HELIXVIER


PRELIMINARY STUDY OF ULTRASONIC DRILLING OF FIBER-
REINFORCED PLASTICS

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INDUSTRIAL SUMMARY

Composite materials possess advantages in structural application thanks to their high specific strength and directional properties. Although in many applications, composites are cured to final shape, machining can be required at both the prepreg and product stages. In traditional drilling, due to the anisotropy and the lamination of composite materials, delamination and splintering at hole edge often occur. Ultrasonic machining is suitable for these materials for its nature of material removal by small individual abrasives. Experiments were conducted on the ultrasonic drilling of Carbon/Epoxy and Carbon/PEEK. The examination of surfaces and abrasives after machining illustrates the hammering and impact of the abrasive particles on the workpiece. Brittle fracture of fibers and plastic deformation of matrix are seen. The research highlighted the influence of the concentration of abrasives, the size of abrasive grains, the energy of ultrasonic oscillation and the feed rate of tool on the machinability in respect of material removal rate, surface roughness and hole clearance. Dimensional analysis synthesizes the significant parameters in machining. Ultrasonic machining produced better surface finish and hole quality than conventional drilling. The cost factors of ultrasonic machining, investment, annual revenue, annual expenditures, economic life and salvage value are analyzed with annual and present worth methods. It shows that ultrasonic machining can earn higher profit than other non-conventional machining processes.

1. Introduction

Advanced fiber-reinforced plastics are being increasingly used due to their high specific strength and stiffness, thermal resistance and damping capacity. However, delamination, fiber pull-out, fuzzing and matrix cratering often occur during machining. Ultrasonic machining using the abrasive slurry excited by high-frequency tool vibration can produce neat cavities of a variety of shapes. It induces no thermal, chemical, electrical or metallurgical threat to the workpiece. It is relatively suitable for metals, ceramics and composites.

The first patent of ultrasonic machining was issued in 1945 [Balamuth, 1945]. One paper reviewed previous fundamental study of ultrasonic cutting and the developed machine tools [Rozenberg, et. al, 1964]. Another reference reviewed the past work until 1975 [Kennedy & Grieve, 1975]. In recent years, experimental investigation on the cutting mechanism of ultrasonic machining was reported [Soundararajan, 1986]. Material removal is found primarily by particle hammering. The grain size of the abrasive shows great effect on surface roughness and cut accuracy [Komaraih, et. al, 1988], and the ratio of material hardness to the modulus of elasticity tends to influence considerably the material removal rates, surface roughness and cut accuracy. The rotary tool was found superior to conventional static tool in ultrasonic machining [Komaraih & Reddy, 1991]. Few papers discuss the ultrasonic machining of composite materials, except drilling of boron fiber composites [Cusumano, et. al, 1974]. The present study is concerned with the machinability of ultrasonic drilling of carbon fiber-reinforced plastics.

2. Experiment and Materials

The experiments were conducted on an 800 W ultrasonic drilling machine with tuned frequency of 20 KHz. The experimental set-up is shown in Fig.1.
frequency of 20 KHz. The experimental set-up is shown in Fig.1.

Boron carbide or silicon carbide abrasives were mixed with water at various volume concentration. The abrasive slurry is circulated and supplied to cutting tool. The mild steel tool is a circular tube of 10mm OD and 2.1 mm thickness brazed on the toolholder. The drilling conditions are listed in Table 1.

<table>
<thead>
<tr>
<th>Abrasives</th>
<th>Volume Concentration [%]</th>
<th>Electric Current [ampere]</th>
<th>Feed Rate [mm/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC / #150, #220, #400, #600</td>
<td>SiC / 13.4%, 18.6%</td>
<td>0.4, 0.5, 0.6, 0.8</td>
<td>0.3, 0.4, 0.5, 0.6</td>
</tr>
<tr>
<td>B$_4$C / #220</td>
<td>B$_4$C / 14.7%, 18.7%, 22.8%, 25.6%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The materials are the thermoset-based Carbon/Epoxy and thermoplastics-based Carbon/PEEK. Sixteen layers of prepreg were laminated and cured.

