

EXPERIMENTAL STUDY ON ROTARY ULTRASONIC MACHINING OF GRAPHITE/EPOXY PANEL

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ABSTRACT

Rotary ultrasonic machining (RUM) is introduced into drilling holes on graphite/epoxy (GREP) panels for the first time. The feasibility to machine GREP using RUM is investigated. Effects of RUM process parameters (ultrasonic vibration, feedrate, and spindle speed) on cutting force, MRR, and hole entrance/exit edge quality are also presented.

INTRODUCTION

Graphite/epoxy (GREP) composites are utilized in aerospace and automotive industries due to their high strength and lightweight [1-4]. For example, GREP composites have been used increasingly in aircraft components like rudders, vertical tail fin skins, and horizontal stabilizer skins, etc. [1-2]. One of the challenging technical issues for GREP is the damage problems (such as delamination and fiber pull-out etc.) resulted from machining [3-4].

Several papers have reported studies on machining of GREP. Ramulu and Arola [4] and Colligan et al. [5] investigated the surface integrity in water jet and abrasive water jet cutting of GREP. Wang et al. [6] and Kohkoner et al. [7] studied cutting and milling of GREP respectively using tungsten carbide and polycrystalline inserts. Ludin [8] investigated trimming of GREP using Nd:YAG laser. Shanmugam et al. [9] conducted a comparative study of water abrasive jet machining over laser machining for GREP. Lau et al. [10] proposed machining of GREP by electrical discharge machining (EDM). Sadat [11] employed finite element method (FEM) to investigate the delamination during drilling of GREP. However, water-jet machining at high cutting speeds produces delamination, laser machining produces thermal stress and a heat-affected

zone, and EDM requires conductive properties of the workpiece and produces surface damage and higher tool wear [3]. Therefore, there is a need to develop more cost-effective machining methods for GREP.

Among non-traditional machining processes, rotary ultrasonic machining (RUM) is a relatively low-cost, environment-benign process. In RUM, a rotating core drill with metal-bonded diamond abrasives is ultrasonically vibrated in the axial direction and fed towards the workpiece. Coolant pumped through the core of the drill washes away the swarf, prevents jamming of the drill, and keeps it cool. This process is illustrated in FIGURE 1.

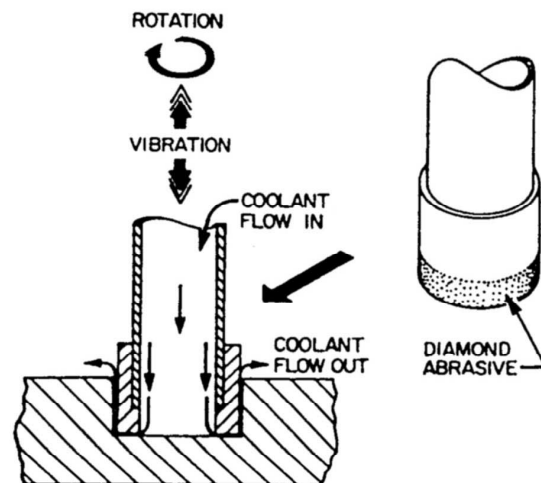


FIGURE 1. Illustration of RUM process.

RUM has been employed to machine many types of materials [12-20]. However, no reports have been published on RUM of GREP. In this paper, the viability of RUM on GREP is studied for the first time. Effects of RUM process parameters (ultrasonic vibration, feedrate, and

spindle speed) on cutting force, MRR, and hole entrance/exit quality are also investigated.

EXPERIMENTAL DETAILS

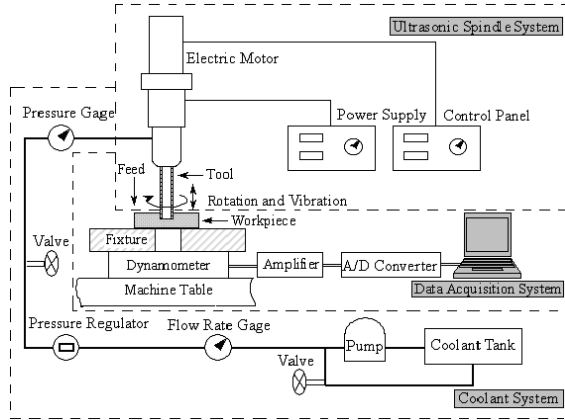


FIGURE 2. Illustration of experimental setup.

