Proc. of the 9th Intl. Conf. of Asian Society for Precision Engg. and Nanotechnology (ASPEN 2022)
15–18 November 2022, Singapore. Edited by Nai Mui Ling Sharon and A. Senthil Kumar
doi://10.3850/978-981-18-6021-8_OR-14-0213

Development of Ultrasonic Transducer with Flexure Hinge for Ultrasonic Spindle Milling

Rendi Kurniawan[1], Moran Xu[1], Minki Choo[1], Shou Chen[1], Yein Kwak[1], Saood Ali[1], Pilwan Han[2], Tae Jo Ko[1,#]

1 Department of Mechanical Engineering, Yeungnam University, 280 Daehak-Ro, Gyeongsan-si, Gyeongbuk-do, South Korea
2 Korea Electrotechnology Research Institute (KERI), 10 beon-gil Bulmosan-ro, Changwon-si, Gyeongsangnam-do, South Korea
Corresponding Author / Email: tjko@yu.ac.kr, TEL: +82-053-810-3836, FAX: +82-053-810-4627

KEYWORDS: Ultrasonic transducer, Simulation transient, Modal analysis, Milling, Cutting force

This article presents the development of ultrasonic transducer with flexure hinge design for ultrasonic spindle milling (USM) system. The ultrasonic transducer has been designed based on the first mode of longitudinal vibration mode. The ultrasonic transducer has been designed to work at ultrasonic frequency about 30 kHz without considered the tool. However, it was found that the working frequency is between 25 and 27 kHz according to impedance measurement when the tool was installed. The flexure hinge (symmetrical circular shape) on the flange has been utilized to increase the vibration amplitude although the stiffness is downgraded. According to the transient structural analysis, it is confirmed that the thickness and radius of the flexure hinge influenced the displacement output of the Ultrasonic transducer. The simulation results confirm that the displacement output can be produced up to 6.5 μm under given dynamic force 5,120 N with flexure hinge radius of 2.5 mm and thickness of 2.4 mm. The experimental measurement of amplitude has been also carried out to validate the simulation which is confirmed that the amplitude can be produced about more than 20 μm. Next, the performance of ultrasonic spindle is tested by side-milling. The experimental results showed that the performance of ultrasonic spindle milling can improve the machinability in the side-milling of Al 6061 material.

1. Introduction

Ultrasonic vibration-assisted milling (UVAM) is converting the high-frequency electrical energy onto the mechanical energy to vibrates the milling tool to obtain intermittent milling process[1]. The intermittent contact between the milling flute and the workpiece decreases the average cutting force as reported by Pang et al[2] during milling Titanium alloy. The UVAM also gives others benefits such as decreasing cutting temperature[3], extending the tool life[4], and improving roughness on the side wall[1].

The UVAM achieves better machinability compared to conventional milling (CM) according to following literature review. Shen et al.[1] examined the UVAM at aluminum alloy with considering the feed-direction of vibration effect in slot-milling. The vibration amplitude of 0, 4, 6, 8 μm was utilized by them. Their result reveals that the average cutting force in UVAM along feed and normal direction is lower than that in the CM. Janghorbanian et al.[4] studied the effect of cutting speed on the tool life in the UVAM. They found that the tool life in the UVAM is longer than that in the CM at rotational speed of 3,150 rpm due to less amount of plastic deformation and less impact contact.

Liu et al.[5] examined the tool wear in UVAM during milling of C/SiC composites. According to their observation, when the ultrasonic vibration amplitude increases from 0 to 10 μm, the tool wear minimum has been found at amplitude of 6 μm. And amplitude of 6 μm is optimum value in their study. It has been found that the excessive vibration amplitude such as 10 μm will damage the stability of the cutting process and increases the surface roughness. Pang et al.[2] analyzed the UVAM by the effect of the longitudinal-torsional vibration during milling Titanium alloy. An excellent surface integrity and regularity has been achieved when the longitudinal-torsional was utilized.

The UVAM performance depends on the characteristic of the ultrasonic transducer as the key. The ultrasonic transducer usually operates in above 20 kHz and with low vibrational amplitude in range 10 μm[6]. In previous development, Amin et al.[7] suggested the horn profile is conical at the top and the cylindrical at the bottom based on optimization using finite element modeling (FEM). Their combination horn between cylindrical and conical shape can produce magnification factor about 8, which is higher than exponential and conical shape alone. Zou et al.[8] designed the vibration horn which is adopted a stepped horn of the half-wavelength. The natural frequency of 20 kHz is the main frequency in their mechanism.

