Ultrasonic vibration-assisted machining of chemically strengthened glass with workpiece bending

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Abstract

This paper deals with axial ultrasonic vibration-assisted machining with workpiece bending. It was proposed as a novel machining method for the reduction of the chippings at the machined holes during micro through-hole drilling of chemically strengthened glass. In micro through-hole drilling of chemically strengthened glass, machining accuracy and efficiency tend to be low because the material's high hardness and brittleness cause rapid tool wear and large chippings at the inlet and outlet of the machined holes. In order to machine small holes with high accuracy, the reduction of the tensile stress that causes large chippings at the outlet of the machined holes is an issue of primary importance that deserves investigation. In the proposed machining method, the glass plate is bent slightly to be convex upward through the application of a compressive stress at the posterior surface of chemically strengthened glass, with a specially designed jig. Using this proposed method that can reduce the tensile stress, the chipping size at the outlet of the machined holes was successfully reduced with applied compressive stress values of 38.9 MPa. In conclusion, it has been clear that the axial ultrasonic vibration-assisted machining with workpiece bending has the potential for achieving high-precision and high-efficiency machining for chemically strengthened glass.

Key words : Workpiece bending, Helical milling, Ultrasonic vibration, Drilling, Glass

1. Introduction

Chemically strengthened glass is attractive for mobile display devices with touch screens, such as smartphones and tablet PCs. The biggest advantage of chemically strengthened glass is its high strength and stiffness. It is approximately five times stronger than soda lime glass owing to the strengthening by ion exchange (Gy, 2008). With the rapid and widespread usage of mobile display devices and the miniaturization of mechanical components, the demand for micro through-hole drilling of chemically strengthened glass is increasing. However, chemically strengthened glass is regarded as one of the materials that have proven difficult to machine. This is attributed to the material's high hardness and brittleness that causes rapid tool wear and chippings at the inlet and outlet of the machined holes. Several techniques, such as laser machining, electric discharge machining (EDM), and electron beam machining, have been used to machine small diameter holes. Laser machining technology can be used to machine a micro hole 10 μm in diameter. However, the machining accuracy tends to be low because of the residual stresses after laser processing (Isobe, et al., 2012). The use of EDM is limited to conductive materials and formed cracks lead to poor surface quality (Yan, et al., 2002). In addition, the production cost for laser machining, EDM, and electron beam machining tends to be prohibitively large. In view of these facts, mechanical processing methods using a solid tool are more suitable for glass drilling. However, the conventional drilling of chemically strengthened glass produces high tensile stress due to high cutting forces, and invariably leads to low-quality machined surfaces. The tensile stress has been cited to be the main cause of the chippings at the machined holes, primarily because glass is strong under compressive loading, but weak under tension (Mizobuchi

and Ogawa, 2010).

As one of the effective cutting methods for materials that are difficult to machine, the ultrasonic vibration-assisted machining technique has been proposed. Several researchers (Liao, et al., 2007, Zhang, et al., 2014, Suzuki, et al., 2011, Nambu, et al., 2011, and Liu, et al., 2012) have shown that ultrasonic vibration-assisted machining resulted in the reduction of the cutting force, the improvement of the machined surface, and the extension of the tool life in the drilling of steel, Inconel, tungsten carbide and composite materials. In a previous study, the authors proposed an ultrasonic vibration-assisted helical milling method, and evaluated the effects of the grinding parameters on surface chipping (Noma, et al., 2014). They also proposed a recommended grinding procedure to machine the hole with high accuracy, based on the elicited experimental results. The grinding parameters of helical milling, including feed velocity and pitch per revolution, were varied according to the machining depth of the holes. Under the proposed grinding procedure, the chipping size and the thrust force were drastically reduced compared to the conventional cutting method. However, a challenge regarding the machining efficiency still remains, primarily because the axial feed rate decreases near the inlet and outlet of the holes upon use of the proposed grinding procedure. Therefore, as a novel effective machining method for chemically strengthened glass, an ultrasonic vibration-assisted machining with workpiece bending is proposed in this study. In the proposed method, a chemically strengthened glass plate is slightly bent by applying compressive stress to its outlet side. It is expected that the tensile stress that promotes the occurrence of chippings at the outlet of the machined holes during conventional drilling, can be effectively reduced by the application of a compressive stress.

2. Principle of ultrasonic vibration-assisted machining with workpiece bending

2.1 Axial ultrasonic vibration-assisted helical milling

In this study, axial ultrasonic vibration was applied to a micro tool using a specially designed spindle and an ultrasonic device. In the conventional drilling process, the contact between the cutting tool and the workpiece is continuous because the feed rate is kept constant. Consequently, the cutting fluid is not efficiently supplied to the cutting point and chip evacuation is further hampered. On the other hand, the application of axial ultrasonic vibration to the cutting tool leads to an intermittent cutting process that results in an improvement in the flow of the cutting fluid and the chip evacuation process. In addition, the workpiece can be fractured by the tool tip at large acceleration, thereby resulting in a reduction in the cutting force.

