Visualization of Stress Distribution on Ultrasonic Vibration Aided Drilling Process*

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Abstract
The ultrasonically assisted machining is suitable to achieve sub-millimeter drilling on difficult-to-cut materials such as ceramics, hardened steel, glass and heat-resistant steel. However, it is difficult to observe the high-frequency and micron-scale phenomenon of ultrasonic cutting. In this report, high speed camera based on photoelastic analysis realized the visualization of stress distribution on drilling process. For the conventional drilling, the stress distribution diagram showed the intensive stress occurred under the chisel because the chisel edge of drill produces large plastic deformation. On the other hand, the ultrasonic drilling produced spread stress distribution and stress boundary far away from the chisel. Furthermore, chipping or cracking of inner wall of silica glass was influenced considerably by cutting fluid.

Key words: Ultrasonic Drilling, Chip Generation, Photoelastic Image, High-Speed Camera

1. Introduction
Enhancement of productivity and efficiency for handling difficult-to-cut materials to maintain competitiveness is a significant demand of profitable company management. Revolutions in manufacturing technology and production engineering have optimized and exhausted up their limits. A development of hard-to-cut material which will be benefit of industrial products motivates to improve conventional cutting technology. A growing demand to drill deep and fine holes into hard-to-cut components requires new advanced technology. There are non-traditional techniques to machine fine holes such as laser, EDM, electron beam, etc. However it is difficult for a laser beam to cut cleanly and efficiently. The production cost by using laser, EDM and electron beam is expensive and the heat-affected layer influences the property of productions. The industrial circles have desired drilling method for fine-hole making. The use of ultrasonic vibration in different manufacturing processes is well documented for more than 50 years (1). Because the removal rates cannot be increased for machining of difficult-to-cut materials, ultrasonic machining suits very well this type of material. Recently, ultrasonic vibration has been applied as a process assisting conventional machining operations: turning and drilling. This technique is called ultrasonic machining or rotary ultrasonic machining. Process assistance involves applying the
ultrasonic technology in the machining of difficult-to-cut materials. Assisted ultrasonic machining has been proven to be an efficient technique for improving the machinability of several aeronautic materials, such as glass, aluminum, inconel, et al. Vibration drilling, classified into unconventional machining technology, is based on the vibration cutting theory. The controllable relative vibration between drill and workpiece falls into three types: axial vibration, twist vibration and complex vibration (combining axial vibration drilling and twist vibration). Bending vibration is unstable for drilling because the deformation component in radial direction results in geometrical error of drilled holes, unwanted generation of burr and excessive wear of drill. Drilling with vibration in axial direction is required for a small diameter drilling. Some researchers have observed chip fragmentation in materials such as inconel or aluminum when ultrasonic vibration was applied in the drilling process. However, the mechanism of vibration drill has not been well explained.

In our research, the visualization system, which captures the chip generation and time-varying stress distribution of work, is constructed to clarify the principle of ultrasonic drilling with comparing conventional drilling. Silica glass is drilled by cemented carbide drill of the diameter of 0.2mm. In this paper, the results of drilling with or without cutting fluid are reported.

2. Machine tool and experimental equipment

2.1 Theory of ultrasonic vibration drilling

Vibration drilling is based on intermittent machining by pulse impact, because of tool separation from the chip. Also, as the cutting velocity reduces, the interval of non-contact situation gradually increases, so that supply of lubrication in working area results in the effective removal of cutting heat. The cutting process in vibration cutting is different from the steady cutting process in conventional cutting as illustrated in Fig.1, which will be changed by employing different vibration parameters and cutting condition. The separation between tool and chip occurs when the cutting speed is less than critical cutting velocity, $V_c$, expressed as

$$V_c = a_0 \omega = 2\pi af$$  \hspace{1cm} (1)

where $a_0$, $\omega$, $f$ are amplitude, angular velocity and frequency of the vibrating tool,
respectively \[7\].