The bolt clamped Langevin type transducer (BLT) design is adopted in this study. The BLT design has been explored in the past 20 years. The BLT generally consists of the horn (emitter), the back mass (reflector), and piezoelectric ceramic actuator (PZT). Recently, the application of the BLT has been growing in precision metal cutting. Beihang University[9] developed a transducer driven by a single actuator for precision cutting. Their transducer works in frequency range of 22.5 kHz and amplitude of 2 – 16 µm. The Yeungnam University[10] developed a transducer for precision texturing of micro-groove. The frequency is about 24 kHz, although the amplitude is small about 0.3 – 0.8 µm.

The development of the ultrasonic transducer for UVAM has been extensively explored. Moreover, the commercial version has been available such as DMG MORI. Corp. and Altrasonic. Corp. It seems that the development has been done for ultrasonic transducer in the UVAM, but the improvement regarding working frequency range and higher amplitude is still interested to be explored more. Recently, the 2D vibrations are also added such as torsional and bending mode into the ultrasonic transducer[11]. Moreover, the torsional and bending mode is required to improve the feasibility of the UVAM [2].

The authors are motivated to explore more the UVAM. Therefore, the ultrasonic transducer has been developed to realize the authors objective. Even though the commercial transducer is already available, but the improvement is still necessary to do. In this paper, the development of ultrasonic transducer design in UVAM is presented regarding to the simulation and experimental analysis. The analysis of the stiffness flexure has been also examined. The variation of the overhanging tool and material is the main factors which are investigated in this study. Furthermore, the feasibility of the UVAM using the developed ultrasonic transducer has been also carried out.

2. Design of the Ultrasonic Transducer

2.1 Construction

The construction of the ultrasonic transducer is shown in Fig. 1. It consists of step horn with flange, piezoelectric actuators (PZT), conical back mass, and preload-bolt. The design of flexure hinge is adopted in the flange. The longitudinal vibration should be transferred smoothly through the flexure hinge. The fixed-point plane is contact to another body as considered zero motion. The flexure hinge of circular symmetrical has been adopted. The titanium material has been selected for the step horn and the back mass.

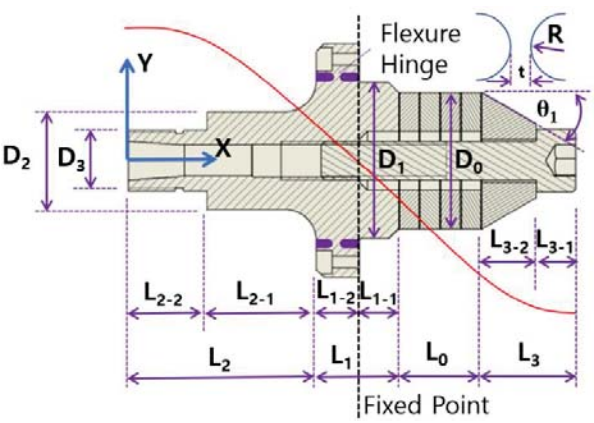

Fig. 1 Structure parameter of ultrasonic transducer

Table 1 Final dimension of the ultrasonic transducer [unit: mm]

L_0	L_1	L_2	L_3	D_0	D_1	D_2	D_3
21.25	18.5	47	16	35	40	25	15

Table 2 Material properties of the ultrasonic transducer (ANSYS)

Part	Materials	Modulus	Density	Poisson
Step horn	Titanium	96,000 MPa	4,620 kg/m^3	0.36
Back mass	Steel	200,000 MPa	7,850 kg/m^3	0.3
Bolt	Steel	200,000 MPa	7,850 kg/m^3	0.3
Piezo[6]	PZT-S44	80,000 MPa	7,700 kg/m^3	0.32

