illustration of the hole and rod machined by rotary ultrasonic machining.

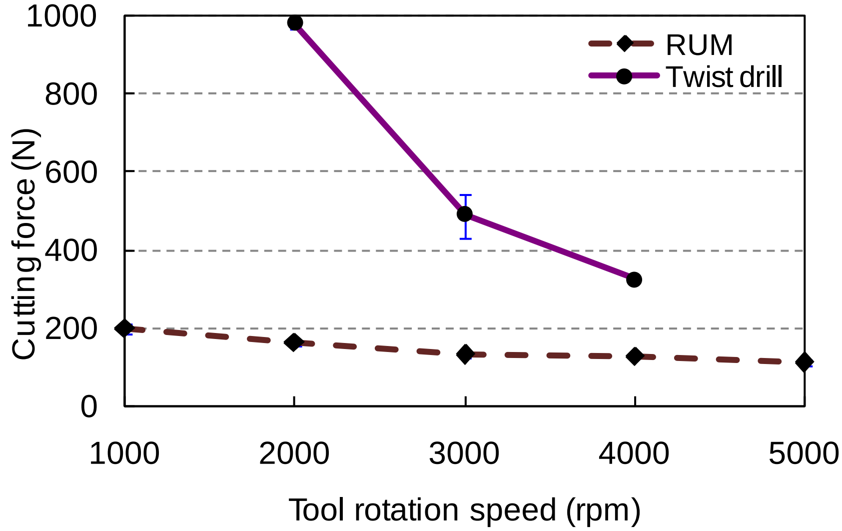

Figure 9 Cutting force comparison between RUM and twist drilling when tool rotation speed changed.

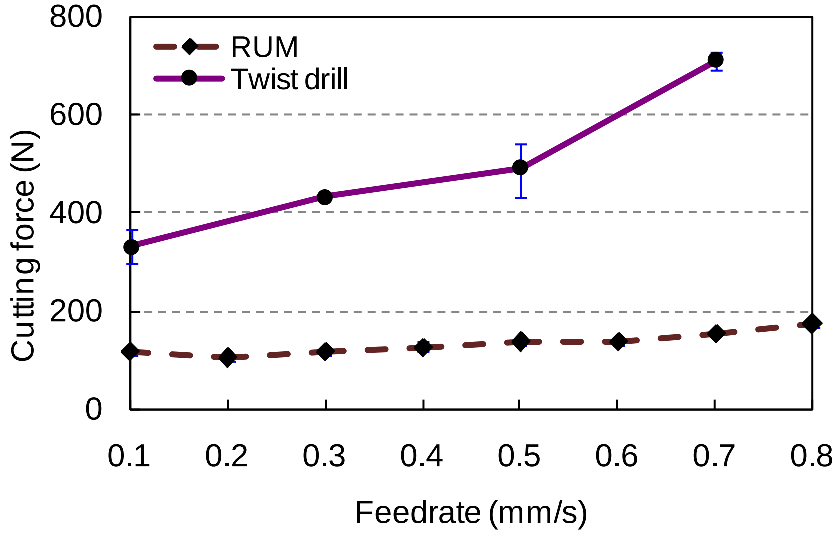

Figure 10 Cutting force comparison between RUM and twist drilling when feedrate changed.

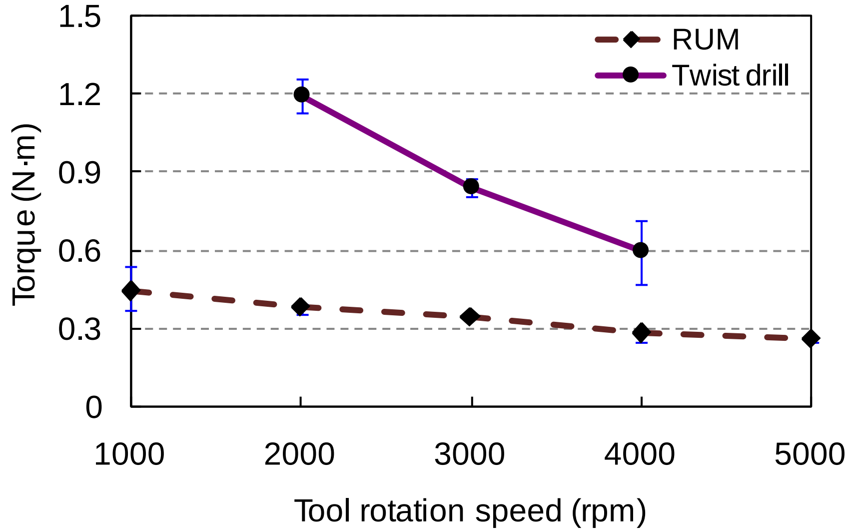

Figure 11 Torque comparison between RUM and twist drilling when tool rotation speed changed.

