The International Journal of Advanced Manufacturing Technology
https://doi.org/10.1007/s00170-017-1347-1

ORIGINAL ARTICLE

A novel free-form transducer for the ultra-precision diamond cutting of die steel

Hao Ni[1] · Yi Wang[1] · Hu Gong[1] · Long Pan[1] · Z. J. Li[2] · Dongfang Wang[3]

Received: 12 April 2017 / Accepted: 8 November 2017

Abstract
For diamond cutting of die steel, it has been shown that ultrasonic vibration-assisted cutting can reduce the chemical wear of diamond tool due to the discontinuous contact between the cutting tool and the workpiece. In this paper, a novel structure of transducer is designed by using free-form surface for ultrasonic vibration-assisted ultra-precision turning die steel. It has two interesting characteristics: The vibration direction of cutting tool tip can be changed by altering vibration frequencies; it can produce an elliptical vibration with only longitudinal vibration actuator. In addition, the structure of this transducer is simple and compact. Finally, several experiments were conducted to demonstrate the effectiveness of this system by diamond ultra-precision turning of STAVAX steel to a mirror surface.

Keywords Vibration cutting · Ultra-precision diamond cutting · Ultrasonic machining · Free-form surface transducer

1 Introduction

It has been proved that ultrasonic vibration-assisted machining technology can provide a lot of advantages, such as lower cutting forces, longer tool life, better surface finish, etc. [1, 2]. For turning ferrous materials by using diamond tools, ultrasonic vibration-assisted turning has been demonstrated to be an effective method to reduce the chemical wear of diamond tool [3–7]. Currently, the vibration in the longitudinal direction of the transducer is very common, as shown in Fig. 1a. But collisions may happen between the tools and the workpiece [8], especially when the workpiece contains large curvature region. This phenomenon either influences the quality of finished surface or causes the edge chipping of tool tip.

To address these problems, the elliptical ultrasonic turning method was developed for ultra-precision cutting. The elliptical vibration can be decomposed into two directions. One is in cutting direction, and the other is in the thrust direction. Thus, compared with conventional longitudinal ultrasonic vibration-assisted cutting, the tool has a velocity component in the chip flow direction in every cutting cycle during penetrating into the workpiece. The friction force between the tool rake and the chip can be effectively reduced because of the reversed velocity [9].

There are two major ways to produce an elliptical ultrasonic vibration on the diamond tool; one is by using two pairs of piezoelectric ceramic or magnetostrictive plates whose vibration directions are orthogonal resulting in their combined vibration forming an elliptical or circular trajectory [10, 11]. The orthogonal piezoelectric ceramic or magnetostrictive plates can be installed at the end of a transducer or on the side faces of a beam transducer [12–14]. But, to make the resonance of two vibration modes at the similar frequencies is not easy for these methods. Furthermore, there are strict requirements for both the input signal phase and piezoelectric ceramic actuators, and the system installation is complicated. A second approach adopts a kind of asymmetric structure which can produce a longitudinal-bended compound vibration using a single-piezoelectric actuator [8]. Similarly, this method also requires that the structure of ultrasonic transducer generates

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00170-017-1347-1) contains supplementary material, which is available to authorized users.

✉ Hu Gong
gonghu@tju.edu.cn

[1] State Key Laboratory of Precision Measuring Technology and Instruments, Tianjin University, Tianjin 300072, China

[2] Tianjin Key Laboratory of High Speed Cutting and Precision Machining, Tianjin University of Technology and Education, Tianjin 300222, China