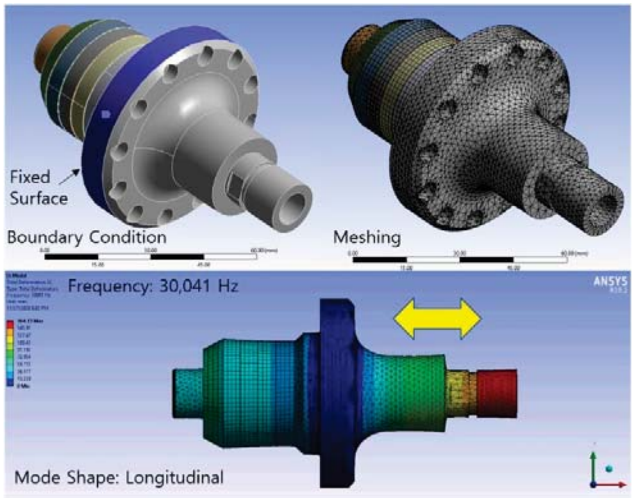

Fig. 2 Boundary condition, meshing, and longitudinal mode shape

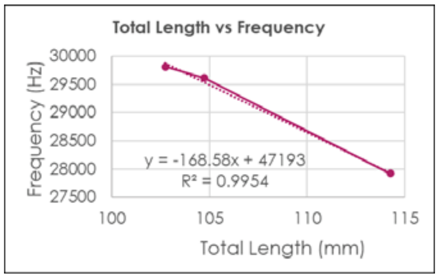

Fig. 3 Relationship between total length and frequency

Table 1 shows the final dimension after modal analysis. The final dimension has been found after the modal analysis in ANSYS has been performed by adjusted the total length. The modal analysis is presented in next sub-chapter 2.2.

2.2 Modal Analysis

The modal analysis has been performed to find the desired frequency of the ultrasonic transducer about 30 kHz. Fundamentally, the modal analysis can find the vibration modes, especially the longitudinal mode shape along x-axis in Fig. 1. The vibration characteristic depends on the material properties, the structure shape, and the boundary conditions (free of fixed vibration). The material properties used in this study is provided in Table 2. The step horn flange material is Titanium alloy, the piezoelectric type is PZT-SS44 which has been provided by SunnyTec (SuZhou) Company.

Fig. 2 shows the result of the longitudinal mode shape where the natural frequency has been shown about 30,041 Hz of the final dimension of the ultrasonic transducer. In this case, the fixed surface on the flange was used as boundary condition and the meshing of fine with element more than 3,000 has been used. Fig. 3 shows the linear relationship between the natural frequency and the total length. In this case, the total length is about 100.75 mm, and the frequency is approximately 30,041 Hz.

2.3 Flexure Hinge Stiffness Analysis

In this study, the dimension of the flexure design must be considered because it has relationship with the stiffness. The analysis adopted Lobontiu[12] which has explained in his textbook. Fig. 4 illustrates the symmetrical flexure hinge with the force and moment acts on it. Fundamentally the stiffness, force/moment, and linear/angular displacement relationship in flexure hinge can be described as follows:

$$\begin{Bmatrix} F_{1x} \\ F_{1y} \\ M_{1z} \end{Bmatrix} = \begin{bmatrix} K_{1,x-F_x} & 0 & 0 \\ 0 & K_{1,y-F_y} & K_{1,y-M_z} \\ 0 & K_{1,y-M_z} & K_{1,\theta_z-M_z} \end{bmatrix} \begin{Bmatrix} u_{1x} \\ u_{1y} \\ \theta_{1z} \end{Bmatrix} \quad (1)$$

The value of $K_{1,x}$, $K_{1,y}$ and $K_{1,\theta}$ can be determined based on relationship of compliance where the detail relationship can be found in Lobontiu's textbook[12]. In this study, the radius dimension has been fixed at 2.5 mm, in which the thickness can be varied. Fig. 5 shows the stiffness value with variation of the thickness dimension {t} of the flexure hinge. As we can see when the thickness increases, the stiffness increases exponentially. Absolutely, the stiffness value depends on the radius and thickness dimension. In this case, the thickness about 3 mm has been chosen because of high stiffness value according to pattern in Fig. 5.

2.4 Amplitude simulation

In this study. The amplitude simulation has been carried out in ANSYS to determine the amplitude under cyclic load. Fig. 6 shows the vibration amplitude about 6.5 µm for input loading of dynamic force of 5120 N. The input force is calculated according to the relationship of the dynamic force for PZT as given in Eq. 2. Two different frequencies were used considering the range of the working frequency of the transducer. The input frequency of 30 kHz yields F_{v_max} of 5120 N and the input frequency of 21 kHz yields F_{v_max} of 2508 N.

$$F_{v\_max} = m_s \cdot 2 \cdot \pi^2 \cdot f^2 \cdot N \cdot d_{33} \cdot V_{p-p} \quad (2)$$

