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ROTARY ULTRASONIC MACHINING OF CARBON FIBER REINFORCED POLYMER: FEASIBILITY STUDY

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ABSTRACT

Carbon fiber-reinforced polymer (CFRP) has been widely used in aircraft components, automotive parts, and sporting goods. Hole machining is the most frequently employed operation of secondary machining for fiber-reinforced composites. However, challenges (delamination, splintering, burr, short tool life, low machining precision, and low surface quality) still remain for their widespread applications. Rotary ultrasonic machining (RUM) is a non-conventional machining process that has been used to drill holes in composite materials. However, it has not been used to drill this type of CFRP. In this article, RUM is introduced into drilling holes in this type of CFRP for the first time. The feasibility to machine carbon fiber-reinforced epoxy using RUM is investigated experimentally. Chips,

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edge chipping, surface roughness, tool wear, and thrust force were measured. Effects of RUM process variables (rotation speed, vibration amplitude, and feedrate) on thrust force and surface roughness were studied. Results showed that RUM could be used to drill holes in CFRP with high productivity and low tool wear. A better surface was produced by higher rotation speed and lower feedrate.

Keyword: Carbon fiber-reinforced polymer; Drilling; Rotary ultrasonic machining; Force; Surface roughness; Tool wear

INTRODUCTION

Carbon fiber-reinforced polymer (CFRP) has been widely used in aircraft components, automotive parts, and sporting goods due to its high specific modulus, high specific strength, high damping capacity, and low thermal expansion coefficient (Kim et al., 2000; Ucar and Wang, 2005). Hole machining is employed the most frequently for CFRP owing to the need to assemble and join composite parts to other structures (Hocheng and Hsu, 1995, Kim et al., 2000).

Drilling by drill bits is the most common method for hole machining of CFRP. Reported drilling tools include twist drills, multi-facet drills, candle stick drills, and drills with modified geometry (various chisel length and rake, clearance, point and helix angle, etc.) (Mathew and Ramakrishnan, 1999; Piquet et al., 2000; Tsao and Hocheng, 2005; Hocheng and Tsao, 2003; Hocheng and Tsao, 2006; Ucar and Wang, 2005). The drilling mechanisms had been studied since 20 years ago (Ho-Cheng and Dharan, 1990; Capello 2004). Fiber-reinforced epoxy was also drilled by ultrasonic vibration-assisted (UV-A) drilling with vibration of the tool in the feed direction (Aoki et al. 2005, 2006). Surface roughness of machined surfaces by UV-A drilling was improved compared with conventional drilling for many conditions. But challenges remain for widespread applications of these drills. Typical problems encountered in drilling of these composites are delamination, splintering, burrs, short tool life, low machining precision, and low surface roughness (Abrao et al. 2007). Although the drilled hole quality can be improved by proper selections of tool geometry and drilling parameters (Chen, 1997; Davim and Reis, 2003), poor hole quality accounts for about 60% of all part rejection, since holes are usually drilled in the finished products (Tsao and Wang, 2005). Ultrasonic machining (USM) has also been used to drill CFRP (Hocheng and Hsu, 1995). However, there are some disadvantages limited the application of USM such as low material removal rate and tapered machined holes.

Rotary ultrasonic machining (RUM) is a non-conventional machining process that has potentials to drill holes in composite materials cost-effectively. Fig. 1 is a schematic illustration of RUM. A rotating core drill with metal-bonded diamond abrasives is ultrasonically vibrated in the axial direction and fed towards the workpiece at a constant feedrate. Coolant is pumped through the hole in the middle of the drill to flush away the debris, prevent jamming of the drill, and keep it cool. RUM has been employed to drill holes in stainless steel (Cong et al., 2010), titanium alloy (Qin et al., 2009), ceramics (Zeng et al., 2005), and ceramic composites (Li et al., 2005), but never on this type of CFRP.

