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Fundamental Study of Hole Machining by Ultrasonic Complex Vibration
超音波複合振動による穴あけ加工の基礎検討

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1. Introduction

Currently, ultrasonic vibration and polishing slurry are used in combination as an effective method for machining holes in brittle materials such as glass. However, conventional methods use only ultrasonic longitudinal vibration, and few studies have been conducted on ultrasonic machining using complex vibration and polishing slurry. Removal rate and machining accuracy are also expected to be improved by using ultrasonic longitudinal-torsional vibration. In a previous study, we examined ultrasonic longitudinal-torsional vibration for hole machining[1)], and we developed a hollow-type stepped horn with diagonal slits as a vibration converter for hole machining by ultrasonic complex vibration. In this paper, we process soda-lime glass with longitudinal vibrators and the complex vibrators. The longitudinal-torsional vibrator has diagonal slits, and the longitudinal vibrator does not; for each type, the vibrator is a hollow-type stepped horn or a uniform rod.

2. Ultrasonic Vibration Source

Figure 1 shows the ultrasonic vibration source. This source consists of a 20 kHz bolt-clamped Langevin-type transducer, a uniform rod with a flange, an exponential horn for amplitude amplification (amplification factor, ≈4.7; material, duralumin), and the hollow-type stepped horn (with dimensions shown in **Fig. 2**) or uniform rod.

Figure 2 shows the hollow-type stepped horn with or without the diagonal slit vibration converter. The dimensions of the hollow-type stepped horn are as follows: length, 120 mm; cross-sectional area of the transducer side S_1, 113 mm^2 (12 mm diameter); cross-sectional area of the tip side S_2, 28.1 mm^2; depth of the hollow part, 60 mm; and cross-sectional area ratio S_1/S_2, 4.0. The uniform rod is a vibrator without the hollow part of the hollow-type stepped horn and has a cross-sectional area ratio of S_1/S_2 = 1.0. In addition, to ensure a regular removal volume, an edge is fabricated at the tip side of the uniform rod (**Fig. 3**). The exterior appearance of the diagonal slits is shown in **Fig. 4**, where the slit specifications are as follows: length, 19 mm; groove width, 0.5 mm; depth, 3.5 mm; inclination angle, 35°; and number of slits, 8.

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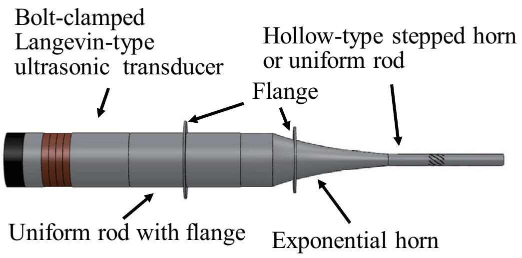

Fig. 1 Ultrasonic vibration source.

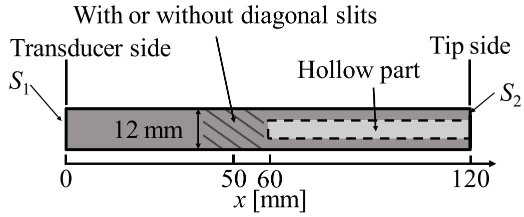

Fig. 2 Hollow-type stepped horn with and without diagonal slits.

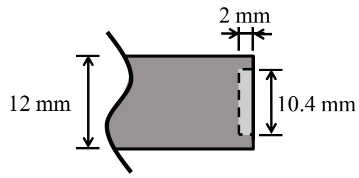

Fig. 3 Edge of uniform rod at tip side.

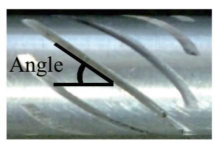

Fig. 4 Appearance of diagonal slits.

3. Experimental Processing of Soda-lime Glass with Each Vibrator

The experiments involved a comparison between hole machining of soda-lime glass which was performed by using the longitudinal vibrators or the complex vibrators. Two soda-lime glass plates were glued together to prevent chipping. **Table I** shows the machining conditions. Polishing slurry was supplied to the cutting side of the glass at approximately 1 L/min. To increase the cutting depth, pressure was applied from the bottom side of the soda-lime glass. **Table II** shows zero-to-peak (0-p) values of the longitudinal and torsional vibration amplitudes at the tip side of each vibrator when machining the holes.