The experimental setup is schematically illustrated in FIGURE 2. It mainly consists of an ultrasonic spindle system, a data acquisition system, and a coolant system. RUM tests are performed on an ultrasonic machine of Sonic Mill Series 10 (Sonic-mill®, Albuquerque, NM, USA). Diamond core drills (N.B.R. Diamond Tool Corp., LaGrangeville, NY, USA) are used to drill the GREP panel (Provided by The Boeing Com., Everett, WA, USA). The drills have outer and inner diameters of 9.54 mm and 7.82 mm respectively, and consist of metal-bonded diamond grains of mesh size from 80 to 100. Mobilemet® S122 water-soluble cutting oil (MSC Industrial Supply Co., Melville, NY, USA) diluted by water with the ratio of 1 to 20 is used as coolant.

Output variables are cutting force, material removal rate (MRR), and hole entrance/exit edge quality. The cutting force along the feedrate direction is measured by a KISTLER 9257 dynamometer (Kistler Instrument Corp, Amherst, NY, US). The dynamometer is mounted atop the machine table and beneath the workpiece to measure the cutting force, as shown in Fig. 2. MRR in the experiments is calculated using the following equation:

$$MRR = \frac{\pi \cdot [(D_{out}/2)^2 - (D_{in}/2)^2] \cdot d}{T}$$

where, D_{out} is the diameter of drilled hole, D_{in} the diameter of drilled rod, d workpiece thickness, and T the time it takes to drill the hole. The drilled hole entrance/exit edge quality is observed under a digital video microscope of Olympus DVM-1 (Olympus America Inc., Melville, NY, US). The process parameters are listed in Table 1.

TABLE 1. RUM process parameters.

Parameter	Value
Spindle speed (rpm)	3000; 4000; 5000; 6000
Feedrate ($\text{mm}\cdot\text{s}^{-1}$)	0.032; 0.04; 0.048; 0.056
Ultrasonic vibration frequency (KHz)	20
Ultrasonic vibration power* (%)	0; 35

*Ultrasonic vibration power controls the amplitude of ultrasonic vibration.

RESULTS AND DISCUSSION

Effects of Ultrasonic Vibration

Cutting Force

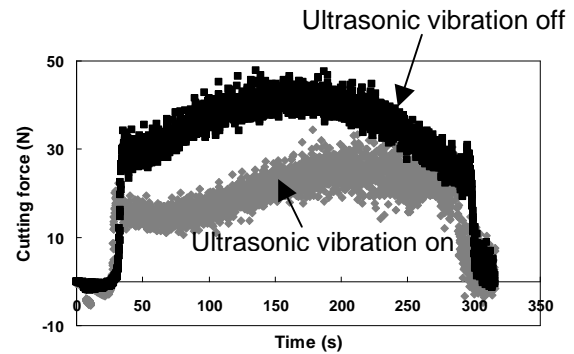
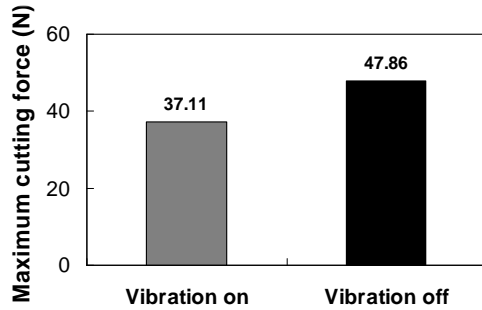
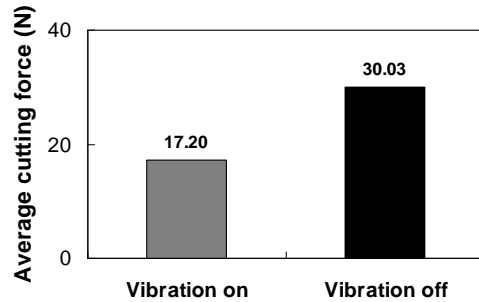


FIGURE 3. Effects of ultrasonic vibration on cutting force.

FIGURE 3 shows the effects of ultrasonic vibration on cutting force. Note that the RUM process becomes a core drilling process with the vibration off. It can be seen that the cutting force decreases significantly when the ultrasonic vibration is on. FIGURE 4 shows the comparisons of the maximum/average cutting force when the ultrasonic vibration is on and off. With the help of ultrasonic vibration, the maximum cutting force decreases about 23% while the average cutting force decreases about 43%.



