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A Study on the Development of Rotary Ultrasonic Machining Spindle

Chang-Ping Li*, Min-Yeop Kim*, Jong-Kweon Park**, Tae-Jo Ko*,#
*School of Mechanical Engineering, Yeungnam University,
**Korea Institute of Machinery & Materials

회전 초음파가공 주축 개발에 관한 연구

이상평*, 김민엽*, 박종권**, 고태조*,#
*영남대학교 기계공학과, **한국기계연구원

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ABSTRACT

Ultrasonic machining (USM) has been considered a new, cutting-edge technology that presents no heating or electrochemical effects, with low surface damage and small residual stresses on brittle workpieces. However, nowadays, many researchers are paying careful attention to the disadvantages of USM, such as low productivity and tool wear. On the other hand, in this study, a high-performance rotary ultrasonic drilling (RUD) spindle is designed and assembled. In this system, the core technology is the design of an ultrasonic vibration horn for the spindle using finite element analysis (FEA). The maximum spindle speed of RUM is 9,600 rpm, and the highest harmonic displacement is 5.4 μm noted at the frequency of 40 kHz. Through various drilling experiments on glass workpieces using a CVD diamond-coated drill, the cutting force and cracking of the hole entrance and exit side in the glass have been greatly reduced by this system.

Keywords : Rotary Ultrasonic Machining(회전초음파가공), Horn(혼), Glass(유리), Spindle(주축), Finite Element Analysis(유한요소해석)

1. Introduction

In recent years, ceramics, glass and other advanced materials are being widely used in the fields of semiconductor, automobile, aerospace and electronics industries. Ultrasonic machining (USM) has been considered as a new cutting technology that is widely used in drilling on workpiece of brittle nature, such as glass, ceramics, stones etc[1].

However, with the rapid development of science and technology, today’s USM is facing challenges from advanced difficult-to-machining materials (tough super alloys, ceramics and composites), high surface quality, tool wear and machining costs. USM is very slow and tool wear dependent, so the entire process has low efficiency[2] and the cost of machining

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Corresponding Author : tjko@yu.ac.kr
Tel: +82-53-810-3836, Fax: +82-53-810-4627

ceramic components by USM has been reported to be as high as 90 % of the total cost[3]. However, a more cost-effective method for machining brittle materials is needed[4].

Rotary ultrasonic machining (RUM) is considered as a strong alternative to USM[5]. RUM, which presents ultrasonic axial vibration with tool rotation and does not need the slurry in the machining process usually. RUM is also considered as a hybrid machining process which combines the mechanism of material removal of conventional processes (grinding, drilling, milling) and USM[6,7,8]. Typically, the cylindrical rod or core drill tools are used in RUM [7,9]. These tools can not drilling micro hole on the brittle materials easily because of the tool shape or the inherent size[2].

The purpose of this research is to develop a high-speed rotary ultrasonic drilling (RUD) spindle and through a large number of experiments to investigate of the performance of the machine and the effect of ultrasonic vibration on crack of hole side and cutting force.

2. Rotary Ultrasonic Drilling System

2.1 RUD system structure

Fig. 1 shows the hybrid machining set-up with developed RUD spindle. The set-up consists of CNC milling (Hyper-15, hybrid precision company), transducer (4545D-40HA, durasonic company), ultrasonic generator (1.5 kHz - 100 kHz, hybrid precision company), RUD spindle, electric flushing pump, PC, spindle inverter (LS company).

2.2 Rotary ultrasonic drilling theory

RUD is a machining process that combines drilling and ultrasonic machining. The trajectory of a single point on the edge of cutting tool for RUD includes rotation, feed motion and ultrasonic vibration in the direction of tool axis as shown in Fig. 2. This trajectory can be defined as

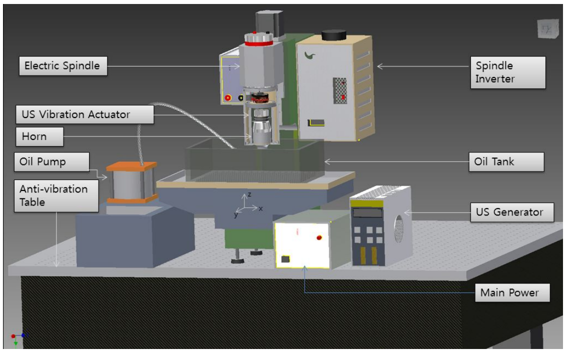


Fig. 1 The structure of RUD system

$$r_{RUM}(t) = \begin{cases} r\sin(\omega t) + x_{feed}t \\ r\cos(\omega t) + y_{feed}t \\ A\sin(2\pi f t) + z_{feed}\,t \end{cases} \tag{1}$$

Where r is the rotation radius, ω is the rotational velocity, A is the amplitude, f is the ultrasonic frequency, t is the time and x_{feed}, y_{feed}, z_{feed} are the feed rates in x, y, z directions, respectively.