The major differences between drilling and helical milling processes result from the differences in the kinematic conditions (Denkena, et al., 2008). In the helical milling process, the diameter of the machined hole is determined by the tool diameter in combination with the radius of the helical path, as shown in Fig. 1. The kinematic of the helical milling process can be described by three grinding parameters: the feed velocity, v_f , the pitch per revolution, a_p , and the cutting speed, v_c . In this milling process, the cutting force is distributed to the X and Y axes and a gap is formed between the cutting tool and the workpiece. In comparison to the conventional drilling process, both the thrust force and the chip evacuation can be improved. Based on prior published research work (Noma, et al., 2014), the authors successfully managed to obtain a synergistic effect by combining the axial ultrasonic vibration-assisted machining and helical milling, in terms of the reduction of the thrust force and the chippings at the machined holes.

Fig. 1 Kinematics of helical milling.

2.2 Machining with workpiece bending

Figure 2 shows the schematic illustration of the conventional machining and the machining with workpiece bending. In the conventional machining process, compressive stress is applied at the inlet, and tensile stress is applied at the outlet because of the thrust force. Higher tensile stress causes large chippings at the outlet of the machined holes. In the machining process with workpiece bending, the glass plate is bent to be convex upward by applying the compressive stress to the outlet side of the chemically strengthened glass. It is expected that the chipping size at the outlet of the machined holes can be effectively reduced because of the application of the compressive stress.

Fig. 2 Schematic illustration of machining with workpiece bending.

3. Experimental setup

To bend the glass plate during processing, a specially designed jig was fabricated. Figure 3 shows the top and side views of the jig for bending the glass plate. The chemically strengthened glass was fixed at the left and right sides by two clamp plates and was bent to be convex upward by pressing with the circular push plate (i.e. the washer). The displacement of the washer along the Z-direction was precisely adjusted by a Z-axis stage, and the center of the glass plate was pushed by the washer.

A three-axis vertical machining center (V33, Makino Milling Machine Co., Ltd.) was used for the grinding tests. Figure 4 shows the experimental setup. A three-component, piezoelectric dynamometer (9257B, KISTLER Co., Ltd.) was set up between the workpiece and the machine tool table to measure the grinding force. A specially designed ultrasonic vibration spindle was used with a maximum rotational speed of 8000 min^{-1} . The vibration spindle was controlled by an ultrasonic vibration controller (Sonic Impulse SD-100, Taga Electric Co., Ltd.). The controller was used to supply the axial ultrasonic vibrations to the milling tool. A piezoelectric crystal oscillator was also fitted in and mounted between the chuck and the collet. The frequency and amplitude of the ultrasonic vibration were 70 kHz and 4.0 μm , respectively. Electroplated diamond tools with 0.4 mm in diameter were used in this study (Fig. 5). These tools were fabricated by affixing a single layer of diamond grains onto the metal core with electroplating. The specification of electroplated diamond tool is summarized in Table 1. The thickness of the chemically strengthened glass was 1.1 mm.

Fig. 3 Top view and side view of jig for machining with workpiece bending.

Fig. 4 Experimental apparatus. (USV, ultrasonic vibration)

(a) Tool dimension

(b) Bottom view

(c) Side view

Fig. 5 Electroplated diamond tool.

Table 1 Specification of electroplated diamond tool.

Diameter	ϕ 0.4 mm
Diamond grains	#400 (average diameter of 40 μ m)
Bonding type	Nickel electroplating
Grains distribution	Random

4. Preliminary tests

4.1 Finite element method analysis of stress distribution

The developed stress distribution upon bending of the glass plate with a specially designed jig was analyzed using FEM software (ANSYS Workbench 15.0). The value of Young's modulus and Poisson's ratio of the chemically strengthened glass are 73.3 GPa and 0.21, respectively. Figures 6 and 7 show the relationships between the displacement of the washer along the Z-direction and the von Mises stress distributions at the anterior and posterior sides of the chemically strengthened glass, respectively. In addition, Fig. 8 shows the von Mises stress distribution of the cross section of the glass plate along the longitudinal direction. When the displacement z is 0 mm, the posterior side of the chemically strengthened glass and the washer are in contact with no indicated bending. From these figures, it is clear that the stresses applied at the anterior and posterior surfaces of the glass plate increase with the increase in the displacement of the washer, i.e. with increases in the bending. Figure 9 depicts the stress values at the anterior and posterior sides of the glass plate. The stress values along the X, Y, and Z directions were calculated at the center of the glass plate. The stress values increased linearly with increases in the washer displacement. Based on the results of the FEM analysis, it is confirmed

that a tensile stress is applied at the anterior side of the glass plate as expected, whereas a compressive stress is applied at the posterior side by bending the glass plate to be convex upward using the specially designed jig. In addition, a compressive stress is also generated along the Z-direction of the glass plate.

