Experimental Verification of Ultrasonic Vibration Aided Drilling Process for Difficult-to-cut Material

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Abstract:

A drilling process to the difficult to cut material such as ceramics, hardened steel, glass and heat-resistant steel is widely requested in the industrial world. In order to achieve sub-millimeter drilling process, ultrasonically assisted machining is suitable to machine difficult-to-cut materials precisely. In this report, high speed camera based on photoelastic analysis realized the visualization of process of ultrasonic drilling. The work materials are silica glass. 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, for ultrasonic drilling, the chipping or cracking of inner wall was influenced considerably by cutting fluid.

Keywords: Ultrasonic drilling, Chip generation, Hard-to-cut materials, photoelastic image

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 [2] or inconel 718[3]. 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 more effective and is adopted in this paper. Some researchers have observed chip fragmentation in materials such as inconel [2, 3, 4] or aluminum [5, 6] 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, thermogram 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 sintered carbide drill of $\phi 0.2$. 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 between the tool and the chip increases gradually, so that supply of lubrication in working area results in the efficiency removal of cutting heat. The cutting process in vibration cutting is different from the steady cutting process in conventional cutting, which will change 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 .

Figure 1: Experimental setup.

(a) 1.3μm

(b) 3.3μm

(c) 5.2μm

Figure 2: Vibrating condition of drill tip in axial direction

$$V_c = a\omega = 2\pi af \quad (1)$$

where a , ω , 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:

$$z(t) = a \sin(2\pi ft) + FNt \quad (2)$$

where F is feed rate per revolution 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, $h_{\min}$, can be expressed as follows [8].

$$h_{\min} = \frac{F}{2} - 2a \sin\left(\frac{60\pi f}{2N}\right) \quad (3)$$

When, $h_{\min} < 0$, the discontinuous chips are generated. When the parameters meet the following condition, intermittent drilling occurs.

$$a > \frac{F}{4 \sin\left(\frac{60\pi f}{2N}\right)} \quad (4)$$

2.2 Ultrasonic drilling machine

Figure 1 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.2. It has sufficient frequency response and resolution to measure the ultrasonic vibration. The distortionless sinusoidal waveform was observed for the amplitude of less than 5.2μm. 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. It is confirmed that the amplitude of drill tip in radial direction which is a component of bending vibration, is smaller than one tenth of the amplitude in axial direction which is a component of longitudinal vibration. The bending vibration will be cause of severe tool wear and unacceptable machining error.

2.3 Real-time Visualization of Strain 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 as shown in Fig.3, 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 x 1024, pixel size: 20 x 20μm, maximum sampling rate: 1MHz, polarization plate set

arrangement: 0, 45, 90 and 135degrees to neighboring pixels of 2×2 array and shortest exposure time: 670ns.

Figure 3: Schematic view of image sensor

3. Experimental results and considerations

3.1 Drilling stress distribution

Generally drilling force has been measured by dynamometer. Fig.4 shows the variation in thrust force with the drilled depth. The drill diameter, rotational speed and chip load were $\phi 1$, 2000rpm and $0.25\mu\text{m}/\text{rev}$, respectively. The maximum thrust forces for a step feed are plotted. It seems that the vibration drilling with the vibration amplitude of $0.3\mu\text{m}$ 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 $4.2\mu\text{m}$. The drill diameter was $\phi 1$. The rotational speed was 500rpm. The chip load was $0.15\mu\text{m}/\text{rev}$. The frame rate for capturing motions of stress distribution was 5,000fps with the shutter speed of $1/10,000\text{sec}$. The image resolution was corresponding to 320×320 (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.5. 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 $0.2\text{W}/\text{m}/\text{K}$ and $1.46\text{J}/\text{g}/\text{K}$, respectively. In contrast to ferrous metal (thermal conductivity: $84\text{W}/\text{m}/\text{K}$ and specific heat: $0.44\text{J}/\text{g}/\text{K}$), heat energy does not diffuse noticeably. As a result, the thermal strain will appear on photoelastic image.

3.2 Drilling for silica glass

Figure 4: Time variation of thrust force

(a) Conventional drilling (b) Ultrasonic drilling

Figure 5: Photoelastic images

Figure 6: Tool wear of drill for conventional drilling

(a) Conventional drilling (b) Ultrasonic drilling

Figure 7: Chipping of drilled hole

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 be 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.6 and 7. Sintered carbide drills of $\phi 0.2$ are used. The rotational speed, feed rate, chip load and step feed was 3000rpm, $1.8\text{mm}/\text{min}$, $0.3\mu\text{m}/\text{rev}$ and 0.15mm , respectively. The feed length of drill was 2mm. The severe tool wear results in disappear of drill tip. Furthermore chipping of drilled hole by conventional drilling was observed. When ultrasonic drilling was applied, the tool was broken and unacceptable chipping occurred. Under dry cutting condition, the

feature of ultrasonic drilling would be spoiled.

3.3 Drilling for silica glass with cutting fluid

Kinematic energy of oscillating drill will be changed of thermal energy of workpiece. Therefore dry cutting accelerates tool wear, especially under ultrasonic drilling condition. The effect of cutting fluid was demonstrated in Fig.8. The drilling condition was listed in Table.1. The cutting fluid, Unicut Jinen MFF: non-water soluble, was dropped on the workpiece 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 μ m/rev. The cutting fluid had an effect to inhibit tool wear and crack of hole. However larger chip load resulted in greater crack because of increase of cutting force. The flank wear was increased with chip load. It was demonstrated that insignificant crack with smooth inner wall of drilled hole was obtained as the chip load was 0.1 μ m/rev.

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 μ m. 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 sintered carbide drill of ϕ 0.2. 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

- [1] O.V. Abramov: High-intensity Ultrasonics -Theory and Industrial Applications, Gordon and Breach Science Publishers, Amsterdam, ISBN 90-5699-041-1, 1998
- [2] D.E. Brehl, T.A.Dow, Review of Vibration-assisted Machining, *Prec Eng*, 32 (2007) 153-172
- [3] B. Azarhoushang, J.Akabari, Ultrasonic-assisted drilling of Inconel 738-LC, *Int J Machine Tools and Manuf*, 47 (2008) 1027-1033
- [4] Y.S.Liao, Y.C.Chen, H.M.Lin, Feasibility Study of the Ultrasonic Vibration Assisted Drilling of Inconel Superalloy, *Int J of Machine Tools and Manuf*,

Table 1 Drilling condition for silica glass

No.	Amplitude of vibration μ m	feed rate mm/min	Chip load μ m/rev
1	0.0	1.8	0.3
2	1.3	0.6	0.1
3	1.3	1.8	0.3
4	1.3	3.6	0.6

Figure 8: Result of drilling for silica grass with cutting fluid

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- [5] R.Neugebauer, A.Stoll, Ultrasonic Application in Drilling, *Journal of Material Processing Technology*, 149 (2004) 633-639
- [6] S.S.F. Chang, G.M.Bone, Burr Size Reduction in Drilling by Ultrasonic Assistance, *Robotics and Computer-Integrated Manufacturing*, 21(2005) 442-450
- [7] J. Du. Kim and I. Hyu Choi, Characteristics of Chip Generation by Ultrasonic Vibration Cutting with Extremely Low Cutting Velocity, *International Journal of Advanced Manufacturing Technology*, 14 (1998) 2-6
- [8] Hobbs, J. W., Grene, R. J. And Patterson, E. A., A novel Instrument for Transient Photoelasticity, *Exp. Mech.*, 43-4 (2003), 403-409