2.3 Horn design

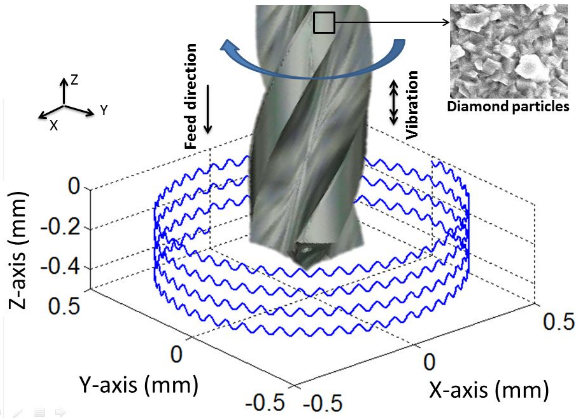


Fig. 2 Trajectory of a single point on the edge of cutting tool for RUD

In the RUD spindle, the core technology is to design an ultrasonic vibration horn for the spindle using finite element analysis (FEA). In fact, a variety of ultrasonic horn is used in the ultrasonic processing machine shown as in Fig. 3. Conical horn, exponential horn and step horn. The horn is necessary because the amplitude provided by the transducers themselves are insufficient for most practical applications of power ultrasound[10] and horn also can transfer the vibration energy form ultrasonic transducer to tool and workpiece.

A step horn is designed, since it can produce the maximum amplitude than other horn in the same conditions and made up of same material i.e. stainless steel. In this system an ultrasonic transducer is used having a resonance frequency of 40 kHz in the longitudinal direction. Therefore, in order to make a horn resonance, resonance frequency must be equal to 40 kHz.

$$L=\frac{1}{2}\times\frac{C}{f} \qquad (2)$$

$$C=\sqrt{\frac{E}{\rho}} \qquad (3)$$

where L is the length of horn, *m*; C is the longitudinal wave sound speed of horn material, *m/s*; f is the resonance frequency of horn, Hz; E is the Youngs modulus of the horn material, Pa; ρ is the density of the horn material, kg/m^3. The analysis properties of the horn as shown Table 1. According to the following formula (2), (3) and parameter values from Table 1, horn length is found to be 63.1 mm. Φ1 and Φ2 is the diameter of input surface and output surface, respectively. Φ1 is equal to the diameter of output surface of ultrasonic transducer and Φ2 depends on the diameter of tool. L1 and L2 have the same length is $\lambda/2$ as 31.55 mm. The value of R is then varied to change the resonance frequency of the horn. R value was solved using FEA as the only unknown data.

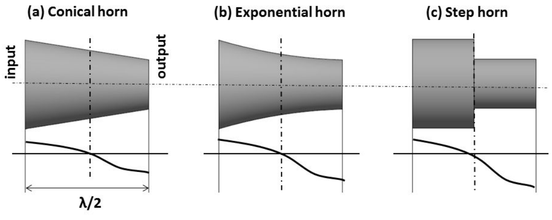


Fig. 3 Schematic of diagram ultrasonic horn and amplitude

FEA is world widely used mothed, because of it's many advantages, such as high calculation accuracy, shorter development time and cost savings. Analysis properties as shown Tabel 1. The material of the horn is SM45C was used and FEA of the horn resonance frequency was performed using the modal and harmonic response method (ANSYS-Workbench).

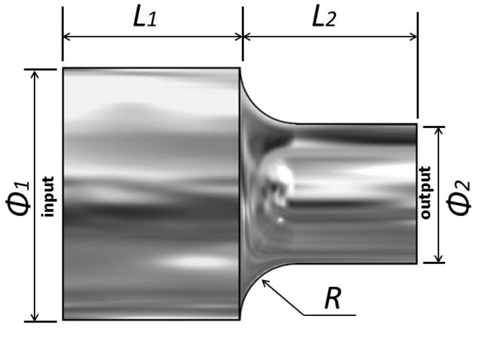
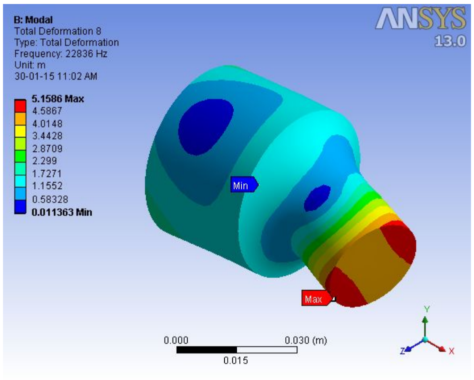