[3] State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China

Published online: 21 November 2017

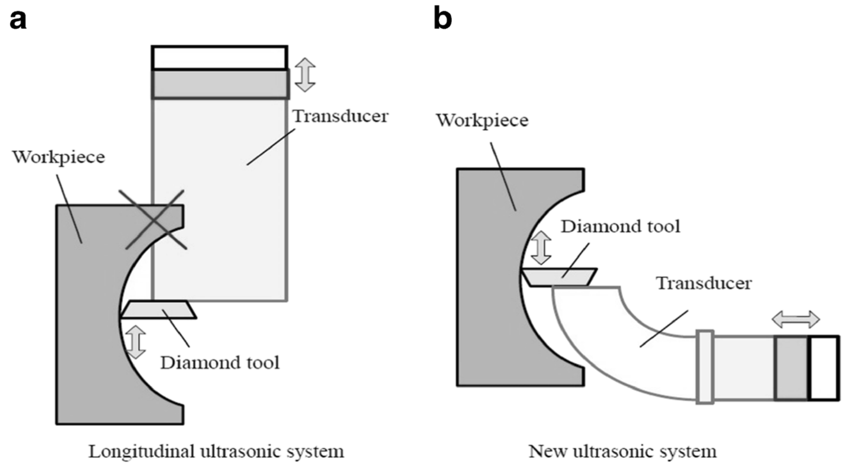


Fig. 1 Ultrasonic vibration-assisted diamond turning

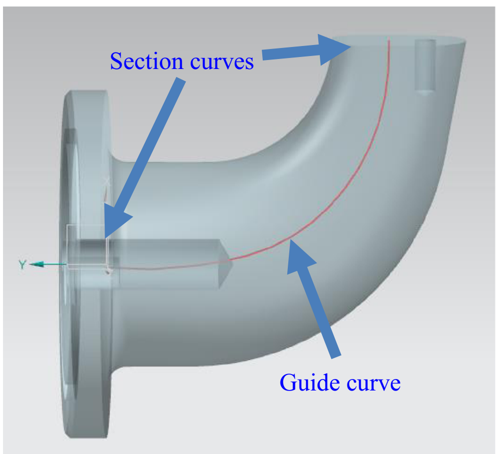


Fig. 2 Modeling in UG NX by using sweep method

a longitudinal-bended compound vibration at a certain resonant frequency, which means vibration direction would be fixed once the structure was determined. To enhance the stiffness of transducer, designer often needs to miniaturize overall size of ultrasonic device. If the overhang of transducer is too short, however, collisions may happen between the workpiece and transducer during machining concave parts. Ping Guo and Kornel F. Ehmann et al. [15, 16] utilized two sets of Langevin transducers with a certain angle to compose an elliptical vibration device which can generate proper vibration directions and amplitudes by changing the phase differences. However, these systems require a relatively large-ultrasonic apparatus that is not convenient to install in most ultra-precision turning machines.

The objective of this paper is to propose a novel and compact structure of the ultrasonic transducer for diamond ultra-precision turning die steel, which can produce an elliptical vibration with only longitudinal vibration actuator. In Section 2, the process of design will be introduced in detail. In Section 3, several cutting experiments with single-crystal diamond tools are conducted to prove the effectiveness of the novel system.

2 The design of free-form surface transducer

The transducer is the most important part of an ultrasonic vibration-assisted turning system. According to the theory of the propagation of sound wave, sound wave reflection happens between two kinds of medium, which leads to the change of the propagation direction of ultrasonic wave with the change of transducers' structures. If the propagation direction and the reflection direction of the ultrasonic wave exist a phase difference, the direction of superposed ultrasonic waves will change. The phase difference will be affected by the relationship between wavelength (or frequency) and the