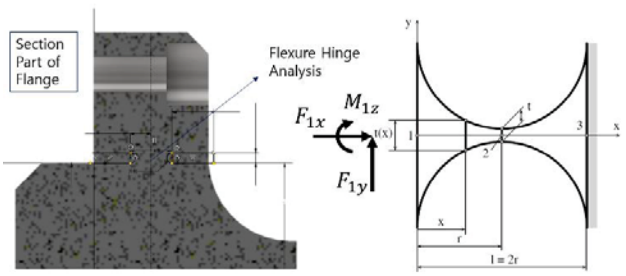

Fig. 4 Flexure hinge analysis diagram

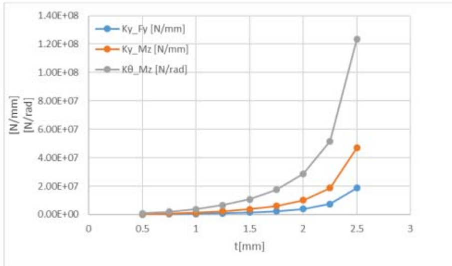

Fig. 5 Stiffness versus flexure hinge thickness

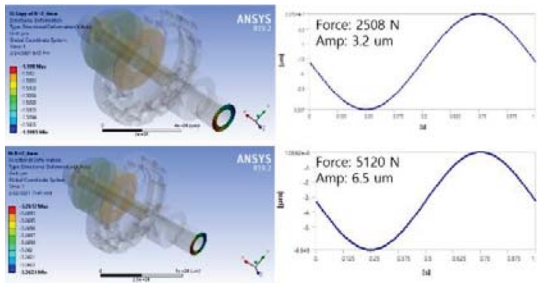

Fig. 6 Structural transient analysis under R = 2.5 mm and t = 2.4 mm

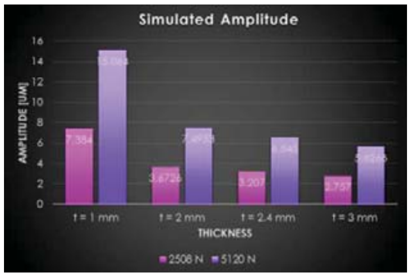

Fig. 7 Simulated amplitude with thickness variation

Fig. 7 shows the variation of the amplitude when the dimension of the flexure hinge is also varied. It shows that the thickness of 1 mm gives high amplitude however considering the low stiffness. It is not suitable for metal cutting. High stiffness is great for metal cutting. Therefore, thickness of 3 mm has been selected. The amplitude in range from 2.7 to 5.6 um on the horn tip is large enough for UVAM.

3. Experimental Results

3.1 Amplitude and FRF Measurement

Fig. 8 shows the experimental results during examining amplitude and frequency peak during amplitude measurement. The optical fiber has been utilized for measuring during direct excitation of 300V peak-to-peak. The amplitude varied when the overhanging of HSS (High Speed Steel) rod bar increases from 40 to 45 mm and then decreases from 45 to 50 mm. The maximum amplitude recorded is shown about more than 32 µm. The excitation frequency decreases as the overhanging distance increases (Fig. 8). Fig. 9 shows the FRF of impedance when the overhanging distance of 40 mm.

3.2 UVAM Result

Fig. 10 shows the experimental results of cutting forces with variation of the feed rate. The effect of vibration in UVAM. The UVAM can decrease the side-milling forces during cutting Aluminum alloy. Fig. 11 shows that the roughness in the UVAM is lower than in the conventional milling under similar feed rate.

4. Conclusion

The ultrasonic transducer with flexure hinge design for ultrasonic spindle milling has been introduced in this paper. As the results, it produces high amplitude more than 30 um under 26.3 kHz. Furthermore, the UVAM produces better machinability compared to the conventional side-milling method in term of lower cutting force and roughness.

ACKNOWLEDGEMENT

We would like to acknowledge the financial support from the Basic Science Program through the National Research Foundation of Korea (NRF) and funded by the Ministry of Education (NRF 2020R1A4A1019227). Also, this research was supported by Korea Electrotechnology Research Institute (KERI) primary research program through the National Research Council of Science & Technology (NST) funded by the Ministry of Science and ICT (MSIT) in 2021 (No. 21A01026).