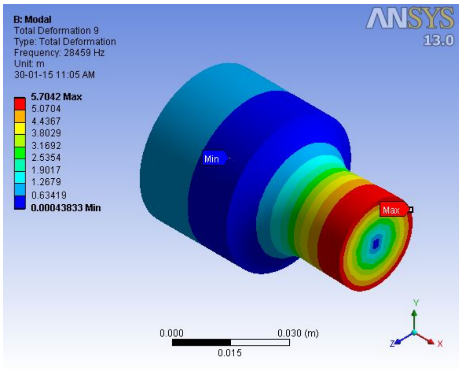
Fig. 4 Step horn design

Table 1 Analysis properties of horn

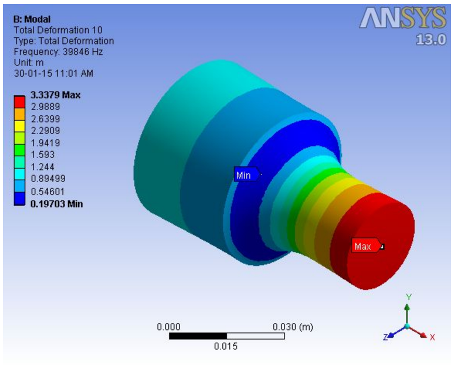
Items	Type
Analysis method	Modal; Harmonic response
Unit	Metric (Kg, m, s, A, N, V)
Horn material	SM45C
Material properties	Young's modulus : 210 GPa
	Poissons ratio : 0.3
	Density : 7850 kg/m^3



(a) 8th mode (22836 Hz)



(b) 9th mode (29845 Hz)



(c) 10th mode (39864 Hz)

Fig. 5 The mode shapes of step horn

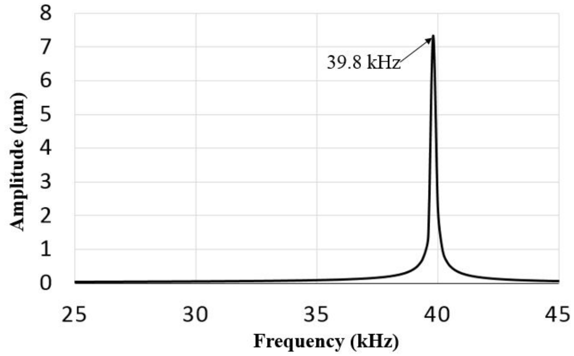


Fig. 6 Harmonic response analysis results

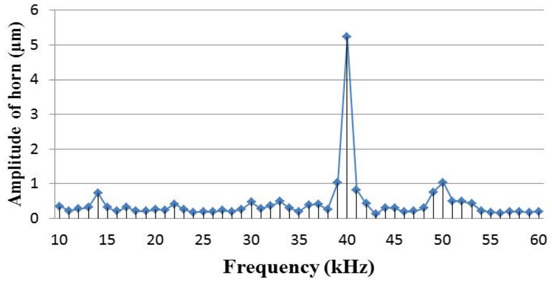


Fig. 7 Amplitude of the horn

In the initial analysis, analysis and target values have a great deviation. After that R value is adjusted performing modal analysis several times. Finally, when R=15 mm, the optimum results are obtained as shown in Fig. 4. The 8th mode (22836 Hz) is the bending vibration, the 9th mode (29845 Hz) is the torsional vibration and the 10th mode (39864 Hz) is longitudinal vibration as shown the Fig. 5 (a), (b) and (c), respectively. From the Fig. 5 (c), the maximum amplitude appears at the output surface of the horn and the minimum amplitude appears in the middle position of the horn are noted. This is due to the fact that the middle position of the horn was fixed as a node point in the spindle system. The results of the harmonic response analysis of the horn as shown in Fig. 6 and the maximum amplitude is noted when the frequency is 39800 Hz.

In order to verify the accuracy of the FEA results, the step horn was manufactured according to the design size and it was installed in the RUD system. The amplitude of the output surface of the horn was measured using a fiber optic sensor and the results are shown in the Fig. 7. The maximum vibration displacement of the horn is 5.4 μm when the frequency is 40 kHz. From the results, the deviation of the actual resonance frequency is compared to FEA resonance frequency and is found to be 0.34%. This result meets the design requirements, So, the usage of FEA to optimize the design of ultrasonic horn is effective and feasible.