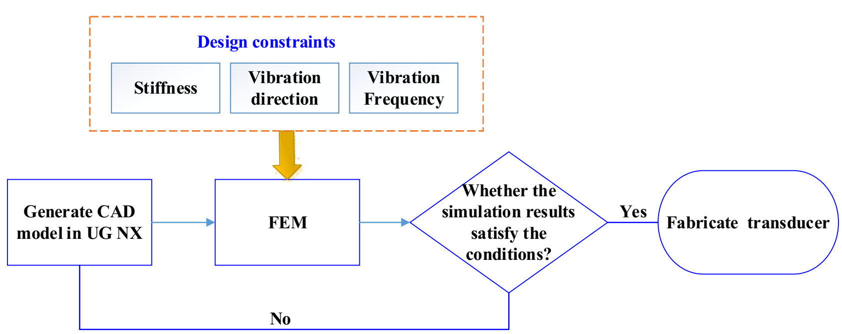


Fig. 3 Design flow chart of new transducer

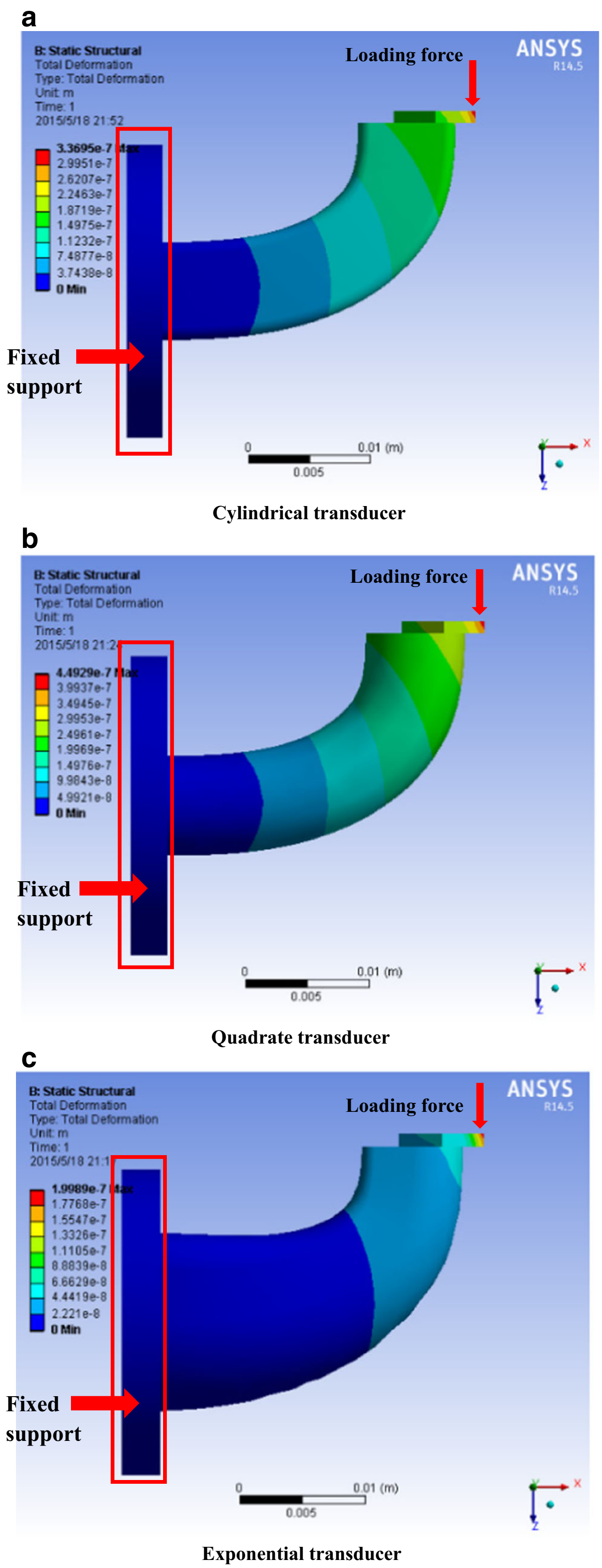


Fig. 4 Static stiffness analysis with FEM

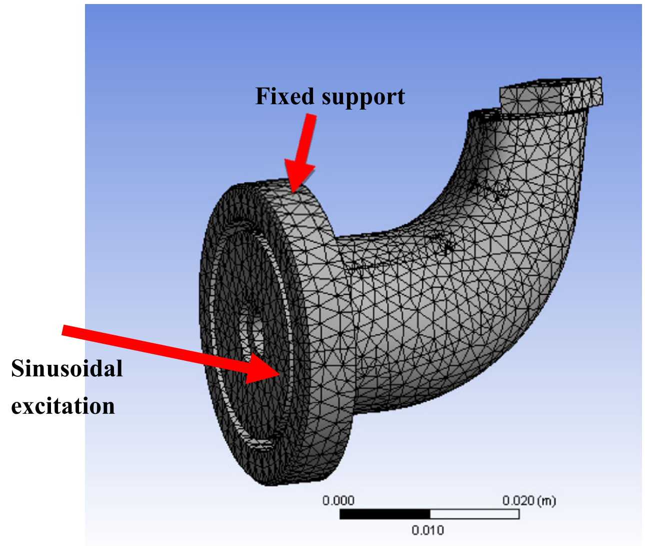


Fig. 5 Boundary conditions and meshing of harmonic response analysis

structure of the transducer (shape and size, etc.). Currently, typical ultrasonic vibration-assisted turning system has a symmetric transducer, so the direction of propagation of ultrasonic wave will not change in the process of propagation. This structure of transducer restricts the vibration directions of tool tip. Consequently, according to above analysis, a novel-bended structure of transducer is proposed to change the vibration direction through propagation and combination of ultrasonic waves in the transducer, as shown in Fig. 1b. A sandwiched structural piezoelectric ceramic actuator was used to generate a longitudinal ultrasonic vibration at the end of transducer. Obviously, the shape design of the transducer is more complicated than traditional symmetrical transducer because there is no standard analytical method. To achieve this goal, a modeling method "Variational Sweep" in UG NX is used to design the transducer, as shown in Fig. 2. The generic design process: (1) A space