In the process of conventional drilling, the drill not only rotates but also feeds axially. The twist drill has two cutting edges. The axial cutting thickness is a constant for any point on the cutting edge. On the other hand, the dynamic axial cutting thickness while the axial vibration acts on the drill is as follows:

\[
z(t) = a_0 \sin(2\pi ft) + 2FNt
\]

where \(F\) is chip load and \(N\) is rotation speed of drill. In the drilling process, a cutting edge makes a surface, then the opposite cutting edge sequentially produce a surface at the same point. The minimum axial cutting thickness, \(h_{\text{min}}\), can be expressed as follows \[8\].

\[
h_{\text{min}} = F - 2a_0 \sin\left(\frac{60\pi f}{2N}\right)
\]

When, \(h_{\text{min}} < 0\), the discontinuous chips are generated. In other word, when the amplitude is greater than the critical amplitude expressed as

\[
a_0 > \frac{F}{\sin\left(\frac{60\pi f}{2N}\right)}
\]

intermittent drilling occurs. Variation of denominator in Eq.4 from 0 to 1 caused by slight change of ultrasonic frequency and/or rotational speed is corresponding to cutting situation change illustrated in Fig.1 (b) and (c). Therefore the critical amplitude introduced by ultrasonic drilling condition is indeterminacy. In this research, because the sweep length for a tool vibration is sufficiently smaller than chip load, the cutting situation is extremely closer to opposite phase cutting as illustrated in Fig 1 (c). Hence the denominator in Eq.4 is assumed to be 1.

2.2 Ultrasonic drilling machine

Figure 2 shows the configuration of the experimental setup. A precise vibration drilling machine is used in the experiments. A commercial cemented carbide solid twist drill is vibrated in axial direction. The vibration amplitude is varied by the ultrasonic frequency oscillator at 40kHz. The vibration conditions are measured by laser Doppler vibrometer as shown in Fig.3. It has sufficient frequency response and resolution to measure the ultrasonic vibration. The distortionless sinusoidal waveform was observed for the amplitude of less than 5.2\(\mu m\). Furthermore, a high-speed camera was employed for observation of vibration mode of drill. The recording rates employed have been of 150,000 frames per second with a shutter speed of 1/FPS sec with a metal-halide lighting and fiber optic light guiding system to ensure good image acquisitions. One of example of FEM analysis of forced vibration is illustrated in Fig.4. The ultrasonic vibration of 40kHz is applied on the solid cemented
carbide drill with a diameter of 0.2mm. The excited bending vibration will be cause of severe tool wear and unacceptable machining error. In this research, the drill is installed on spindle by using specially designed tool holder. The vibration system is consist of spindle rotor, holder and tool. The system has been tuned by modifying the dimension of tool holder with a longitudinal vibration mode at ultrasonic vibration cutting frequency of 40kHz. It is confirmed that the amplitude of drill tip in radial direction caused by component of bending vibration is smaller than one tenth of the amplitude in axial direction by component of longitudinal vibration.

2.3 Real-time Visualization of Stress Distribution

New polarization high-speed camera was developed by means of advanced image analysis, taking advantage of polarization techniques. This camera can capture images of polarization information in various directions as a temporal surface distribution pattern. This special feature makes it possible to simplify the equipment by removing the polarization-plate driving mechanism, which is inevitably needed in the conventional surface distribution imaging of polarization information. As a result, the recording and analysis of dynamic events with constantly varying polarization are made possible.

The imaging sensor has a set of polarization plates, arranged in 0, 45, 90 and 135degrees as shown in Fig.5, attached to an array of 2 x 2 neighboring pixels. This being the basic unit, 512 x 512 sets of polarization plates are arranged along the horizontal and
vertical lines over the entire sensor surface. The specifications of the imaging element are maximum number of pixels: 1024 × 1024, pixel size: 20 × 20µm, maximum sampling rate: 1MHz and shortest exposure time: 670ns.