(A) Carbon/Epoxy

(i) 123°C at atmospheric pressure for 60 minutes, followed by

(ii) 183°C at 1.05 MPa for 120 minutes, followed by

(iii) air cooling to room temperature

(B) Carbon/PEEK

(i) 390°C at 1.4 MPa for 20 minutes, followed by

(ii) 390°C at 5.5 MPa for 20 minutes, followed by

(iii) air cooling to room temperature

The laminate thickness is 2.0 mm and 230 mm by 210mm in area. The fiber volume content is 60%. 2$^4$ factorial design of Taguchi method was employed to reduce the number of experimental cycles.

3. Dimensional Analysis

The material removal mechanism is often complex to construct a sound theoretical model. Experiments involving a number of parameters are time-consuming and are liable to incomprehensible results. Dimensional analysis provides a preliminary insight at reduced experimental expense. For the average surface roughness ($R_a$, $\mu$m) and the material removal rate ($V$, mm/sec), the dominant parameters are the tool feed rate ($f$, mm/min), abrasive size ($S$, $\mu$m), abrasive density ($\rho$, g/cm$^3$) and hardness ($H$, N/mm$^2$), input energy of tool oscillation ($W$, watt), and abrasive flow rate ($A$, cm$^3$/sec). Being nondimensionalized by PI theorem, the relationship can be obtained as:

$$Ra/S = \text{function}(A/fS^3, \rho S^3f^3/W, HfS^2/W)$$

and
\[ \frac{V}{fS^2} = \text{function}(A/fS^2, \rho S^2 f^3/W, HfS^2/W) \]  

The experimental results are then incorporated. The relationship between the non-dimensionalized surface roughness and material removal rate and machining parameters can be shown as:

\[ \frac{R_a}{S} = 0.19 \left( \frac{A}{fS^2} \right)^{0.64} \left( \frac{\rho S^2 f^3}{W} \right)^{0.27} \left( \frac{HfS^2}{W} \right)^{-0.43} \]  

\[ \frac{\dot{V}}{fS^2} = 3.6 \left( \frac{A}{fS^2} \right)^{0.33} \left( \frac{\rho S^2 f^3}{W} \right)^{0.93} \left( \frac{HfS^2}{W} \right)^{-0.74} \]  

Further discussions of the effects of individual machining parameters are summarized in the following section.

4. Drilling Results and Discussions

4.1 Machined Surface under Cutting Tool

The machined surface is shown in Fig. 2. There are craters on the workpiece caused by abrasive particle hammering or impact. The ultrasonic machining consists of continual material removal in small craters. Fig. 3 illustrates abrasive particles and chips after machining. The size of the chip is about one tenth of the abrasive particle, or several micrometers. The chips are produced by the hammering or free impacting of abrasives. The SEM photographs (Fig. 4 and Fig. 5) of the machined surface show plastic deformation of matrix and brittle fracture of fibers. No significant difference exists between carbon/epoxy and carbon/PEEK in the tested range of cutting conditions.

4.2 Hole Roughness

The surface roughness values obtained in ultrasonic machining are plotted in Fig. 6 through Fig. 9. The major parameters are the grain size, the input current of ultrasonic oscillations and the concentration of abrasives. The feed rate of tool has negligible effect on surface roughness. The increasing roughness value with the grain size and the energy of ultrasonic oscillations is explained by the produced larger craters on the workpiece. Larger amount of material removal by each abrasive results in rougher surface. The higher the concentration of abrasives is, the more frequent the abrasives scrape on the workpiece, hence the machined surface is slightly rougher. The feed rate of tool determines the rate of generation of the new surface only, it has no effect on the number and the size of produced craters on the machined surface.

The optical microscope photograph (Fig. 10) and the above figures show uniform surface roughness parallel and perpendicular to fibers. Table 2 shows the measured values. Besides, no significant difference exists between thermoset and thermoplastic composite material. These facts are explained by the micro material removal by abrasives, which involves little macro matrix deformation, thus the produced surface is independent of the fiber direction or the matrix thermoplasticity. The same discussions apply to the negligible difference in material removal rate in Table 2.