3.1 Machining time

Figure 5 shows the experimental results for machining time. The vertical and horizontal axes represent the machining time and the vibrator conditions, respectively, where the measured and average values of the machining time are plotted. According to Fig. 5, the machining times by complex vibration were found to be more stable when compared with the longitudinal vibration. Clearance for circulation of the slurry is assumed to be more easily generated by the torsional vibration. Additionally, the average machining time for all the vibrators—both longitudinal and complex— was similar at around 90 s. Therefore, torsional vibration had almost no effect on the average machining time in the measurement range at this time.

3.2 Hole roundness

Figure 6 shows the experimental results for hole roundness error. Methods for evaluating roundness error are least square circle (LSC) method. The vertical and horizontal axes in Fig. 6 represent the hole roundness error (LSC) and the vibrator conditions, respectively, and the measured and average values are plotted. According to Fig. 6, the roundness error values attained its minimum value of ≈13 μm for the case of the complex vibration with the uniform rod. Consequently, the density of the slurry along the circumference is thought to be equal when the torsional vibration is used. Furthermore, the average roundness error was lower for the complex vibration of the uniform rod. However, the average roundness error for the complex vibration of the hollow-type stepped horn, and for both the longitudinal vibrators, were similar. This similarity can be attributed to the torsional vibration amplitude of the hollow-type stepped horn being smaller than the longitudinal vibration amplitude.

4. Conclusions

In this study, the machining of soda-lime glass with the longitudinal vibrators and the complex vibrators was investigated. As a result, the following issues were clarified: firstly, the average machining time was similar for both the longitudinal vibrators and the complex vibrators; and secondly, roundness error was improved by complex vibration, especially when using a uniform rod vibrator.

Acknowledgment

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Table I Machining conditions.

Material of vibrator	Duralumin
Process material	Soda lime glass
Processing depth	1.3 mm
Abrasive grain	Silicon carbide 320(40 μm) Weight ratio grain:water = 1:10
Processing fluid	Water
Processing pressure	14 N
Processing frequency	19.9–20.9 kHz

Table II Machining vibration at the tip side.

	Vibration amplitude at the tip side	
	Longitudinal	Torsional
$S_2/S_1 = 1.0$ with slits	≈ 10 $\mu m_{0\text{-}p}$	≈ 15.2 $\mu m_{0\text{-}p}$
$S_2/S_1 = 1.0$ without slits	≈ 10 $\mu m_{0\text{-}p}$	≈ 0 $\mu m_{0\text{-}p}$
$S_2/S_1 = 4.0$ with slits	≈ 10 $\mu m_{0\text{-}p}$	≈ 3.4 $\mu m_{0\text{-}p}$
$S_2/S_1 = 4.0$ without slits	≈ 10 $\mu m_{0\text{-}p}$	≈ 0 $\mu m_{0\text{-}p}$

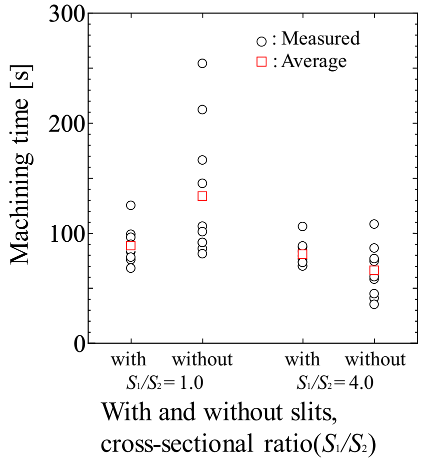

Fig. 5 Relationship between the vibrator conditions and machining time.

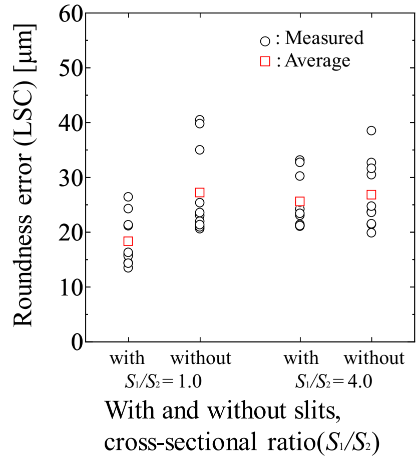

Fig. 6 Relationship between the vibrator conditions and hole roundness error.

References

1) T. Asami and H. Miura : Jpn. J. Appl. Phys. **50** (2011), 07HE31.