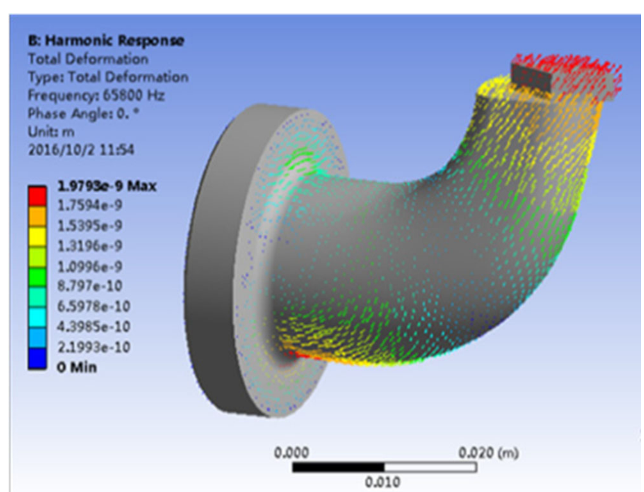


Fig. 6 Vibration direction of transducer at 65800 Hz

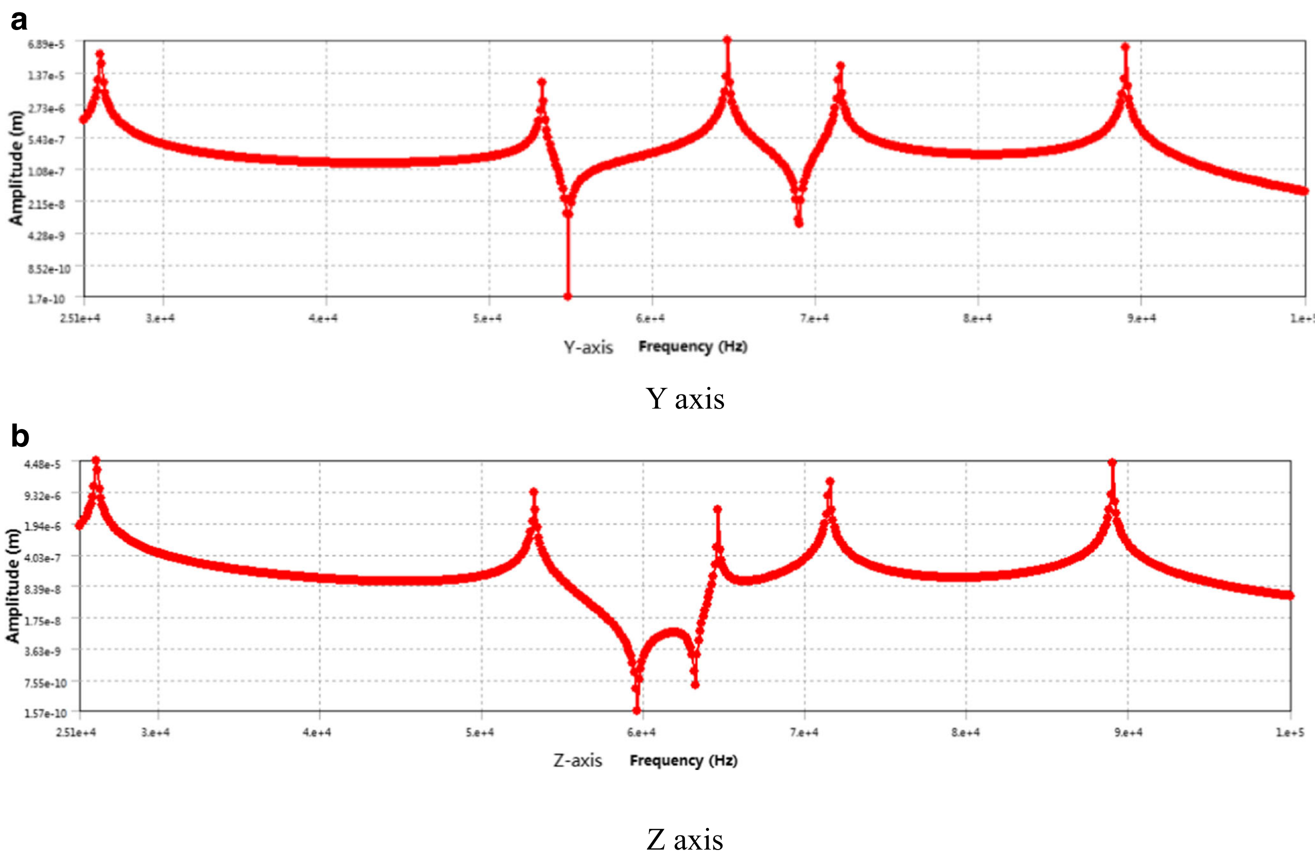


Fig. 7 Amplitude of vibration components

curve is designed as a guide curve, which represents the tool path of sweep; (2) section curves are defined to sweep along the guide curve and generate a free-form surface. According to this process, many shapes of transducers can be designed. But unfortunately, for this kind of transducer, there is no analytical method to analyze its vibration. Therefore, finite element method (FEM) was adopted to do this work. The basic design process is presented in Fig. 3. In the design process, three major factors must be considered: (a) stiffness, (b) vibration direction, (c) vibration frequency. We will give detailed explanation hereinafter.

2.1 Static analysis of the stiffness of transducer

During machining process, the cutting force was applied on the tip of diamond tool, as shown in Fig. 4. Therefore, the stiffness of transducer directly affects the machined surface quality, especially for ultra-precision-turning mirror surface. Insufficient stiffness will cause deformation of the transducer and influence processing stability. Therefore, a static analysis of stiffness of tool tip with FEM was carried out to design the shape of the transducer in order to improve the stiffness as high as possible.