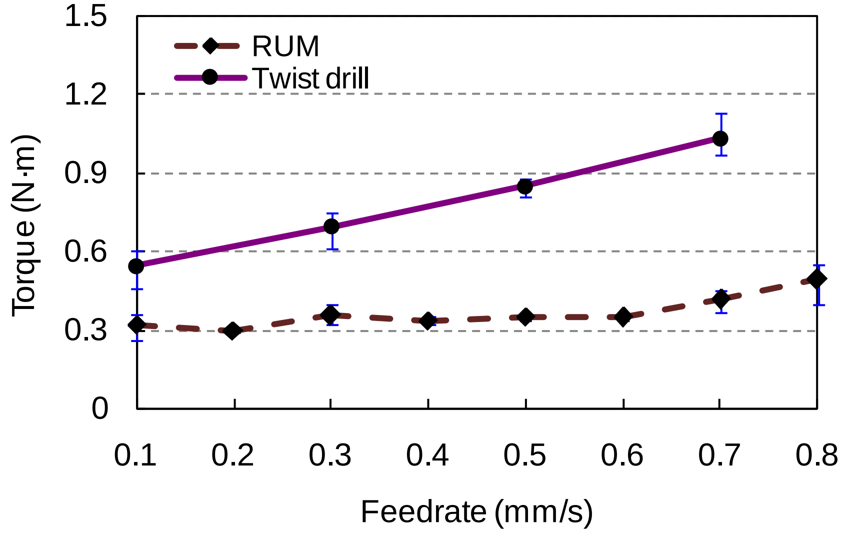

Figure 12 Torque comparison between RUM and twist drilling when feedrate changed.

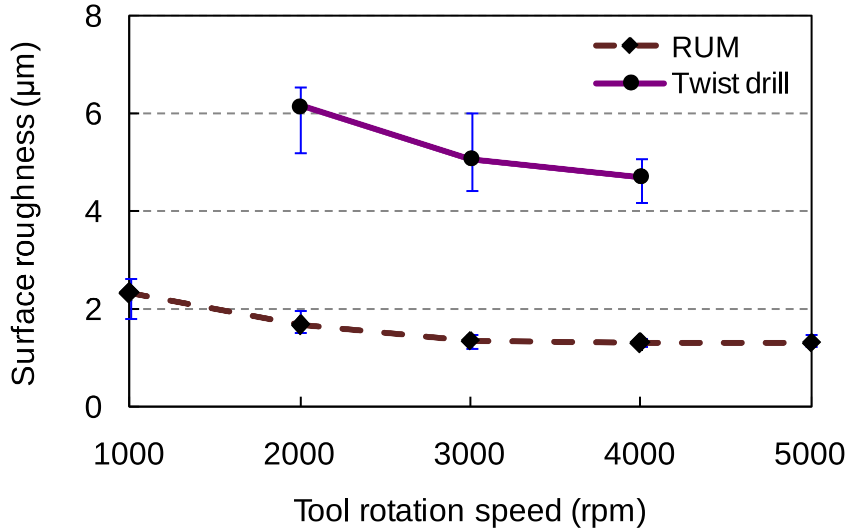

Figure 13 Surface roughness comparison between RUM and twist drilling when tool rotation speed changed.

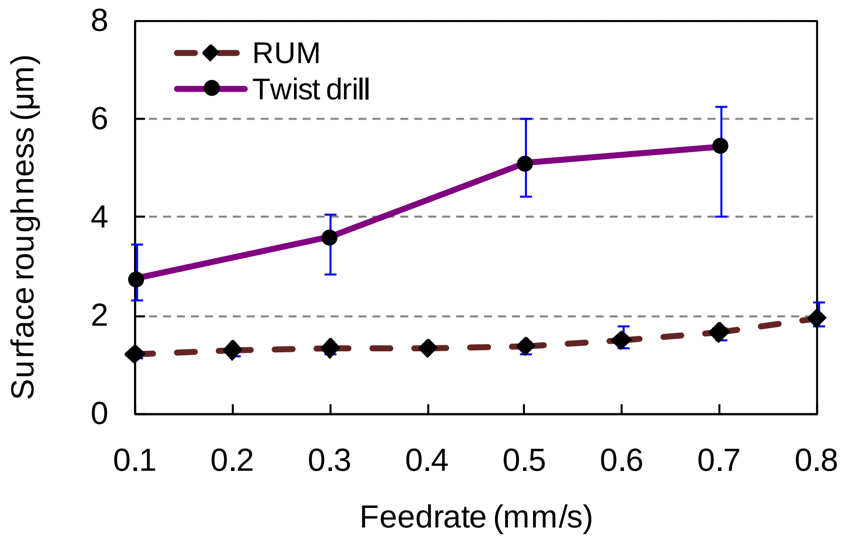

Figure 14 Surface roughness comparison between RUM and twist drilling when feedrate changed.