4.3 Edge Quality

The optical projection photographs (Fig. 11 and Fig. 12) show clean hole edge, no delamination occurs. At high energy input, the thermoplastics-based carbon/PEEK presents minor fuzz at exit due to the relatively viscous deformation of matrix and decreased cooling by slurry toward exit. With the aid of liquid nitrogen, the viscosity of thermoplastics is reduced, thus the exit edge is free of fuzz. Fig. 13 illustrates the SEM photograph of the hole exit. The thick thermoplastic recast covering fibers and the built up edge at exit can be seen in (a), while (b) shows less thermoplastic flow of the matrix with neat hole wall and recognizable fibers are seen.
Table 2 Material Removal Rate and Surface Roughness in Ultrasonic Cutting of C/Epoxy and C/PEEK

<table>
<thead>
<tr>
<th>Material</th>
<th>Removal Rate</th>
<th>Surface Roughness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>// Fibers</td>
</tr>
<tr>
<td>Carbon / Epoxy</td>
<td>0.249</td>
<td>1.36</td>
</tr>
<tr>
<td>Carbon / PEEK</td>
<td>0.245</td>
<td>1.39</td>
</tr>
</tbody>
</table>

4.4 Hole Clearance

The diameter clearance between the produced hole and the cutting tool is enlarged with the grain size and the energy of ultrasonic oscillations, as shown in Fig.14 and Fig.15. The feed rate of tool or the volume concentration of abrasives does not affect the hole clearance significantly.

5. Analysis of Drilling Economy

Three nonconventional machining processes are compared, i.e. abrasive water-jet, laser and ultrasonics. The main cost factors are the investment, economic life, salvage value, annual revenue and expenditures. For the current workpiece, water-jet or laser cuts in average fifteen times faster than ultrasonic machining. However, ultrasonic machine can readily perform multi-hole production for equal production rate. The following analysis presents the results of single-hole and multi-hole ultrasonic cutting.

The investment and annual expenditures are shown in Table 3 and 4. The analysis is based on 8 hours/day and 240 days/year. All values are in US Dollars. Using the annual worth method or present worth method (see Table 5 and 6), the ultrasonic machining is less economical than the other two processes in the case of single-hole production, due to its much slower material removal rate. With multi-hole production, however, ultrasonic machining prevails over the other two processes.

6. Conclusions

The major cutting mechanism of ultrasonic drilling is abrasive particle hammering or impacting on the workpiece to remove material in micro craters. The obtained surface roughness increases with the grain size, the energy of ultrasonic oscillations and the concentration of abrasives, and is independent of the feed rate of tool, the fiber direction or the matrix thermoplasticity. The experimental results can be integrated into the dimensional analysis. No delamination occurs at the hole edge. The thermoplastics-based carbon/PEEK presents minor fuzz at exit due to its thermoviscosity. With the aid of liquid nitrogen, the produced exit edge is neat. The grain size and the energy of ultrasonic oscillations significantly affect the hole clearance. Multi-hole production elevates the productivity of ultrasonic drilling of composite materials.

Acknowledgement

This research is supported by the grant from National Science Council, Republic of China, under contract NSC 82-0115-E0007-292. The results are also presented in the NSC-sponsored Sino-German Joint Symposium on Precision and High Speed Manufacturing Technology, Taipei.
TABLE 3 Annual Expenditure Analysis [unit: US Dollar]