For example, as shown in Fig. 4, three free-form surface transducer models with different cross sections were designed in UG NX 8.0 for FEM analysis. These CAD models were imported into the ANSYS to predict the largest deformation of the tool tip under the same cutting force. The three different free-form surface transducers are based on three kinds of typical structures: cylindrical transducer, quadrate transducer, and exponential transducer. The front ends of these three transducers kept the same size, which is determined by the size of diamond tools. For comparison, their lengths in the horizontal direction are also consistent. Cr45-steel was used in the models, and its physical properties including elasticity modulus, Poison's ratio, and density were given in FEM model. A fixed constraint is applied on the flange of transducer, and a constant force is applied on the tip of the diamond tool, which is fixed on the end of the transducer. The results of the largest deformations are shown in Fig. 4. In this case, exponential transducer with larger cross section can effectively restrain deformation and strengthen its stiffness. The largest deformation occurred on the exponential transducer, only 30 and 18% of the deformation of the cylindrical transducer and quadrate transducer, respectively. And the range of deformation on exponential transducer is the smallest among these three transducers. Based on these results, the exponential transducer was selected in the following design.

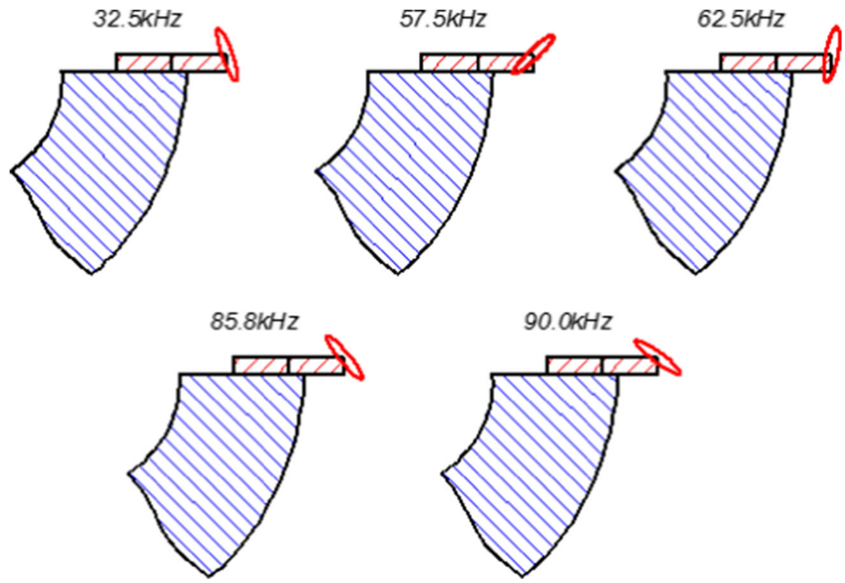


Fig. 8 Vibration trajectories at different frequencies

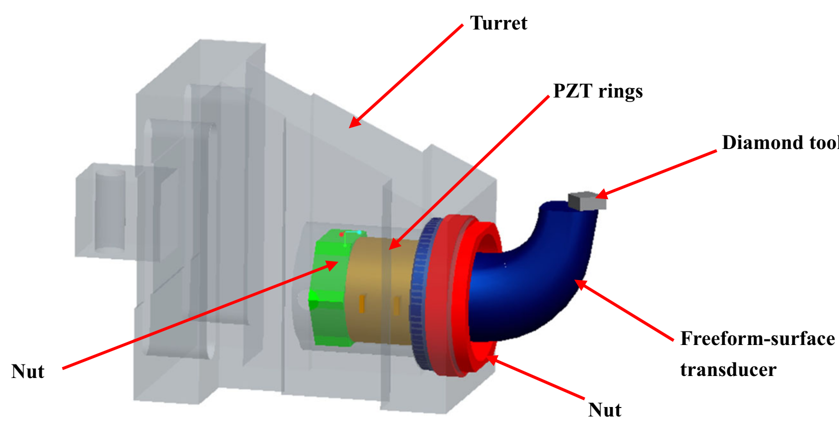


Fig. 9 The ultrasonic vibration-assisted turning device with free-form transducer

2.2 Harmonic response analysis

Besides stiffness, two other important factors must be considered: (a) vibration direction, (b) vibration frequency. According to the previous analysis, the vibration direction is related to the vibration frequency for the free-form surface transducer. Harmonic response analysis was used to simulate the vibration at different response frequencies. It should be mentioned that modal analysis was not adopted to calculate vibration direction at natural frequency. That is because the merit of free-form surface transducer is to achieve a specific vibration direction by changing the excitation frequencies.