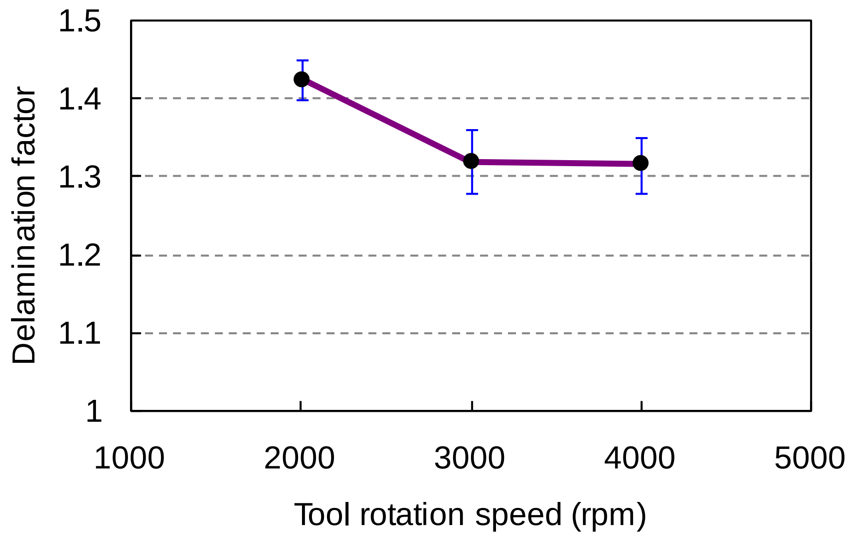

Figure 15 Effects of tool rotation speed on delamination factor in twist drilling.

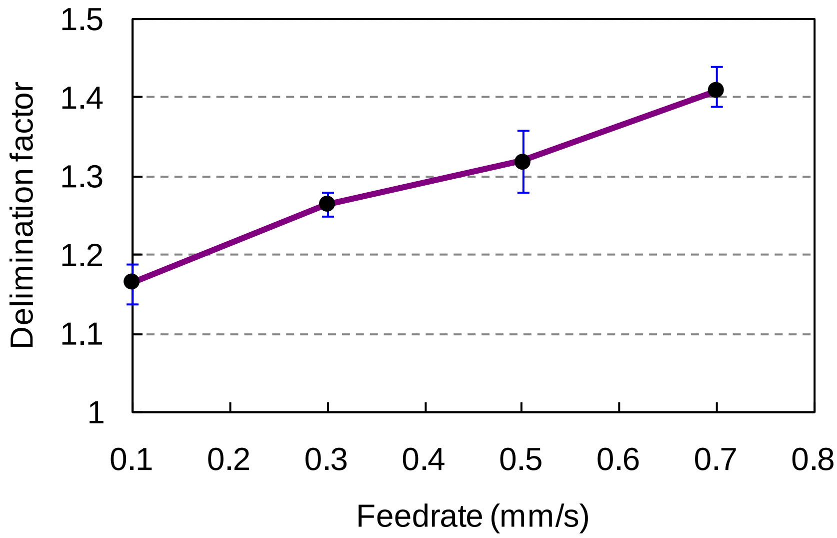

Figure 16 Effects of feedrate on delamination factor in twist drilling.

Figure 17 A new RUM tool and a used RUM tool after drilling more than 200 holes.

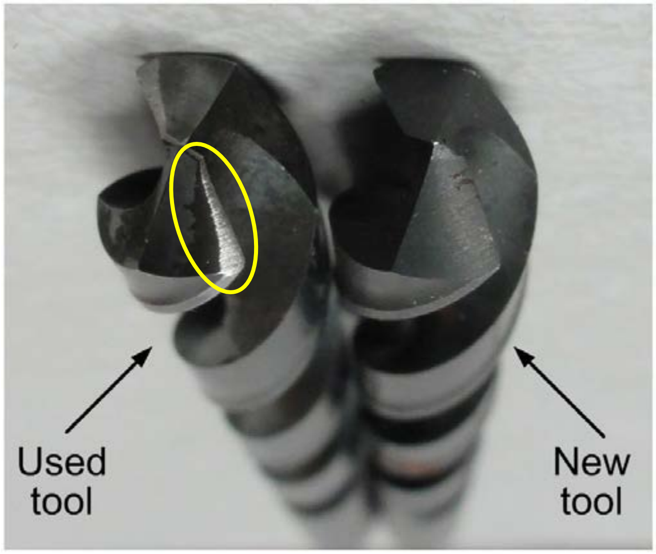

Figure 18 A new twist drill and a used twist drill after drilling five holes.