In this paper, RUM is used to drill holes in this type of CFRP for the first time. The feasibility of machining carbon fiber-reinforced epoxy using RUM is investigated experimentally. Chips, edge chipping, surface roughness, tool wear, and thrust force were measured. Effects of RUM process variables (rotation speed, vibration amplitude, and feedrate) on thrust force and surface roughness were studied.

EXPERIMENTAL SETUP

Workpiece

A carbon fiber-reinforced epoxy plate was used in this study. The size of specimen was 200 × 150 × 16 mm. The composite laminates were prepared from carbon fiber (orthogonal woven fabric by two layers 0° and 90°) with epoxy resin. The thickness of the woven fabric was 150 μm. 42 laminas produced a plate thickness of 11 mm. The fiber volume fraction was 38%. The workpiece material properties are shown in Table 1.

Experimental setup

Experiments were performed on a RUM machine. The experimental set-up is illustrated in Fig. 2. Power supply converted conventional voltage (50 Hz) into high frequency (20 kHz) electrical energy. A piezoelectric converter located in the ultrasonic spindle changed the high-frequency electrical energy into mechanical motion. The amplified motion caused the diamond tool attached to the spindle to vibrate along feed direction. The vibration frequency is 20 kHz. The vibration amplitude could be adjusted by changing the output control of the power supply. An electric motor attached atop the ultrasonic spindle supplied the rotational motion of the tool and different speeds could be obtained by adjusting the motor speed controller on the control panel. A fixture to hold the specimen was mounted on a dynamometer attached to the machine table. Outer and inner diameters of the metal bonded diamond core drill were 9.5 mm and 7.8 mm respectively. The mesh size of the diamond abrasives was 80/100. Water-soluble cutting oil diluted by water with the ratio of 1 to 20 was used as coolant.

Machining conditions

In the experiments, three process variables (vibration amplitude, rotation speed, and feedrate) were varied. The vibration amplitude of the tool was controlled by ultrasonic power. A larger ultrasonic power percentage produced a higher vibration amplitude. Five levels of ultrasonic power were used for the investigations (0%, 20%, 40%, 60%, and 80%), which corresponding to vibration amplitudes of 0, 9, 29, 50, and 69 μm respectively. Based on preliminary experiments, five levels of rotation speed (1000, 2000, 3000, 4000, and 5000 rpm) and eight levels of feedrate were used (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8

mm/s). Other process variables were kept the same for the investigations. For all the drilling tests, the frequency of the ultrasonic vibration was 20 kHz. The flow rate of the coolant was kept the same at 1.5 Lpm. There were sixteen unique experimental conditions. Under each condition, three tests were conducted. The total number of tests was 48. Table 2 lists the test matrix and machining conditions.

RESULTS

Chips

Machining chips were collected and observed under a digital microscope. Typical chips in RUM of carbon fiber-reinforced epoxy are shown in Fig. 3. The chips can be classified into three types: composite chip (fiber fragment bonded with epoxy), epoxy powder, and fiber fragment. The size of the chips was less than 300 μm. Most of the chips were composite chips with irregular edges and shapes (as chip 1 in Fig. 3). Fibers can be observed on the surface and edge of the chips. In addition to the individual composite chips, small composite chips (as chip 2 in Fig. 3), powder-like fine epoxy chips (as chip 3 in Fig. 3), and free fiber fragments (as chip 4 in Fig. 3) were also observed. These chips are similar to those in turning, drilling, and milling of CFRP (Ucar and Wang, 2005).

Edge quality

Fig. 4 shows photographs of machined holes under different machining conditions. It can be seen that the edge at hole entrance is free of split, fiber pull-out, or chippings, and the edge conditions are unaffected by machining conditions. But the edge quality at hole exit is different from that at the entrance. A few splits exist on the hole edge in **a** brittle way (areas 1 and 2 in Fig. 4). The splits occur at the connection of two holes on the top laminate. All the holes were machined without **a** taper (the diameters at the entrance were the same as those at the exit). The variation coefficient (standard deviation divided by mean) of the diameter between all the produced holes was less than 1%.