3. Experiments verification

3.1 Design of experiment

This RUD spindle was manufactured and was installed on the CNC machine tools as shown Fig. 9 and the Fig. 10 shows schematic diagram of the RUM process. The maximum spindle speed with ultrasonic vibration, ultrasonic frequency, and amplitude were 9,600 rpm, 40 kHz, and 5 µm, respectively. Rotary ultrasonic drilling on glass experiments are conducted on this system. The experiments setup mainly consists of a RUD spindle, a CNC machine system, high frequency oscilloscope (200 MHz) and two cooling systems that are the first one is for machining process using kerosine and the second one is for the spindle using air pressure. The cutting force data is acquired by a dynamometer (Kistler, Switzerland). The cutting tool was the CVD diamond-coated drill (GCT GmbH, Germany) that is ideally suitable for drilling glass, quartz, technical ceramics due to application-specific design and thicker diamond coating. This tool is differs from the electroplated diamond abrasive hollow cylindrical tool

Fig. 8 CVD diamond-coated drill[11]

Table 2 Experimental conditions

Items	Type	
Ultrasonic frequency	40 kHz	
Ultrasonic displacement	5 µm	
Spindle speed	5000 rpm	
Feed rate	10 (µm/s)	
Tool	Type	CVD diamond-coated drill
	Diameter	0.5 mm
Workpiece	Type	Soda lime glass
	Thickness	1 mm

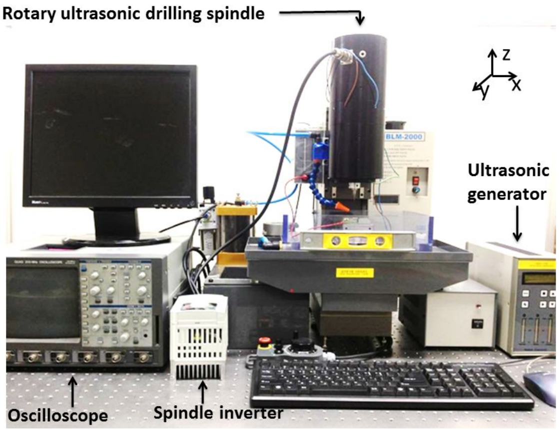


Fig. 9 Experimental set-up

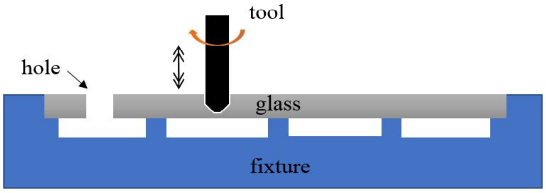
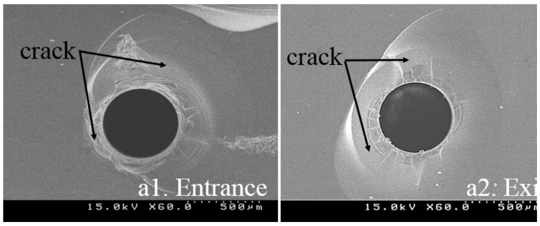


Fig. 10 schematic diagram of the RUM process as shown Fig. 8.

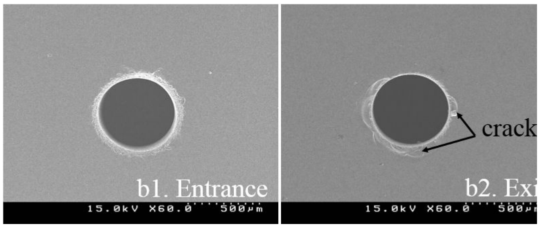
The conditions of the experimental are shown in Table. 2. Ultrasonic frequency, type of tool and workpiece are 40 kHz, CVD diamond-coated drill (diameter is 0.5 mm) and soda lime glass (thickness is 1 mm), respectively. The cutting parameters, such as spindle speed and feed rate are 5000 rpm and 10μm/s, respectively. In order to investigate the effect of ultrasonic vibration on the machining, amount of ultrasonic displacement are 0 and 5 micrometers were used.

