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Development of an innovative device for ultrasonic elliptical vibration cutting

Ming Zhou, Linhua Hu *

School of Mechanical and Electrical Engineering, Harbin Institute of Technology, No. 92, West Da-Zhi Street, Harbin 150001, Heilongjiang Province, China

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ABSTRACT

An innovative ultrasonic elliptical vibration cutting (UEVC) device with 1st resonant mode of longitudinal vibration and 3rd resonant mode of bending vibration was proposed in this paper, which can deliver higher output power compared to previous UEVC devices. Using finite element method (FEM), resonance frequencies of the longitudinal and bending vibrations were tuned to be as close as possible in order to excite these two vibrations using two-phase driving voltages at a single frequency, while wave nodes of the longitudinal and bending vibrations were also adjusted to be as coincident as possible for mounting the device at a single fixed point. Based on the simulation analysis results a prototype device was fabricated, then its vibration characteristics were evaluated by an impedance analyzer and a laser displacement sensor. With two-phase sinusoidal driving voltages both of 480 V_{p-p} at an ultrasonic frequency of 20.1 kHz, the developed prototype device achieved an elliptical vibration with a longitudinal amplitude of 8.9 μm and a bending amplitude of 11.3 μm. The performance of the developed UEVC device is assessed by the cutting tests of hardened steel using single crystal diamond tools. Experimental results indicate that compared to ordinary cutting process, the tool wear is reduced significantly by using the proposed device.

1. Introduction

Ultrasonic elliptical vibration cutting (UEVC), which is a promising cutting technique especially in cutting difficult-to-cut materials, weak stiffness parts and high precision components, was first proposed by Shamoto and Moriwaki [1]. The working principle of the cutting technique is that the tool set at the end of the UEVC device vibrates in an elliptical locus in the plane formed by the cutting direction and the chip flow direction as shown in Fig. 1.

The relative motion locus of tool can be expressed as:

$$x = a\cos(2\pi ft) - v_c t \tag{1}$$

$$y = b\cos(2\pi ft + \varphi) \tag{2}$$

where v_c is the cutting speed, a is the amplitude of cutting direction vibration (i.e., x-axis), b is the amplitude of the chip flow direction vibration (i.e., y-axis), f is the vibration frequency of the tool, φ is the phase shift in vibration.

The benefits of UEVC become noticeable when the vibration velocity of the tool in the cutting direction is higher than the cutting speed (Eq. (3)). This permits an intermitted cut, so the tool is separated from the workpiece in each cycle.

$$v_c < (v_t)_{\max} \tag{3}$$

$$(v_t)_{\max} = 2\pi af \tag{4}$$

where $(v_t)_{\max}$ is the maximum vibration velocity of the tool in the cutting direction.

Compared to 1-directional ultrasonic vibration cutting, in the UEVC, a pulling upward movement processed by the elliptical locus of the tool improves the rake angle of the tool, avoids the friction between the flank face of the tool and the machined face of the workpiece, assists to pull out the chips away from the workpiece during the vertical vibration motion of the tool and reduces the cutting force and cutting energy significantly [1–4]. So significant advantages of UEVC were obtained in lots of works with intermittent cutting as summarized below: saving tool life [5,6], improving surface finish and form accuracy [2,7,8], enabling the use of diamond tools for cutting ferrous materials [5,9], improving cutting stability [3,5,10], and suppressing burr and regenerative chatter [5,11,12].

Ma and Hu designed an UEVC device with dual bending resonance mode, of which vibration amplitudes were in the range of 6–18 μm [13]. The relatively low-efficiency operating mode of

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* Corresponding author. Tel./fax: +86 451 86413157.
E-mail addresses: zhouming@hit.edu.cn (M. Zhou), hlhchina@163.com (L. Hu).

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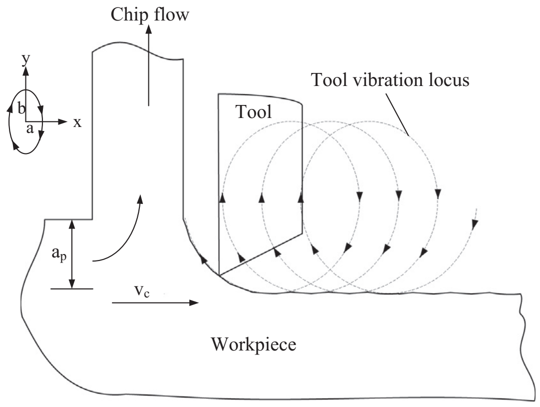

Fig. 1. Ultrasonic elliptical vibration cutting.

d_{31} of PZT ceramics was adopted in their work, and PZT ceramics were glued to the metal base of the device. Both of the tensile strength of PZT ceramics and shear strength of the glue layers will limit the further improvement of the output capacity of the UEVC device. Adopting the mode of d_{33} of PZT ceramics, Suzuki et al. designed an UEVC device with 2nd resonant mode of longitudinal vibration and 5th resonant mode of bending vibration, of which resonant frequency is approximately 39 kHz [7]. However, the vibration amplitudes of the device designed by Suzuki et al. in two directions were both 2 μm, according to Eq. (3), the machining efficiency of the device is too low, and the device is mainly suitable for ultra-precision cutting.