3. Experimental results and considerations

3.1 Observation of Chip Generation

The effect of ultrasonic vibration of drill on the chip generation and removal is observed by using a high speed camera. Because the transparent acrylic resin is drilled, the chip generating condition at the cutting edge of drill tip can be visualized. The drilling condition is listed in Table 1. The critical amplitudes expressed in Eq.(4) are $a_{cr}=0.5\mu m$ for $F=1\mu m$ and $a_{cr}=0.075\mu m$ for $F=0.15\mu m/rev$, respectively. In order to verify the performance of ultrasonic vibration drilling, the amplitude of drill vibration $a_0$ was varied from 0 to 5.2µm. The amplitude of zero means conventional drilling. Because the minimum amplitude of 1.3µm is greater than the critical amplitude, fragment chip will be produced under any condition of ultrasonic vibration drilling. A captured photo, which is an extracted arbitrary flame from the movie captured by high speed camera at chip load of 1µm/rev and 0.15µm/rev are shown in Fig.6 and Fig.7, respectively. It was observed that the conventional drilling generated continuous chips. On the other hand, distinct chips were generated under ultrasonic drilling condition. Ultrasonic oscillation motivated the chips actively being removed along the twist flutes from the cutting edges. The ultrasonic vibrating drill with the amplitude of 2.2µm or less made the inner wall transparency. However, at the amplitude of 3.3µm, transparent acrylic resin was to be opaque. We measured that the temperature of chips excreted immediately from the drilled hole exceeded 50ºC by infrared thermography. Therefore the temperature of cutting point, bottom of drilled hole will exceed 80ºC which is glass transition temperature of acrylic resin. The kinematic energy of ultrasonic oscillation that is transformed into heat energy will rise the temperature of the resin. Excessive amplitude is result in thermal affected layer.

### Table 1 Drilling conditions for acrylic

<table>
<thead>
<tr>
<th>Work material</th>
<th>Acrylic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill diameter, $D$</td>
<td>1 [mm]</td>
</tr>
<tr>
<td>Spindle speed, $N$</td>
<td>500 [rpm]</td>
</tr>
<tr>
<td>Feed rate</td>
<td>1 [mm/min]</td>
</tr>
<tr>
<td>Chip load, $F$</td>
<td>1, 0.15 [µm/rev]</td>
</tr>
<tr>
<td>Step feed</td>
<td>0.1 [mm]</td>
</tr>
<tr>
<td>Hole depth</td>
<td>1 [mm]</td>
</tr>
<tr>
<td>Vibration frequency, $f$</td>
<td>40 [kHz]</td>
</tr>
<tr>
<td>Vibration amplitude, $a_0$</td>
<td>1.3, 2.2, 3.3, 4.2, 5.2 [µm]</td>
</tr>
</tbody>
</table>

3.2 Drilling stress distribution

Generally drilling force has been measured by dynamometer. Fig.8 shows the variation in thrust force with the drilled depth. The drill diameter, rotational speed and chip load were 1mm, 2000rpm and 0.25µm/rev, respectively. The maximum thrust forces for a step feed are plotted. It seems that the vibration drilling with the vibration amplitude of 0.3µm decreases the thrust force about 40%. Many researchers reported that the ultrasonic cutting dramatically reduce the time-averaged cutting force. However the frequency response of dynamometer is insufficient to evaluate the dynamic cutting process of ultrasonic drilling. In order to assess the performance of ultrasonic drilling with 40kHz driving frequency, the dynamic time variation of stress distribution caused by drilling should be observed.
Instantaneous photoelastic images are captured for conventional and ultrasonic drilling with the amplitude of 4.2µm. The drill diameter, rotational speed and chip load were 1mm, 500rpm and 0.15µm/rev, respectively. The frame rate for capturing motions of stress distribution was 5,000fps with the shutter speed of 1/10,000sec. The image resolution was corresponding to 320x320 (Note that irrelevant image area was trimmed). Because the relation between frame rate and image resolution is trade-off, the time variation of stress distribution was captured by moderate frame rate. The photoelastic images are shown in Fig.9. More color variations within small area means higher intensive stress. For conventional drilling, the intensive stress observed under the chisel of drill. It will be caused that chisel edge, which has no cutting speed, deforms a work with high stress and following cutting edge remove work. On the other hand, under ultrasonic drilling condition, intensive
stress occurred 0.2mm below the chisel edge. Ultrasonic vibrating drill has alternating velocity in axial direction. As a result, ultrasonic vibration will reduce the force result from chip deformation by providing cutting ability for the chisel edge. However, the ultrasonic vibration causes repetition of compression and decompression of work. Heat energy which is transformed from kinematic energy of tool vibration rises the temperature of acrylic. Thermal conductivity and specific heat of acrylic are 0.2W/m/K and 1.46J/g/K, respectively. In contrast to ferrous metal (thermal conductivity: 84W/m/K and specific heat: 0.44J/g/K), heat energy does not diffuse noticeably. As a result, the thermal strain will appear on photoelastic image.
3.3 Drilling for silica glass