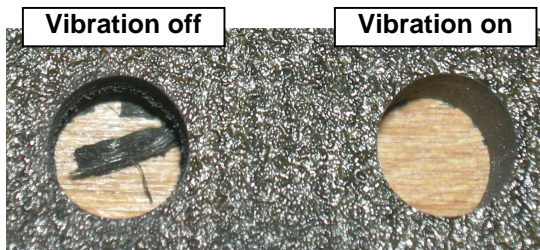
(a) Maximum cutting force



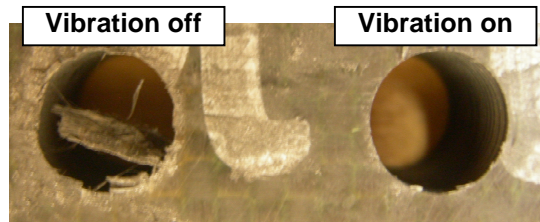
(b) Average cutting force

FIGURE 4. Effects of ultrasonic vibration on cutting force.

Hole Entrance/Exit Edge Quality



(a) Hole entrance side



(b) Hole exit side

FIGURE 5. Effects of ultrasonic vibration on hole entrance/exit edge quality.

FIGURE 5 shows the effects of ultrasonic vibration on hole entrance/exit edge quality. There are no delaminations around the hole entrance edges in either case, as shown in FIGURE 5(a). For the hole exit side, the edge quality of the hole drilled when the vibration is off is much worse than the hole drilled when the

vibration is on. There exist significant GREP delaminations and fiber pull-out around the exit edge for the hole drilled when ultrasonic vibration is off, as shown in FIGURE 5(b). It can be concluded that the hole exit edge quality can be improved significantly when the ultrasonic vibration is on.

Process Stability

It is also found that ultrasonic vibration has a great effect on the process stability during RUM of GREP. Fig. 6 shows the comparison of “wastes” drilled off from the GREP panel when the vibration is on or off. When the ultrasonic vibration is off, the tool is easy to be jammed by the GREP scraps, as shown in FIGURE 6. The jammed tool has to be taken apart from the machine. The drilling process is much more stable when the ultrasonic vibration is on. A whole GREP rod (or plug) can be achieved, as shown in FIGURE 6, and there is no tool jamming.

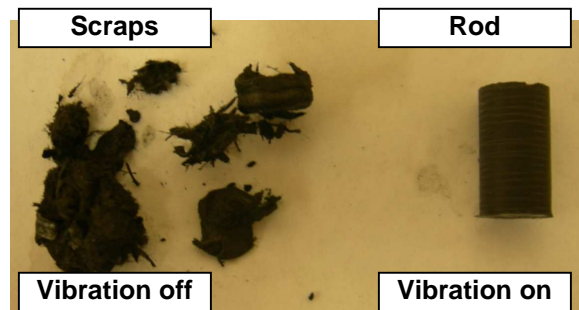
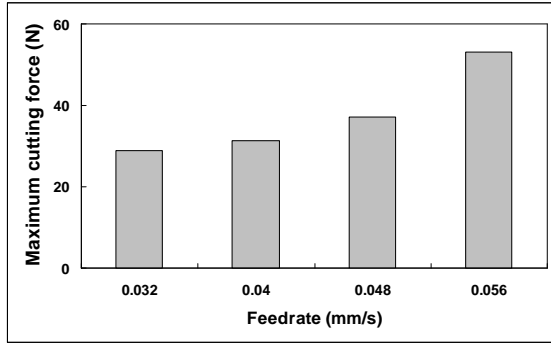


FIGURE 6. Effects of ultrasonic vibration on rod/scrap formation.

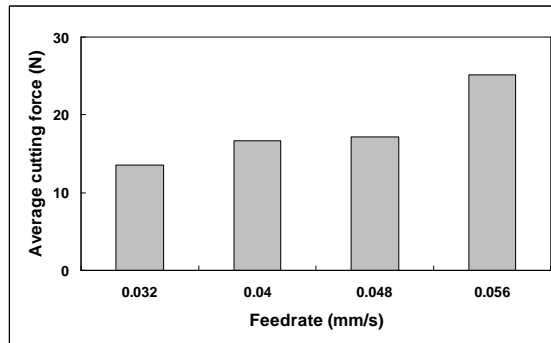
Effects of Feedrate

Cutting Force

FIGURE 7 shows the effects of feedrate on cutting force. As the feedrate increases from 0.032 mm/s to 0.056 mm/s, the maximum cutting force increases from 30 N to 55 N as shown in FIGURE 7(a) while the average cutting force increases from 13 N to 25 N.