Fig. 6 (a-d) FEM results of washer displacement effects on the von Mises stress at the anterior surface.

Fig. 7 (a-d) FEM results of washer displacement effects on the von Mises stress at the posterior surface.

Fig. 8 (a-d) FEM results of washer displacement effects on the von Mises stress of the cross section.

Fig. 9 Stress variation with respect to the washer displacement.

4.2 Strain measurement by strain gauge

The relationship between the displacement of the washer and the generated strains was investigated using a strain gauge. A three-element strain gauge (KFG-1-120-D17-11L1M2S, Kyowa Electronic Instruments Co., Ltd.) was used for strain measurements. Figure 10 shows the schematic diagram of the strain measurement setup. The strain gauge was attached to the center of the chemically strengthened glass using a dedicated instantaneous adhesive. The displacement of the washer was varied at 0.05 mm intervals along the Z-direction, and the generated strains were measured along radial directions at 0°, 45°, and 90° at the anterior and posterior surfaces of the chemically strengthened glass. The maximum principal stress was then calculated according to the following equation:

$$\sigma_{\max} = \frac{E}{2(1-\nu^2)} \left[(1+\nu)(\varepsilon_a + \varepsilon_c) + (1-\nu) \times \sqrt{2\{(\varepsilon_a - \varepsilon_b)^2 + (\varepsilon_b - \varepsilon_c)^2\}} \right] \quad (1)$$

where E is the Young's modulus, ν is the Poisson's ratio, and ε_a , ε_b , ε_c are the strains generated along the three radial directions. The results of the strain measurement and the measured maximum principal stress are shown in Fig. 11 and 12, respectively. It is obvious that the generated strains and stresses exhibit a linear relationship with the displacement of the washer along the Z-direction. In addition, tensile strain was applied at the anterior surface, whereas compressive strain was applied at the posterior surface of the chemically strengthened glass. The generated strains along the X-direction were larger than the corresponding strains along the Y-direction. This was because the length of the glass plate along the X-direction was larger than the length along the Y-direction. As a result, analytical and experimental approaches showed that the tensile and the compressive stresses are applied at the anterior and posterior faces, respectively, and that the compressive stress is also applied at the inner part of the chemically strengthened glass.

Fig. 10 Schematic diagram of the strain measurement apparatus.

Fig. 11 Relation between measured strains and washer displacement.

Fig. 12 Relation between measured maximum principal stress and washer displacement.

5. Grinding tests

Grinding tests were carried out with the application of ultrasonic vibration. The through-holes with diameter of 0.6 mm were machined in the center of the glass plate. The displacement of the washer along the Z-direction was varied at 0.05 mm intervals during the grinding tests. Table 2 shows the grinding conditions for ultrasonic vibration-assisted helical milling.

5.1 Evaluation of machined hole accuracy

The effects of the proposed method on the accuracy of the machined holes were evaluated. The chipping sizes at the inlet and outlet of the machined holes were measured using a digital microscope (VHX-600, KEYENCE Co., Ltd.). As shown in Fig. 13, the chipping size was defined as the maximum chipping width generated along the radial direction. Grinding tests were repeated four times for each grinding condition, and the results are shown in Fig. 14. This figure shows the average values of the chipping size on the vertical axis and the measured maximum principal stresses (Section 4.2) along the horizontal axis. The machining time per hole was 20 seconds. Figures 15 and 16 show the observed results for the machined holes at the inlet and outlet, respectively. As shown in Fig. 14 and 15, the chipping sizes at the inlet of the machined holes increased with increases in the tensile stress. When no bending was imposed (tensile stress of 0 MPa), the chipping size at the inlet of the machined holes was the smallest. This was because glass is weak under tensile loading, and large tensile stress caused large chippings at the inlet of the machined holes. On the other hand, at the outlet of the machined holes, the chipping sizes were reduced upon the application of compressive stresses with absolute values less than 40 MPa. The chippings were successfully reduced upon application of the compressive stress. However, the chipping

sizes increased with applied compressive stresses higher than 40 MPa in absolute value. With respect to the outlet of the machined holes, the chipping size was the smallest at a compressive stress with a value of 38.9 MPa. As shown in Fig. 16, the chipping size at the outlet of the machined hole is strongly influenced by the intensity of the applied compressive stress.

Table 2 Grinding conditions for helical milling.