3.2 Experimental results and discussion

The SEM images of machining results are shown in Fig. 10. The Fig. 11(a) and Fig. 11(b) display the results of conventional drilling and RUD, respectively. One phenomenon is the appearance of catastrophic chipping as shown Fig. 11(a). In contrast to entrance crack is almost zero after RUD as shown in Fig. 11(b). Fig. 12 displays the cutting force of Z-axis with and without ultrasonic vibration. Cutting force reduced to about one-half when ultrasonic vibration is used.



a. The results after conventional drilling (without ultrasonic)



b. The results after RUD

Fig. 11 Comparison with RUD and conventional drilling process

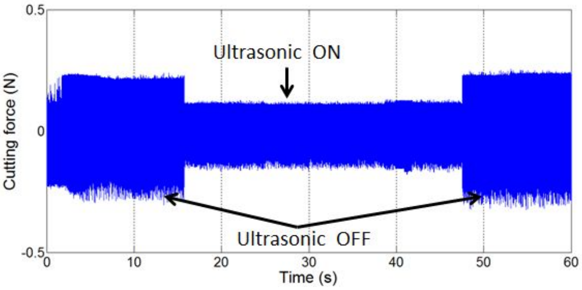


Fig. 12 Cutting force of Z-axis with and without ultrasonic vibration

4. Conclusion and remarks

In this study, we have developed a RUD hybrid machining system by FEA method. The maximum spindle speed, maximum amplitude of horn and resonance frequency are 9,600 rpm, 5.4 μm and 40 kHz, respectively. The results of amplitude measurements and harmonic response analysis are almost identical as shown in Fig. 6 and Fig. 7, respectively. The RUD process combines cutting action and ultrasonic vibration using a CVD diamond-coated drill. In this experimental investigation, the effect of ultrasonic vibration on entrance and exit crack were examined. Experiments were performed on soda lime glass workpiece at different ultrasonic amplitude conditions. The results have shown conventional drilling leads to a more severe cracks as shown in Fig. 11(a) and a reduction in crack propagation significantly than traditional drilling process as shown in Fig. 11(b). Moreover, about 50% decrease in cutting force can also be observed as shown in Fig. 12. This possible decrease in cutting force is associated with high ultrasonic vibration.

In future, experiments will be designed to control the generation of crack during drilling of variety of brittle material. response surface method will be used to find optimal conditions of amplitude, feed rate, and spindle speed.

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References

1. Legge, P., "Ultrasonic drilling of ceramics," Ind Diam Rev, Vol. 24, No. 278, pp. 20–-24, 1964.
2 Liu, J. W., Jin, J., Ko. T. J. and Baek. D. K., "Study of Optimal Machining Conditions of Ultrasonic Machining by Taguchi's Method," T. of KSME A, Vol. 37 No. 2, pp. 213-218, 2013.
3. Jahanmir, S., Ives, L. K. and Ruff, A. W., "Ceramic machining: assessment of current practice and research needs in the United States", NIST Special Publication 834, 1992.
4. Li, Z. C., Cai, L. W., Pei, Z. J and Treadwell C., "Edge-chipping reduction in rotary ultrasonic machining of ceramics: finite element analysis and experimental verification," Int J. Mach Tools Manuf, Vol. 46, No. 12-13, pp. 1469–1477, 2006.
5. Liu, J. W., Baek, D. K. and Ko. T. J., "Chipping Minimization in Drilling Ceramic Materials with Rotary Ultrasonic Machining", Int J. Adv Manuf Technol., Vol.72, No.9-12, pp. 1527-1535, 2014.
6. Zeng, W. M., "Experimental observation of tool wear in rotary ultrasonic machining of advanced ceramics," Int J. Mach Tools Manuf., Vol. 45, No. 12-13, pp. 1468-1473, 2005.
7. Kadivar, M. A,. Akbari, J., Yousefi, R., Rahi, A., and Nick, M. G., "Investigating the Effects of Vibration Method on Ultrasonic-assisted Drilling of Al/SiCp Metal Matrix Composites," Robotics and Computer-Integrated Manufacturing, Vol. 30, No. 3, pp. 344-350, 2014.
8. Li, C. P., Kim, M. Y., Ko, T. J. and Park, J. K., "The Effects of Ultrasonic Vibration on Surface Finish and Tool Wear in End-milling Machining," Int Conference on 3M-NANO, pp. 330-334, 2012.
9. Zeng, W. M. and Li, Z. C., "Experimental Observation of Tool Wear in Rotary Ultrasonic Machining of Advanced Ceramics", Int J. Mach Tools Manuf, Vol. 45, No. 12-13, pp. 1468-1473, 2005.
10. Peshkovsky, S. L. and Peshkovsky, A. S., "Shock-wave Model of Acoustic Cavitation", Ultrason. Sonochem., Vol. 15, No. 4, pp. 618-628, 2008.
11. "CVD diamond-coated drill," (2015) http://www.gctool.com(accessed 11, Feb., 2015)