Edge chipping of the drilled hole at the hole exit is a key barrier of drilling high-quality holes **in brittle materials** by RUM. Chipping size and chipping thickness on the machined rod are two additional criteria to evaluate the hole quality in RUM. Fig. 5 illustrates chipping size and chipping thickness in RUM. Lower values of chipping size and chipping thickness mean better hole quality.

Fig. 6 shows a machined rod and edge chipping observed under a digital microscope from the top to the bottom direction. It can be seen that the cylindrical surface of the rod was free of any fiber-pullout or fracture except edge chipping. The edge chipping consisted of three laminated layers. The first layer consisted of fibers in a clockwise direction (area 1 in the Fig. 6). Only a few fibers can be observed from the picture. The second layer is the matrix layer with clear brittle fracture edges (area 2 in the Fig. 6). Micro-cracks can be observed on this layer. A few fiber fragments can also be observed on the layer. The last layer is made up of fibers in counter-clockwise direction (area 3 in the Fig. 6). Chipping size of the last layer (from a to b) is about 600 μm and is nearly twice the size of the second layer.

The edge chipping was further analyzed in three-dimensions (3D). A 3D topography of the edge chipping (as shown in Fig. 7) was made by a microscope. Chipping thickness on the 3D topography was measured through measuring software. By this software, a measured profile on the 3D topography was obtained on a certain section plane and the height of any point on the profile could be measured. The measuring section plane was along the direction from a to b in Fig. 6 and interacted with all the three layers of the composite material (as areas 1, 2, and 3 in Fig. 7). It is seen that the chipping thickness of layer 3 was 207.9 μm. Layer 2 was not uniform in thickness, but was thinner in the edge and thick near the rod. However, compared with the size of the hole, the proportion of the chipping size and chipping thickness to radius and length of the machined hole were only 6.25% and 1.89% respectively.

From Figs. 6 and 7, it can be seen that layer 2 was made up of remaining material that was not machined completely by the abrasive tool. The epoxy matrix in layer 2 was partly removed by the abrasive tool until layer 3 was fractured. Then the rod was pressed out from the hole.

Thrust force

Thrust force along the feedrate direction and torque during the machining process were measured by a dynamometer. The dynamometer was mounted atop the machine table and beneath the workpiece, as shown in Fig. 2. The electrical signals from the dynamometer went through an amplifier and then were displayed and saved in the computer with a software DynoWare. The sampling frequency to obtain the thrust force and torque signals was 10 Hz. Typical curves for thrust force and torque in an entire process to drill a hole are shown in Figs. 8 and 9. The machining condition for Figs. 8 and 9 was ultrasonic power = 20%, rotation speed = 5000 rpm, and federate =0.5 mm/s.

The torque curve in Fig. 9 and the thrust force curve in Fig. 8 were obtained from the same drilling test. The torque values during the first stage were small and negligible compared with those before and after the tool was n contact with the workpiece. The first peak of the torque curve occurred at the same time as the fluctuation amplitude of thrust force decreased abruptly in Fig. 8. It is an indication of the end of the first stage and beginning of the second stage.

The results on cutting force are presented in Table 3. The effects of process variables on thrust force are shown in Fig. 10 - 12. The maximum value of the thrust force (as illustrated in Fig. 8) during each test was chosen to represent the thrust force in that test. The average of three force values from the three tests under each machining condition was used for plotting in Figs. 10-12. The maximum and minimum force values among the three force values were presented as the error bars in these figures. .

It can be seen that lower thrust force was obtained by higher ultrasonic power, higher rotation speed, and lower feedrate. Variation of the thrust force values under each machining condition was small.