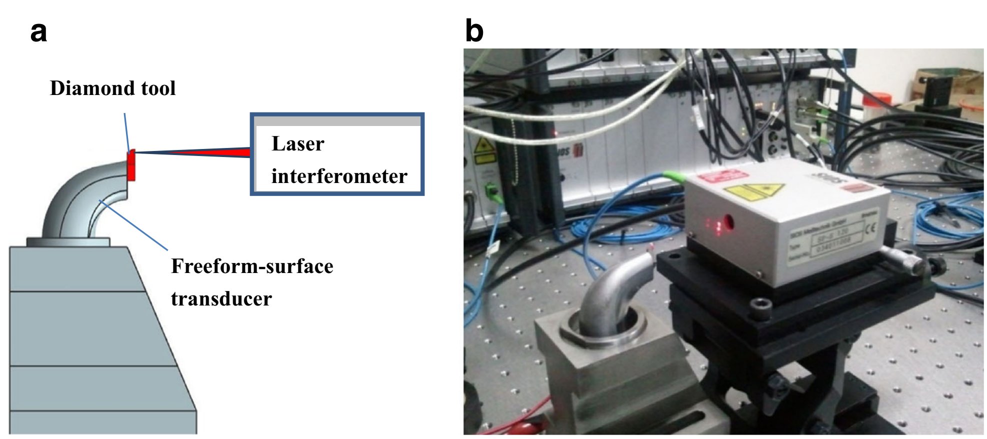


Fig. 10 Measurement of the displacement of tool tip by using laser interferometer

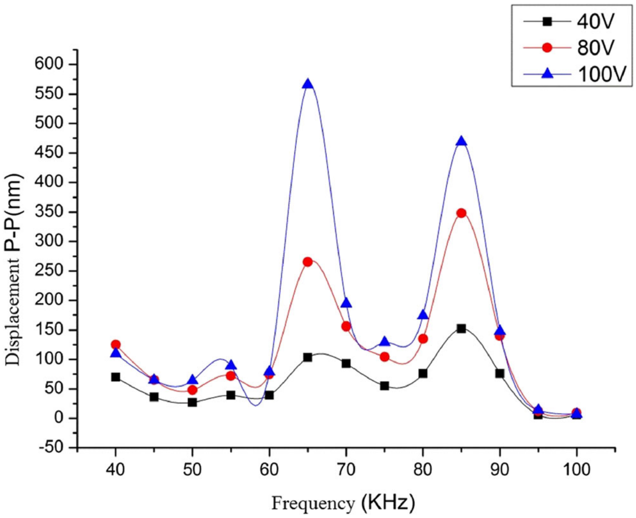


Fig. 11 The measurement results by using laser interferometer

Therefore, it is impossible to keep every vibration direction at a specific natural frequency. In the free-form surface transducer, proper vibration directions are achieved by combining kinetic condition of different order modals. In this work, the transducer is designed for ultra-precision-turning mirror surface. Usually, the vibration amplitude is very small. Therefore, we pay more attention to vibration direction than vibration amplitude.

In harmonic response analysis, a sinusoidal excitation was applied on the input side of the transducer, and a fixed constraint was applied on the flange of the transducer, as shown in Fig. 5. The transducer was meshed. The vibration trajectories of the tool tip of the free-form surface transducer can be observed at different frequencies. In order to produce proper vibration direction at the tip of tool within the certain frequency range, the free-form structure is designed and modified through combination of modeling in UG NX and simulating in ANSYS, as shown in Fig. 6. The vibration components in the directions of y and z at different frequencies are shown in Fig. 7. It is clear that for different vibration direction components, their amplitudes are significantly changed with frequencies. According to the vibration components and largest vibration displacement, the vibration trajectories at the tip of the tool could be approximately drawn. The elliptical trajectories at different frequencies are shown in Fig. 8.

After the design of transducer was finished, the tool turret was designed, as shown in Fig. 9. The free-form surface transducer was assembled through a nut, and the flange was pressed as well. The PZT actuators were embedded in the turret.

3 Experiments

Since the transducer is a free-form surface, a 5-axis NC machining center was used to machine it. In order to verify the result of the simulation in Section 2.2, SIOS laser interferometer was used to measure the displacement of the tool tip in the direction of Y, as shown in Fig. 10. The results are shown in Fig. 11. Comparing between Figs. 7a and 11, we find that although deviations exist due to all kinds of errors, the basic trend is same.

The whole ultrasonic device was installed on a Nanotech 250UPL Ultra-Precision Lathe, as shown in Fig. 12. The experiment of cutting die steel was conducted. In this experiment, a single-crystal diamond (SCD) tool was used, with a nose radius of 0.5 mm and the rake angle is 0°. The workpiece material was made of STAVAX die steel, and workpiece diameter was 20 mm. The cutting parameters and results are shown in Table 1.

Since the tool wear directly determines the finished surface quality in ultra-precision machining, we mainly focused on the surface finished quality and tool wear under different frequencies. If the tool wear is serious in the machining process, a mirror surface usually cannot be obtained. Specifically, machining die steel with diamond tools will cause excessive tool wear due to the strong-chemical affinity of carbon to iron [17]. In this experiment, when the ultrasonic frequency was 85 kHz, serious tool wear occurred at the tip of the diamond tool and the surface roughness was also very poor. Similarly, the flank face of the diamond tool occurred serious wear at 90 kHz. Whereas at frequencies near 63–66 kHz, a better surface finished quality was processed and lower surface roughness Ra was obtained, as shown in Table 1. Choosing appropriate