In this study, an innovative UEVC device using longitudinal and bending composite transducer is developed. In this new design, the UEVC device works at 1st resonant mode of longitudinal vibration and 3rd resonant mode of bending vibration. Compared to the previous designs, the output power and the vibration amplitude of the developed device were improved. A higher power and a larger vibration amplitude of the UEVC device could be helpful to increase the machining efficiency. After fabricating a prototype, the characteristics of the developed device were investigated through experiments.

2. Design configuration and structure of the UEVC device

Fig. 2 shows the structure of proposed device, the device is composed of one longitudinal and bending composite transducer. The ultrasonic horn generates the amplitude amplification. A tool set at the end of the ultrasonic horn was vibrated elliptically by combining the two resonant vibrations with some phase shift. As the UEVC device works at 1st resonant mode of longitudinal vibration and 3rd resonant mode of bending vibration, the single node fixed support was adopted and the flange provided the mounting point. Compared to two nodes fixed support for the same work type, the interference of the node points on the longitudinal vibration is avoided, the heat problem is less than two nodes fixed support. Since the sensitivity of the bending vibration is stronger than that of the longitudinal vibration, the node of bending vibration closest to that of longitudinal vibration was selected for the mounting point in the design. The ultrasonic horn, flange, longitudinal PZT ceramics, bending PZT ceramics and end cap are fasten together with a screw bolt. The device belongs to the bolt-clamped type ultrasonic device, and d_{33} working mode of PZT ceramics is adopted. Compared to the bonded type device adopting the d_{31} working mode of PZT ceramics, the UEVC device proposed in this work could exhibit higher output power and efficiency. Meanwhile, as this structure can deliver higher output power compared to previous UEVC devices, the cutting efficiency could be improved by using the device.

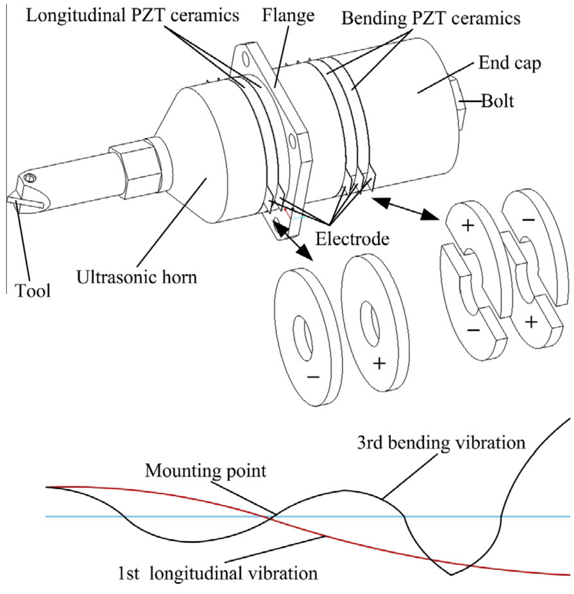

Fig. 2. Structure of the proposed device.

Up to now, it is still hard to mathematically analyze the bending vibration of the complex shape elastic solid. In this work, the working frequency and dimensions of the longitudinal ultrasonic device are firstly defined and calculated, then based on the structure of longitudinal vibration, the bending PZT ceramics are set in the device and the design parameters are modified to make the resonance frequencies of longitudinal and bending vibrations close to each other. Fig. 3 shows the schematic of half-wavelength longitudinal vibration device.

The dimension of the device can be determined by the following equations:

$$l_1 = c/4f = \lambda/4 \tag{5}$$

$$\tan kl_4 \times \tan kl_3 = (d_1/d_2)^2 \tag{6}$$

$$l_2 + l_5 = l_4 \tag{7}$$

$$l_6 + l_7 = l_3 \tag{8}$$

where $c, f, \lambda, k, d_1, d_2$ and l_5 are the longitudinal vibration velocity in ultrasonic horn material, resonant frequency, wave length, wave number, end cap diameter, ultrasonic horn output diameter and the thickness of the PZT, respectively.

The resonance frequency is defined as 20 kHz, steel (mass density $\rho = 7800\ \mathrm{kg/m^3}$, Young's modulus $E = 2.06 \times 1011\ \mathrm{N/m^2}$, Poisson ratio $\sigma = 0.3$) is selected as the material of ultrasonic horn,

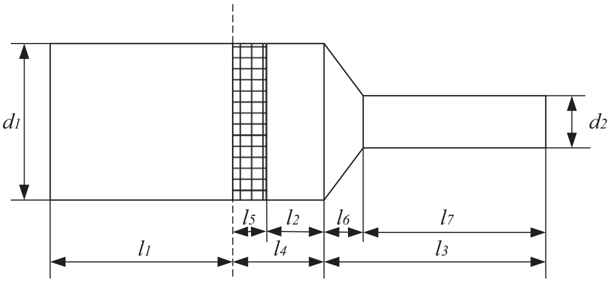

Fig. 3. Schematic of half-wavelength longitudinal vibration device.