Machined surface

A drilled hole was cut along the axis and the hole surface was observed under a digital microscope. Fig. 13 shows the machined surface for a hole at both the entrance and exit. The machining condition was ultrasonic power =80%, rotation speed 1000 rpm, and federate =0.1 mm/s.

The figure shows that the machined surface quality varies from the entrance side to the exit side. The hole edge on the entrance side was trim and neat without any fibers. The matrix material adjacent to fibers remained intact. Clear boundaries between the laminated materials were observed. However, at the exit, the boundaries between laminated materials are unclear compared with those near the hole entrance. As it got closer to the boundary, the problem got worse. A few fiber rollouts on the hole edge were observed near the exit.

To learn the effects of process variables on machined surface quality, surface roughness was measured at two locations along the feeding direction for each hole: near entrance and near exit. Surface roughness was measured with a surface profilometer. The test range was

4 mm and the cut-off length was 0.8 mm. The results on surface roughness are presented in Table 4. Figs. 14 to 16 further illustrated that machined surface quality near the entrance was better than that near the exit.

Effects of ultrasonic power on surface roughness are shown in Fig. 14. The surface roughness was lower near the hole entrance. The effect of ultrasonic power on the surface roughness near the entrance was negligible. The best surface near the exit was found when ultrasonic power was 40%. The variation of surface roughness was higher near the exit than near the entrance.

Fig. 15 shows effects of rotation speed on surface roughness. Surface roughness decreased with increasing rotation speed. There was no significant improvement in surface roughness when rotation speed was above 4000 rpm.

Effects of feedrate on surface roughness are shown in Fig. 16. Surface roughness increased with increasing feedrate. The difference between surface roughness values at different locations increased with increasing feedrate.

Material removal rate (MRR)

MRR in RUM was determined by feedrate. A higher feedrate yielded a higher MRR. In since the workpiece was 11 mm in thickness, a through hole could be drilled within 14 s (with feedrate 0.8 mm/s) with an acceptable surface roughness Ra value less than 3 μm. A better hole with surface roughness Ra value less than 2 μm could be obtained within 19 s (with feedrate 0.5 mm/s).

Tool wear

Wheel wear mechanisms in grinding would be instrumental to the study of tool wear mechanisms in RUM. One commonly used method to study the wheel wear mechanism was to examine the wheel surface with a microscope (Zeng et al., 2005). Similar approach was applied in this study. Both the end face and lateral face of the tool were observed under a digital microscope with magnification from 50 to 200. In order to ensure that the same area of the tool surface was observed every time, a special fixture was used for holding the tool.

After 30 holes were drilled, there were no visible differences in the appearances of the diamond grains on the tool lateral face. This means that the wear of diamond grains on the tool lateral face was very small. However, wear of the diamond grains at the end face was obvious. Fig. 17 shows the tool topographies on the end face (in the same place) before and after 30 holes were drilled under the conditions presented in Table 2. Attritions wear was observed on the diamond grains. The sharp cutting edges on grains 1 and 2 wore significantly. No wear flats were observed on the entire tool end surface.

Pulling out of a grain was found on the tool end face. Fig. 18 shows the tool topographies on the end face (in the same place) before and after 30 holes were drilled. It can be seen that the diamond grain marked in the picture was pulled out from the metal bond. A hole was formed on the tool end face. Furthermore, after the drilling tests, only one grain was pulled out. Compared with the wear conditions of other grains, it was clear that the grain was pulled out prematurely before completing its effective working life.

In Fig. 18, there is no visible grain in the right picture (after drilling tests). Compared with the picture before drilling, grooves on the metal bond surface after drilling are deeper, and the metal bond was found brighter and flatter. These suggest that the metal bond wore during the machining process.