Fig. 12 Cutting experiment using the new ultrasonic vibration-assisted system

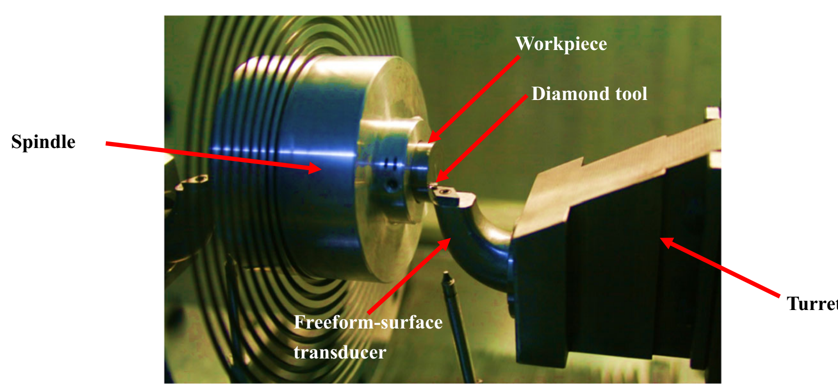
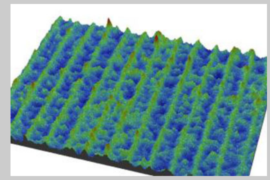
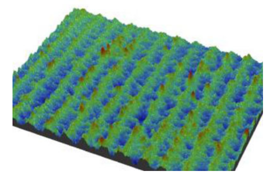
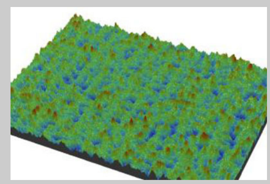
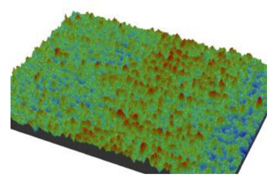
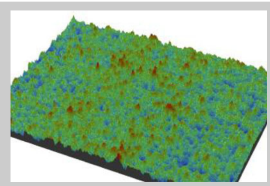


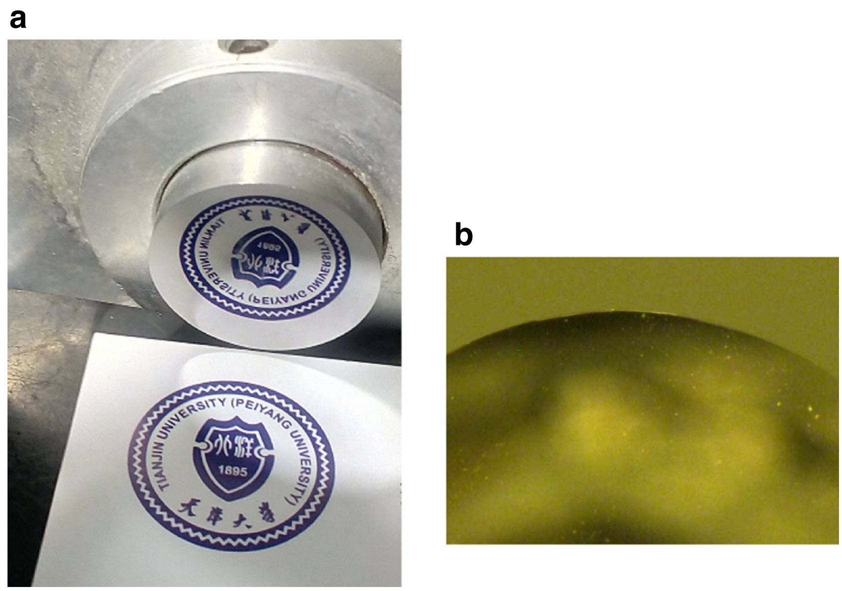
Table 1 Cutting experiment conditions and results with free-form ultrasonic transducer

No.	Depth of cut (μm)	feed (mm/min)	Spindle speed (r/min)	Frequency of ultrasonic vibration (kHz)	Power of ultrasonic vibration (V)	Roughness Ra (nm)	Morphology of surface
1	3	0.25	25	63	200	19.44	
2	3	0.25	25	65.8	200	30.01	
3	3	0.18	20	63	200	10.45	
4	3	0.045	16	63	100	7.57	
5	3	0.045	16	65.8	100	7.9	

processing parameters (feed and spindle speed), we can obtain the surface quality below 10 nm, respectively, at frequencies of 63 kHz (Ra = 7.57) and 65.8 kHz (Ra = 7.9). Finally, frequency of 63.5 kHz was selected and a complete mirror effect workpiece was machined as shown in Fig. 13a. Figure 13b shows that tool wear is not obvious. The supplementary videos show the vibration trajectories under the three frequencies (63.5, 85, and 90 kHz). From the videos, it can be found that the vibration trajectories at 85 and 90 kHz are similar and due to their specific vibration direction, collision may happen easily. However, the vibration direction changes at the frequency of 63.5 kHz as shown in the video, leading to less tool wear. Therefore, we can prove that this novel ultrasonic vibration-assisted cutting device can reduce tool wear of diamond tool with proper vibration direction.