Condition type	Condition
Axial USV	70 kHz/4.0 μm
Workpiece	Chemically strengthened glass ($60 \times 30 \times 1.1 \text{ mm}^3$)
Tool	Electroplated diamond tool (ϕ 0.4 mm)
Grinding fluid	Soluble type
Feed velocity	80 mm/min
Pitch per revolution	0.05 mm
Rotation speed	8000 min^{-1}
Hole depth	1.1 mm (penetrated)

Fig. 13 Surface chipping image captured with a digital microscope.

Fig. 14 Relation between chipping size and measured maximum principal stress.

Fig. 15 (a-d) Effects of tensile stress on the accuracy of the inlet of machined holes.

Fig. 16 (a-d) Effects of compressive stress on the accuracy of the outlet of machined holes.

5.2 Evaluation of thrust force

The relationship between the average thrust force and the displacement of the washer was also evaluated. The average thrust force was calculated from the thrust force measured through entire hole-machining. Figure 17 shows the average thrust force. The thrust force increased with the increase in the displacement of the washer. This was due to the compressive stress applied at the inner parts of the chemically strengthened glass. Based on the results of the FEM analysis, compressive stresses were generated along the direction of the thickness of the chemically strengthened glass (Z-direction), and it is considered that the compressive stress acting in the opposite direction to the thrust force increased the average thrust force. Increases in the thrust force associated with washer displacements of 0.25 mm and 0.3 mm contributed to the increase in the chipping size at the outlet of the machined holes.

Fig. 17 Relation between average thrust force and washer displacement.

5.3 Grinding test under optimum grinding procedures

From the grinding tests, the compressive stress of 38.9 MPa, which was generated with a washer displacement of 0.2 mm, was the most appropriate value for suppressing the chippings at the outlet of the machined holes. A possible reasoning for this finding is that the value of the tensile stress that occurred when the milling tool penetrated the posterior surface of the chemically strengthened glass was close to 38.9 MPa. The tensile stress that causes large chippings at the outlet of the machined holes was effectively canceled by a compressive stress of a similar magnitude generated along the opposite direction to the direction of the generated tensile stress. The compressive stress that was larger than the tensile stress led to an increase in the thrust force, and consequently, to large chippings. With respect to the inlet of the machined holes, the chipping size increased with the tensile stress. The chipping size was the smallest at a stress value of 0 MPa (displacement of 0 mm).

Based on the results of the grinding tests, an optimum grinding procedure was proposed to machine holes at both the inlet and the outlet of chemically strengthened glass with high accuracy. The grinding process was performed without bending up to a depth of 0.7 mm. At that depth, the chemically strengthened glass was penetrated upon bending of the glass plate. The compressive stress generated at the posterior surface was adjusted to a value close to 40 MPa by adjusting the displacement of the washer to 0.2 mm. Fig. 18 shows the schematic diagram of the proposed optimum grinding procedure. The grinding tests were carried out twice and the chipping sizes under the optimum grinding procedure are summarized in Table 3. As shown in Table 3, high-precision holes were machined at both the inlet and outlet using this optimum grinding procedure. In a previous study, the authors proposed an ultrasonic vibration-assisted helical milling method under recommended grinding procedure that can drastically reduce the chipping size (Noma, et al., 2014). However, the machining time per hole was about 120 seconds, and a challenge regarding machining efficiency remains. Using the proposed method in this study, the machining time per hole can be reduced by 83% compared with previous method. As a result, it is concluded that axial ultrasonic vibration-assisted machining with workpiece bending has the potential to improve the processing time and the quality of the machined surface.

Fig. 18 Schematic diagram of optimum grinding procedure.

Table 3 Chipping sizes under optimum grinding procedure.

Test number	Chipping size μm	
	Inlet	Outlet
1st	41.69	74.40
2nd	59.17	72.20

6. Conclusion

Axial ultrasonic vibration-assisted machining with workpiece bending was proposed in this study, and the validity of this method was evaluated. From the experimental results, the following conclusions are deduced:

1. Based on the analysis results of stress distribution by FEM, it has been shown that compressive stresses can be applied at the posterior side of the chemically strengthened glass with a specially designed jig.
2. The relationship between the displacement of the circular push plate (i.e. the washer) and the

generated strains was investigated using strain gauges. It was found that the generated strains exhibit a linear relationship with the amount of bending.

3. The chipping sizes at the outlet of the machined holes were successfully reduced by the application of a compressive stress. It is inferred that an appropriate stress value exists for suppressing the chippings at the outlet of the machined holes.
4. The thrust force increased with the increase in the displacement of the washer because of the compressive stress acting in the opposite direction to the thrust force. It is considered that the higher thrust forces developed at the washer displacement of 0.25 mm and 0.3 mm contributed to the increase in the chipping sizes.
5. Under the optimum grinding procedure, high-precision outcomes were obtained both at the inlet and the outlet of the machined holes. In addition, using the proposed method in this study, the machining time per hole can be reduced by 83% compared with previous method.

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