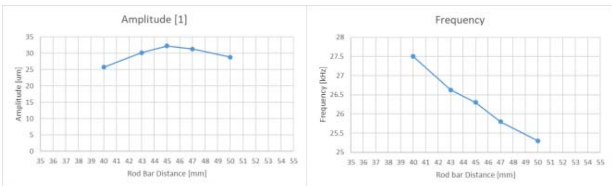

Fig. 8 Amplitude and frequency with variation of rod bar distance

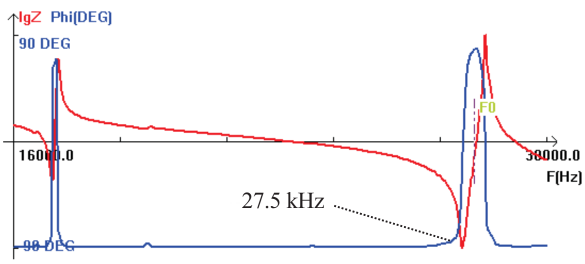

Fig. 9 Frequency response function (FRF) of Impedance measurement

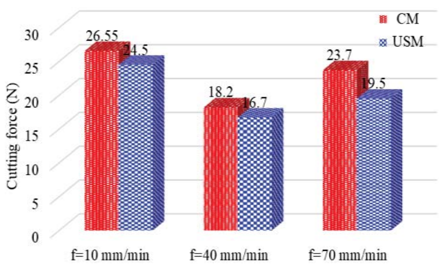

Fig. 10 Average cutting force with variation of feed rate

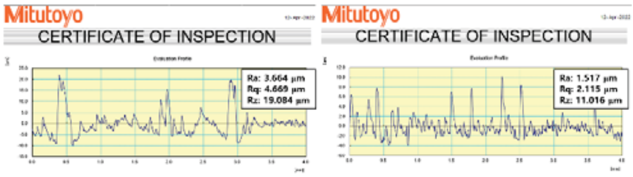

Fig. 11 Surface roughness profile without and with vibration at feed rate = 70 mm/min

REFERENCES

1. Shen, X. H., Zhang, J. H., Li, H., Wang, J. J., and Wang, X. C. "Ultrasonic vibration-assisted milling of aluminum alloy," Int. J. Adv. Manuf. Technol., Vol. 63, No. 1–4, pp. 41–49, 2012.
2. Pang, Y., Feng, P., Wang, J., Zha, H., and Xu, J. "Performance analysis of the longitudinal-torsional ultrasonic milling of Ti-6Al-4V," Int. J. Adv. Manuf. Technol., Vol. 113, No. 5–6, pp. 1255–1266, 2021.
3. Liu, X., Wang, W., Jiang, R., Xiong, Y., Lin, K., Li, J., and Shan, C. "Analytical model of workpiece temperature in axial ultrasonic vibration-assisted milling in situ TiB2/7050Al MMCs," Int. J. Adv. Manuf. Technol., No. 0123456789, 2021.
4. Janghorbanian, J., Razfar, M. R., and Zarchi, M. M. A. "Effect of cutting speed on tool life in ultrasonic-assisted milling process," Proc. Inst. Mech. Eng. Part B J. Eng. Manuf., Vol. 227, No. 8, pp. 1157–1164, 2013.
5. Liu, Y., Liu, Z., Wang, X., and Huang, T. "Experimental study on tool wear in ultrasonic vibration–assisted milling of C/SiC composites," Int. J. Adv. Manuf. Technol., Vol. 107, No. 1–2, pp. 425–436, 2020.
6. Kurniawan, R., Ali, S., Park, K. M., Li, C. P., and Ko, T. J. "Development of a Three-Dimensional Ultrasonic Elliptical Vibration Transducer (3D-UEVT) Based on Sandwiched Piezoelectric Actuator for Micro-grooving," Int. J. Precis. Eng. Manuf., 2019.
7. Amin, S. ., Ahmed, M. H. ., and Youssef, H. . "Computer-aided design of acoustic horns for ultrasonic machining using finite-element analysis," J. Mater. Process. Technol., Vol. 55, pp. 254–260, 1995.
8. Zou, P., Xu, Y., He, Y., Chen, M., and Wu, H. "Experimental investigation of ultrasonic vibration assisted turning of 304 austenitic stainless steel," Shock Vib., Vol. 2015, 2015.
9. Li, X., and Zhang, D. "Ultrasonic elliptical vibration transducer driven by single actuator and its application in precision cutting," J. Mater. Process. Technol., Vol. 180, No. 1–3, pp. 91–95, 2006.
10. Kurniawan, R., Ko, T. J., Ping, L. C., Thirumalai Kumaran, S., Kiswanto, G., Guo, P., and Ehmann, K. F. "Development of a two-frequency, elliptical-vibration texturing device for surface texturing," J. Mech. Sci. Technol., Vol. 31, No. 7, pp. 3465–3473, 2017.
11. Du, P., Han, L., Qiu, X., Chen, W., Deng, J., Liu, Y., and Zhang, J. "Development of a high-precision piezoelectric ultrasonic milling tool using longitudinal-bending hybrid transducer," Int. J. Mech. Sci., Vol. 222, No. March, pp. 107239, 2022.
12. Lobontiu, N. "*Compliant Mechanisms: Design of Flexure Hinges*," America (NY)., (CRC Press, 2002).