4 Conclusions

In this paper, a novel structure of transducer is designed by using free-form surface for ultrasonic vibration-assisted ultra-precision-turning die steel. 3D CAD system and FEM are used to optimize the structure by considering three factors: (a) stiffness, (b) vibration direction, (c) vibration frequency. The structure of the system is simple and compact. More importantly, it has interesting characteristics: The vibration direction of the tool tip can be changed by altering vibration frequency. Through experiment of cutting STAVAX die steel on ultra-precision lathe, we can prove that the new ultrasonic vibration-assisted turning system is able to reduce tool wear and improves surface quality effectively for ultra-precision diamond-turning die steel.



Machined surface

Tool wear

Fig. 13 Machine Stavax die steel

Acknowledgements The authors appreciate supports of the National Natural Science Foundation of China (Grant No. 51275344) and the State Key Laboratory of applied optics of P. R. China.

References

1. Brehl DE, Dow TA (2008) Review of vibration-assisted machining. Precis Eng 32(3):153–172. https://doi.org/10.1016/j.precisioneng.2007.08.003
2. Ma C, Shamoto E, Moriwaki T, Zhang Y, Wang L (2005) Suppression of burrs in turning with ultrasonic elliptical vibration cutting [J]. Int J Mach Tool Manu 45(11):1295–1300. https://doi.org/10.1016/j.ijmachtools.2005.01.011
3. Moriwaki T, Shamoto E (1991) Ultraprecision diamond turning of stainless steel by applying ultrasonic vibration. Annals of the CIRP 40(1):559–562. https://doi.org/10.1016/S0007-8506(07)62053-8
4. Moriwaki T, Shamoto E (1991) Ultraprecision diamond cutting of hardened steel by applying elliptical vibration cutting. Annals of the CIRP 48(1):441–444
5. Klocke F, Dambon O, Bulla B, Heselhaus M (2008) Ultrasonic assisted turning of hardened steel with mono-crystalline diamond. In: Proceedings of the 23rd annual ASPE meeting. Portland, Oregon
6. Xiao M, Wang QM, Sato K, Karube S, Soutome T, Xu H (2006) The effect of tool geometry on regenerative instability in ultrasonic vibration cutting. Int J Mach Tool Manu 46(5):492–499. https://doi.org/10.1016/j.ijmachtools.2005.07.002
7. Brinksmeier E,Gläbe R (1999) Elliptical vibration cutting of steel with diamond tools, Proc. of the 1999 ASPE annual meeting
8. Li X, Zhang D (2006) Ultrasonic elliptical vibration transducer driven by single actuator and its application in precision cutting. J Mater Process Technol 180(1-3):91–95. https://doi.org/10.1016/j.jmatprotec.2006.05.007
9. Suzuki N, et al. (2003) Ultraprecision machining of hard materials by applying ultrasonic elliptical vibration cutting. International symposium on micromechatronics and human Science:195
10. Moriwaki T, Shamoto E (1995) Ultrasonic elliptical vibration cutting. CIRP Ann Manuf Technol 44:31–34
11. Zhang J, Shamoto E, Suzuki N et al (2014) Ultra-precision nano-structure fabrication by amplitude control sculpturing method in elliptical vibration cutting. Precis Eng 39:86–99
12. Shamoto E, Suzuki N, Tsuchiya E, Hori Y, Inagaki H, Yoshino K (2005) Development of 3 DOF ultrasonic vibration tool for elliptical vibration cutting of sculptured surfaces. CIRP Ann Manuf Technol 54(1):321–324. https://doi.org/10.1016/S0007-8506(07)60113-9
13. Shamoto E, Moriwaki T (1999) Ultaprecision diamond cutting of hardened steel by applying elliptical vibration cutting. CIRP Ann Manuf Technol 48(1):441–444. https://doi.org/10.1016/S0007-8506(07)63222-3
14. Nath C, Rahman M, Neo KS (2009) Machinability study of tungsten carbide using PCD tools under ultrasonic elliptical vibration cutting. Int J Mach Tool Manu 49(14):1089–1095. https://doi.org/10.1016/j.ijmachtools.2009.07.006
15. Guo P, Ehmann KF (2013) Development of a tertiary motion generator for elliptical vibration texturing. Precis Eng 37(2):364–371. https://doi.org/10.1016/j.precisioneng.2012.10.005
16. Zhang C, Ehmann K, Li Y (2015) Analysis of cutting forces in the ultrasonic elliptical vibration-assisted micro-groove turning process. Int J Adv Manuf Technol 78(1–4):139–152. https://doi.org/10.1007/s00170-014-6628-3
17. Paul E et al (1996) Chemical aspects of tool wear in single point diamond turning. Precision Eng 18 1:4–19