After each drilling test, the tool was also removed from the RUM machine for measuring tool length and tool weight loss. The weight was measured by a scale. The relation between tool weight loss and number of drilled holes is shown in Fig. 19. It can be seen that the majority of the weight loss (less than 5 mg) happened when the first 5 holes were drilled. The difference of the tool length before and after 30 holes were drilled was negligible (less than 1 μm). Tool weight loss increased slightly with increasing number of drilled holes.

DISCUSSION

Chips

As discussed in section 3.1, three types of chips were found: composite chip, epoxy powder, and fiber fragment. Composite chips were formed due to the impulse cutting process by the abrasive grain on the tool end face. The fiber on the chip edge was cut down with the matrix material in the chip formation process. These chips were formed due to the milling effect between the tool lateral face and the machined hole wall, as illustrated in Fig. 1. Composite chips formed at the interface between the tool end face and the workpiece were brought to the interface between the tool lateral face and the machined hole wall by coolant. The tool lateral face rotated and vibrated against the hole wall, acting as a milling process on these chips. Some of the composite chips were milled into small composite chips. The small composite chips were further decomposed into epoxy powder and fiber fragment before they were washed out from the tool-workpiece contact area.

Machined surface

Variation on surface roughness in different positions for a same hole could be explained by two main reasons. One was the polishing effect of the tool, and the other was the deformation of the laminated materials. As discussed in the previous section, the relative movement between the lateral face of the diamond tool and the machined hole wall acted as a polishing process with lubrication by the coolant between them. It further improved the surface quality. The polishing time was longer near the entrance than the exit. When the workpiece surface was “polished” for a longer period of time, its roughness would be lower.

Deformation of the laminated material was the other reason for the difference in machined surface roughness. Fig. 20 illustrates workpiece deformation in RUM of CFRP. c is the outer radius of the RUM tool, t the thickness of the tool, F the thrust force, h the uncut depth under the tool , a the radius of the delamination. For a certain machining condition, the tool size (c and t) and thrust force F are known. A thinner uncut depth under the tool h implies a larger deformation of the workpiece material, and a larger radius of the delamination a.

On the other hand, the radius of delamination a increases with increasing thrust force F when the uncut depth under the tool h is known. It is clear that, as drilling progresses, the uncut thickness of workpiece become insufficient to resist the thrust force and the laminated workpiece material deforms toward the hole exit with the feeding of the tool. The deformation is much higher near the exit since the uncut thickness of the workpiece material is reduced along the feeding direction. The deformation makes the materials between different layers removed unevenly since the epoxy matrix is not flexible as the fiber. When the deformation is high, the matrix is removed and the fibers are more exposed than the surrounding matrix. This produces a rougher machined surface. This phenomenon was illustrated in Fig. 13. Furthermore, machined surface roughness is related to the thrust force. A higher thrust force produced a rougher machined surface. This trend is further indicated by a comparison between the results on thrust force and machined surface roughness (Fig. 11 vs. Fig. 15, and Fig. 12 vs. Fig. 16).

CONCLUSIONS

In this study, RUM of carbon fiber reinforced epoxy was investigated experimentally. The conclusions can be drawn as following.

RUM could be used to drill holes in CFRP. Holes were drilled without fiber pull-out and any taper. Chipping size was about 600 μm and chipping thickness was about 200 μm. The variation coefficient of diameter between all the produced holes was less than 1%.

The chips in RUM of carbon fiber-reinforced epoxy could be classified into three types: composite chip (fiber fragment bonded with epoxy), epoxy powder, and fiber fragment. The size of the chips was smaller than 300 μm.

Machined surface roughness was related to the thrust force. Lower thrust force and a lower surface roughness was produced by higher rotation speed and lower feedrate. The deformation of the composite in the machining process led to a fluctuation of the thrust force and also produced a rougher surface in a same hole. Machined surface roughness lower than 2 μm was obtained.

Tool wear on the end face was severer than that on the lateral face. No grain fracture was found during the drilling test. Grain pulled out, metal bond wear, and grain attritions wear contributed to the total weight loss of a RUM tool.

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