<table>
<thead>
<tr>
<th>Process</th>
<th>Item Of Expenditure</th>
<th>Quantity Of Annual Consumption</th>
<th>Annual Expenditure</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Machining</td>
<td>gas</td>
<td>164 m³ / month</td>
<td>19,872</td>
<td></td>
</tr>
<tr>
<td></td>
<td>electricity</td>
<td>10 kW / hour</td>
<td>1,536</td>
<td></td>
</tr>
<tr>
<td></td>
<td>maintenance</td>
<td>1,600 / year</td>
<td>1,600</td>
<td>36,832</td>
</tr>
<tr>
<td>Abrasive Water-jet Machining</td>
<td>nozzle set</td>
<td>one set / 100hour</td>
<td>6,912</td>
<td></td>
</tr>
<tr>
<td></td>
<td>garnet abrasives</td>
<td>436 kg / day</td>
<td>23,040</td>
<td></td>
</tr>
<tr>
<td></td>
<td>electricity</td>
<td>3.75 kW / hour</td>
<td>5,760</td>
<td></td>
</tr>
<tr>
<td></td>
<td>maintenance</td>
<td>400 / year</td>
<td>400</td>
<td>36,112</td>
</tr>
<tr>
<td>Ultrasonic Machining</td>
<td>SiC abrasives</td>
<td>4 kg / day</td>
<td>7,680</td>
<td></td>
</tr>
<tr>
<td></td>
<td>electricity</td>
<td>3 kW / hour</td>
<td>4,608</td>
<td></td>
</tr>
<tr>
<td></td>
<td>maintenance</td>
<td>200 / year</td>
<td>200</td>
<td>12,488</td>
</tr>
</tbody>
</table>

TABLE 4 Investment Analysis [unit: US Dollar]

<table>
<thead>
<tr>
<th>Process</th>
<th>Ultrasonic Machining</th>
<th>Laser Machining</th>
<th>Abrasive Water-jet Machining</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>single hole / machine</td>
<td>five holes / machine</td>
<td>fifteen holes / machine</td>
</tr>
<tr>
<td>Investment</td>
<td>180,000</td>
<td>36,000</td>
<td>12,000</td>
</tr>
<tr>
<td>Economic Life</td>
<td>Six Years</td>
<td>Nine Years</td>
<td>Nine Years</td>
</tr>
<tr>
<td>Salvage Value</td>
<td>1,800</td>
<td>360</td>
<td>120</td>
</tr>
<tr>
<td>Annual Expenditure</td>
<td>187,320</td>
<td>37,464</td>
<td>12,488</td>
</tr>
</tbody>
</table>

the lowest rate of return: 15%
### TABLE 5 Profit Analysis By Annual Worth Method [unit: US Dollar]

<table>
<thead>
<tr>
<th></th>
<th>Ultrasonic Machining</th>
<th>Laser Machining</th>
<th>Abrasive Water-jet Machining</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>single hole / machine</td>
<td>five holes / machine</td>
<td>fifteen holes / machine</td>
</tr>
<tr>
<td>Capital Recovery =</td>
<td>Investment*(A/P, i%, N)</td>
<td>-Salvage* (A/F,i%,N)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>47,358</td>
<td>9,472</td>
<td>3,157</td>
</tr>
<tr>
<td></td>
<td>187,320</td>
<td>37,464</td>
<td>12,488</td>
</tr>
<tr>
<td>Annual Expenditure</td>
<td>187,320</td>
<td>37,464</td>
<td>12,488</td>
</tr>
<tr>
<td>Annual Cost</td>
<td>234,678</td>
<td>46,936</td>
<td>15,645</td>
</tr>
</tbody>
</table>

i % : Lowest Rate of Return  N : Period  F : Future Worth  
A : Uniform Payment  P : Present Worth

### TABLE 6 Profit Analysis By Present Worth Method [unit: US Dollar]

<table>
<thead>
<tr>
<th></th>
<th>Ultrasonic Machining</th>
<th>Laser Machining</th>
<th>Abrasive Water-jet Machining</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>single hole / machine</td>
<td>five holes / machine</td>
<td>fifteen holes / machine</td>
</tr>
<tr>
<td>Investment</td>
<td>180,000</td>
<td>36,000</td>
<td>12,000</td>
</tr>
<tr>
<td>First Reset (investment-salvage) * (P/F,i%,N)</td>
<td>77,036</td>
<td>15,407</td>
<td>51,358</td>
</tr>
<tr>
<td>Second Reset (investment-salvage) * (P/F,i%,N)</td>
<td>30,278</td>
<td>6,056</td>
<td>2,019</td>
</tr>
<tr>
<td>Annual Expenditure (annual expenditure) * (P/A , i% , N)</td>
<td>1,147,897</td>
<td>229,579</td>
<td>76,526</td>
</tr>
<tr>
<td>Salvage after 18 years -salvage*(P/F,i%,N)</td>
<td>-145</td>
<td>-29</td>
<td>-9.7</td>
</tr>
<tr>
<td>Present Worth-Cost</td>
<td>1,435,065</td>
<td>287,013</td>
<td>95,671</td>
</tr>
</tbody>
</table>

i % : Lowest Rate of Return  N : Period  F : Future Worth  
A : Uniform Payment  P : Present Worth
References


Kennedy, D.C. & Grieve, R.J., 1975, "Ultrasonic Machining -- A Review", The Production Engineer, September, pp.481-486.