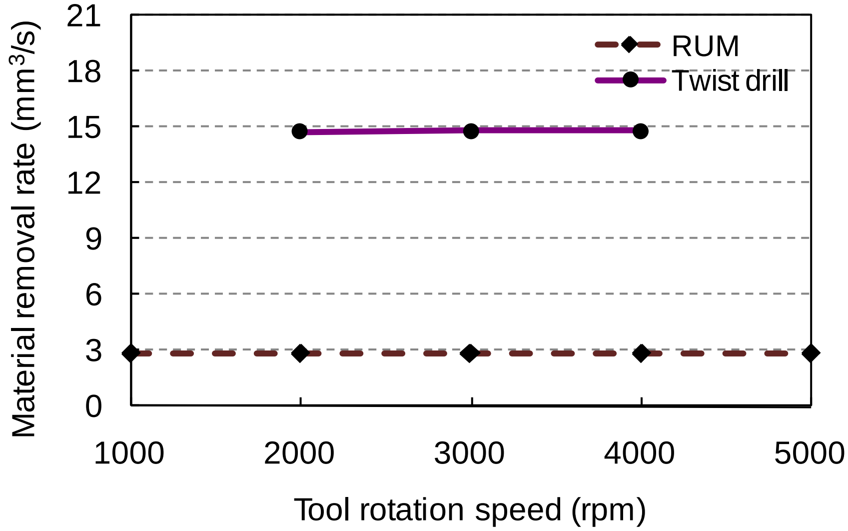

Figure 19 Material removal rate comparison between RUM and twist drilling when tool rotation speed changed.

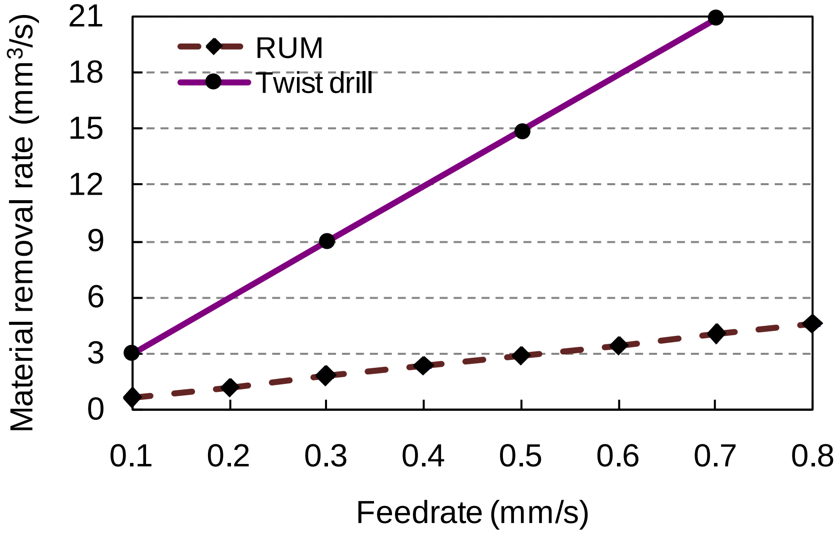

Figure 20 Material removal rate comparison between RUM and twist drilling when feedrate changed.

Table 1 Properties of workpiece material.

Property	Unit	Value
Density	kg/m^3	155
Hardness (Rockwell)	HRB	70-75
Elastic modulus of epoxy matrix	GPa	2.06 - 2.15
Tensile strength of epoxy matrix	MPa	80 - 85
Elastic modulus of carbon fiber	GPa	75 - 80
Tensile strength of carbon fiber	MPa	400 - 450

Table 2 Tool parameters.

Parameter	RUM tool	Twist drill
Outer diameter (mm)	9.6	9.6
Inner diameter (mm)	7.8	N/A
Tuning length/Tool length (mm)	44.5	127
Tool material	Diamond	High speed steel
Grit size (mesh #)	60/80	N/A
Grain concentration	100	N/A
Number of slots	0	N/A
Bond type	B	N/A
Point angle (°)	N/A	135

Table 3 Machining conditions.

Feedrate (mm/s)	Tool rotation speed (RPM)	RUM	Twist drilling
0.1	3000	√	√
0.2	3000	√	
0.3	3000	√	√
0.4	3000	√	
0.5	1000	√	
0.5	2000	√	√
0.5	3000	√	√
0.5	4000	√	√
0.5	5000	√	
0.6	3000	√	
0.7	3000	√	√
0.8	3000	√	