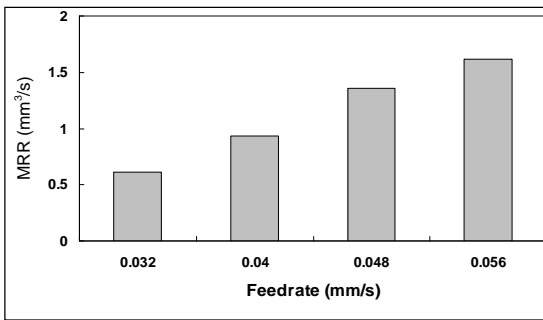
(a) Maximum cutting force



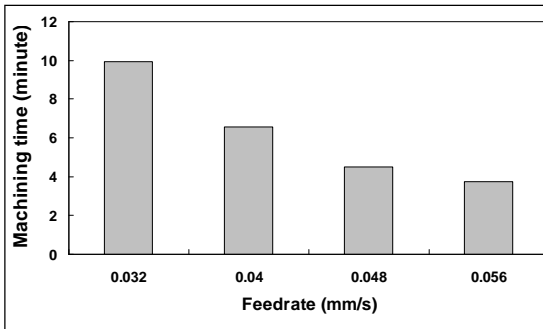
(b) Average cutting force

FIGURE 7. Effects of feedrate on cutting force.

MRR



(a) MRR



(b) Machining time

FIGURE 8. Effects of feedrate on MRR and machining time.

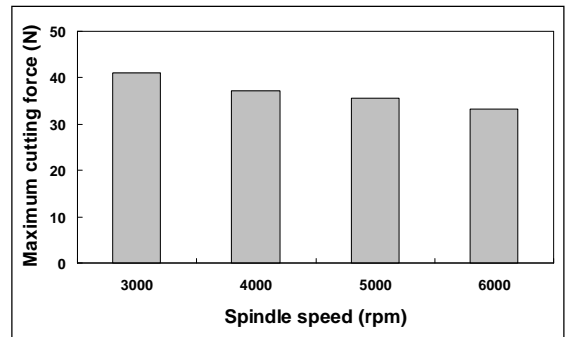
FIGURE 8 shows the effects of feedrate on MRR. As the feedrate increases from 0.032 mm/s to 0.056 mm/s, the MRR increases from 0.61 mm³/s to 1.62 mm³/s as shown in FIGURE 8(a) while the time it takes to drill through the GREP panel (the thickness of the panel is 14.11 mm) is reduced from ~10 mins to ~3.5 mins as shown in FIGURE 8(b).

Hole entrance/exit edge quality

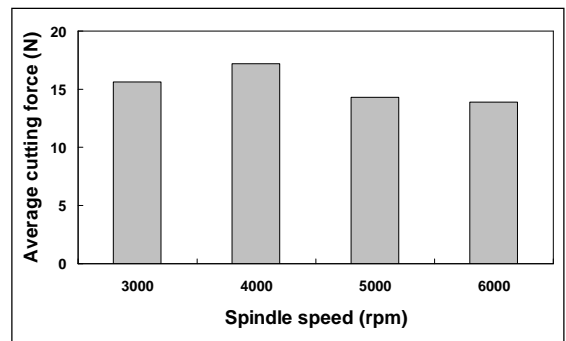
There are no significant delaminations and fiber pull-out around the hole entrances and exits as the feedrate increases.

Effects of Spindle Speed

As the spindle speed increases from 3000 rpm to 6000 rpm, the maximum cutting force shows a slight decrease as the spindle speed increases, as shown in FIGURE. 9(a). There are no significant changes in the average cutting force, as shown in FIGURE. 9(b). There are no observable delaminations and fibre pull-out around the hole entrances and exits.



(a) Maximum cutting force



(b) Average cutting force

FIGURE 9. Effects of spindle speed on cutting force.

CONCLUSIONS

In the present paper, rotary ultrasonic machining (RUM) is introduced into drilling GREP panels for the first time. The effects of RUM process parameters (ultrasonic vibration, feedrate, and spindle speed) on the RUM performances are also studied. The following conclusions can be drawn from the study:

- 1) The drilled hole exit edge quality can be improved significantly with the help of ultrasonic vibration. There are nearly no delaminations and fibre pull-out around the hole exit.
- 2) The drilling process when ultrasonic vibration is on is much more stable than that when ultrasonic vibration is off.
- 3) The cutting force decreases significantly when the ultrasonic vibration is on.
- 4) As the feedrate increases from 0.032 mm/s to 0.056 mm/s, the maximum/average cutting force increases significantly; the MRR increases from 0.61 mm³/s to 1.62 mm³/s while the time it takes to drill through the panel can be reduced from ~10 mins to ~3.5 mins.
- 5) The maximum cutting force decrease slightly as the spindle speed increases. The spindle speed does not affect the average cutting force and hole entrance/exit edge quality significantly.

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