Glass is brittle, hard and low thermal conductivity, therefore it is obviously hard-to-cut material. Generally, diamond electrodeposited grinding tool is used with supplying a large amount of grinding fluid to remove the grinding heat. It is well known that ultrasonic drilling reduces thrust force and extends tool life. However, in previous section it was pointed out that ultrasonic oscillation has possible to cause of temperature rise of interface between tool and work under dry cutting condition. Drilling the glass makes a consideration of influence of thermal reaction. The photograph of tool wear and chipping of hole by drilling for silica glass under dry cutting condition are shown in Fig.10 and 11. Sintered carbide drills with the diameter of 0.2mm are used. The rotational speed, feed rate, chip load and step feed was 3000rpm, 1.8mm/min, 0.3µm/rev and 0.15mm, respectively. The feed length of drill was 2mm. The severe tool wear results in disappear of drill tip. The

Table 2 Drilling condition for silica glass

<table>
<thead>
<tr>
<th>No.</th>
<th>Amplitude of vibration µm</th>
<th>feed rate mm/min</th>
<th>Chip load µm/rev</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>1.8</td>
<td>0.3</td>
</tr>
<tr>
<td>2</td>
<td>1.3</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>3</td>
<td>1.3</td>
<td>1.8</td>
<td>0.3</td>
</tr>
<tr>
<td>4</td>
<td>1.3</td>
<td>3.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Fig.12 Result of drilling for silica glass with cutting fluid
3.4 Drilling for silica glass with cutting fluid

Kinematic energy of oscillating drill will be changed to thermal energy of workpiece. Therefore dry cutting accelerates tool wear, especially under ultrasonic drilling condition. The effect of cutting fluid was shown in Fig.12. The drilling condition was listed in Table 2. The cutting fluid, Unicut Jinen MFF: non-water soluble was dropped on the workpiece surface before drilling. The rotational speed and step feed was 3000rpm and 0.15mm, respectively. The feed length of drill was 2mm. The feed rate was varied from 0.6 to 3.6mm/min. Consequently, the chip load was varied from 0.1 to 0.6 µm/rev. The cutting fluid had an effect to inhibit chipping on the edge of hole. There are some unacceptable chippings on the edge of hole and cracks on the side wall drilled by conventional way, condition No.1. The width of flank wear was 0.2 µm. On the other hand, by applying ultrasonic vibration with condition No.2, chippingless hole with transparent side view was drilled. In this case, a slight tool wear was observed. However larger chip load resulted in greater chippings because of increase of cutting force. The immoderate cutting force will be cause of the bending of hole and the increase of flank wear.

4. Conclusion

In order to clarify the principle of ultrasonic drilling, the visualization system is constructed to capture the chip generation, thermogram and time-varying stress distribution of work. The stress imaging system is based on phase-shifted photoelastic image. The 40kHz ultrasonic drilling was carried out for acrylic with the amplitude of 0 and 4.2 µm. Excessive amplitude of drill resulted in severe heat-affected layer. The stress distribution showed that the intensive stress observed under the chisel of drill for conventional drilling. On the other hand, intensive stress is observed 0.2mm below the chisel edge for ultrasonic drilling. The difference of stress distribution will be caused by evolution of heat by ultrasonic oscillation. The ultrasonic drilling was applied to silica glass by using cemented carbide drill with the diameter of 0.2mm. The importance of cutting fluid was demonstrated for tool wear. For the drilling to silica glass, one of difficult-to-cut material, lower feed rate resulted in reduction of tool wear, chipping around the shoulder of the hole and crack of internal wall of hole.

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References

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