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c : Abrasive Volume Concentration
i : Input Current
f : Tool Feed

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Fig. 1 Ultrasonic Machining Set-up

(a) 
#220 B₄C c=18.7%, Carbon/Epoxy
i = 0.5 amp, f = 0.4 mm/min

(b) 
#220 B₄C c=25.6%, Carbon/PEEK
i = 0.8 amp, f = 0.3 mm/min

Fig. 2 Optical Microscope Photograph of Machined Surface under Cutting Tool
c: Abrasive Volume Concentration
i: Input Current
f: Tool Feed

(a)
#220 B₄C c=18.7%, Carbon/PEEK
i = 0.8 amp, f = 0.4 mm/min

(b)
#220 B₄C c=22.8%, Carbon/Epoxy
i = 0.6 amp, f = 0.6 mm/min

Fig. 3 SEM Photograph of Abrasive and Chip

(c)
#220 B₄C c=18.7%, Carbon/Epoxy
i = 0.5 amp, f = 0.4 mm/min

(b)
#220 B₄C c=25.6%, Carbon/PEEK
i = 0.5 amp, f = 0.5 mm/min

Fig. 4 SEM Photograph of Fiber Failure
c : Abrasive Volume Concentration
i : Input Current
f : Tool Feed

(a) #220 B_4C c=25.6% , Carbon/PEEK
    i = 0.4 amp, f = 0.6 mm/min

Fig.5 SEM Photograph of Plastic Deformation of matrix

(b) #220 B_4C c=18.7% , Carbon/Epoxy
    i = 0.8 amp, f = 0.6 mm/min

Fig.6 Influence of Grain Size on Surface Roughness

Fig.7 Influence of Input Current on Surface Roughness
Influence of Tool Feed on Surface Roughness

![Graph showing the influence of tool feed on surface roughness.]

Fig. 8: Influence of Tool Feed on Surface Roughness

Influence of Volume Concentration of Abrasives on Surface Roughness

![Graph showing the influence of volume concentration of abrasives on surface roughness.]

Fig. 9: Influence of Volume Concentration of Abrasives on Surface Roughness

- c: Abrasive Volume Concentration
- i: Input Current
- f: Tool Feed

Fig. 10: Optical Microscope Photograph of Machined Hole Wall

- (a) perpendicular to fibers
- (b) parallel to fibers

#220 B₄C c=14.7%, Carbon/Epoxy
i = 0.5 amp, f = 0.4 mm/min
c : Abrasive Volume Concentration
i : Input Current
f : Tool Feed

Fig. 11 Optical Projection of Hole Exit of Carbon/Epoxy

(a) 
#220 B₄C c = 22.8%
i = 0.6 amp, f = 0.6 mm/min

(b) 
#220 B₄C c = 25.6%
i = 0.8 amp, f = 0.3 mm/min

(c) 
#220 B₄C c = 14.7%, w/ Liq. N₂
i = 0.8 amp, f = 0.6 mm/min

Fig. 12 Optical Projection of Hole Exit of Carbon/PEEK
c: Abrasive Volume Concentration
i: Input Current
f: Tool Feed

(a) Without liquid nitrogen

(b) With liquid nitrogen
#220 B₄C  c=14.7%, Carbon/PEEK
  i = 0.8 amp, f = 0.6 mm/min

Fig. 13 SEM Photograph of Machining with and without Liquid Nitrogen

Fig. 14 Effect of Abrasive Size on Hole Clearance

Fig. 15 Effect of Input Current on Hole Clearance