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Development of a Novel Ultrasonic Drill Using Longitudinal-Bending Hybrid Mode

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ABSTRACT Machining of hard and brittle materials is usually troublesome due to their high stiffness. In order to improve the processing speed of hard and brittle materials, ultrasonic assisted processing was developed. This paper reports a novel ultrasonic drill method, where longitudinal-bending hybrid ultrasonic vibration is used instead of single longitudinal or bending vibration. The cutting tool in this process is a core drill attached to an ultrasonic transducer, which generates longitudinal and bending vibrations. Thus an elliptical movement with ultrasonic frequency that is vertical to the working surface is formed at the cutting edge. The longitudinal vibration can help the cutting edge impact the workpiece and thus crush it. With the rotation of the cutting tool, the cutting edge scratches a groove on the working surface. While the bending vibration speeds up the movement of the cutting edge toward the workpiece in the working surface so as to amplify the fracture region. Moreover, a radial clearance assisting chip removal is made by the bending vibration. Merits of this machining method, including improved processing speed and avoidance of jamming are verified by experiment.

INDEX TERMS Ultrasonic drill, longitudinal vibration, bending vibration, hybrid mode.

I. INTRODUCTION

As the progress of material science, many high performance materials such as engineering ceramics and carbon fiber reinforced plastic have been widely used [1]–[4]. Nevertheless, their high stiffness and poor machinability bring in challenge for the machining process, especially for drill [5]. Conventional machining methods have problems of high cutting force and torque and high tool wear when cutting these materials. In order to solve these problems, some nontraditional methods have been developed to deal with hard and brittle materials [6]–[11].

Rotary ultrasonic machining (RUM) is one of these nontraditional machining methods. RUM is a hybrid machining method which combines two kinds of cutting mechanisms, namely, rotary cutting and ultrasonic machining. Traditionally, the cutting tool of RUM is a core drill attached to an ultrasonic transducer. Axial ultrasonic vibration is generated by the transducer and then delivered to the cutting edge. When machining, the cutting tool rotates and vibrates at a high frequency (>20 kHz) along the axis direction at the same time. With this vibration, cutting edges contact with the surface of the workpiece intermittently. An enormous local stress is produced so that the cutting edge impacts into the surface of the workpiece and scratches a groove. Thus brittle fracture and plastic flow occur on the surface of materials [12]–[15]. Chips of materials generate at the surface of the workpiece in this process and then easily removed by the cutting tool. As a result, the material removal rate increases dramatically. Advantages of this process include low tool pressure, low tool wear rate, higher machining rate and superior surface finish [16].

Another ultrasonic machining method used for drill is called rotary ultrasonic elliptic machining (RUEM), where bending-bending hybrid ultrasonic vibration instead of longitudinal vibration was used [17], [18]. These two bending vibrations have the same resonance frequency, thus an elliptic locus of the cutting edge is generated on the cutting surface. The locus of the cutting edge has the same direction with the chip flow, thus the fractional force between the tool and chip is reduced. Also this elliptic locus helps to cut the side surface of the workpiece and makes a radial clearance between the tool and workpiece which facilitates cutting chips' removing.

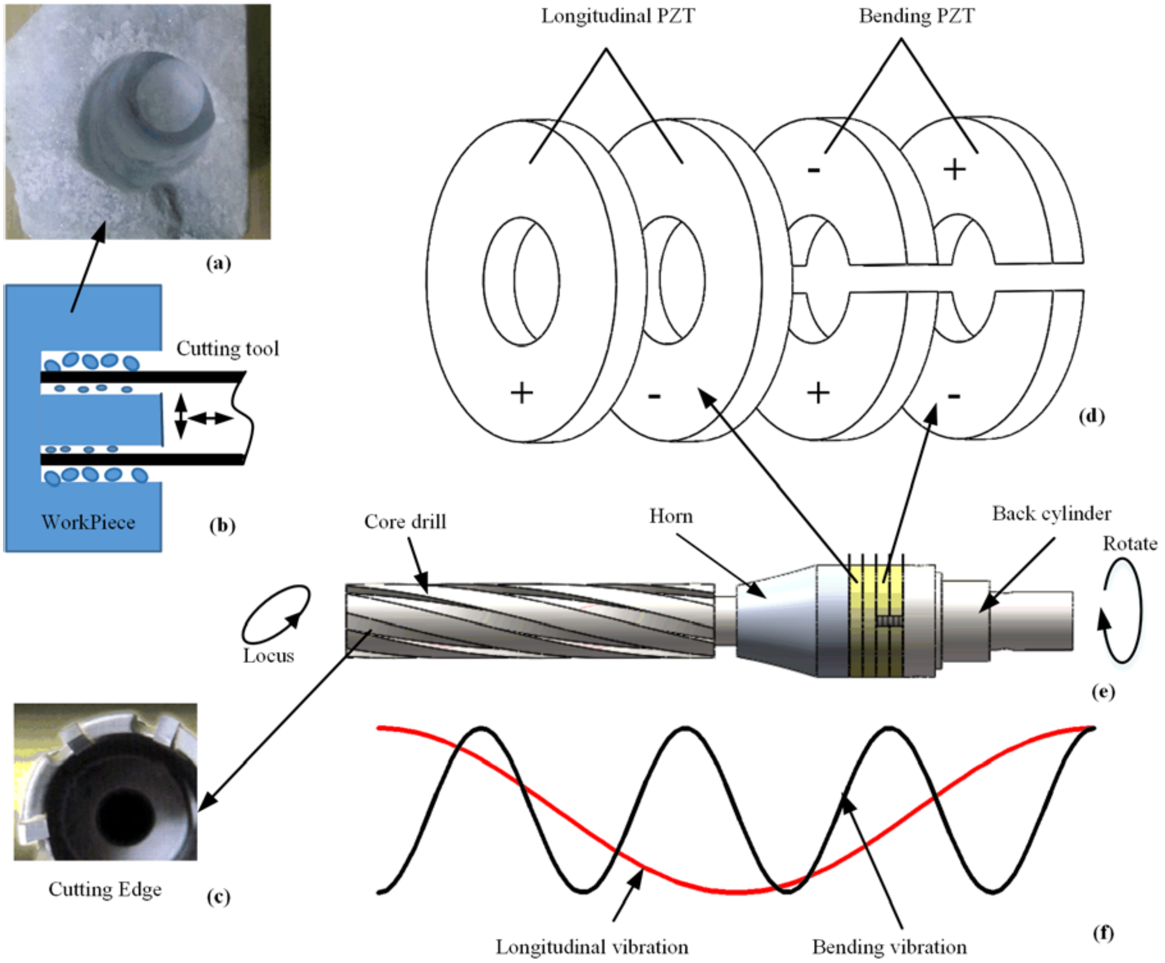

FIGURE 1. Illustration of LBUD process: (a) picture of workpiece (marble), (b) workpiece with cutting tool, (c) cutting edge, (d) the placement of the PZT elements, (e) the cutting tool, (f) longitudinal and bending vibration curves.

Merits of RUEM contain lower cutting force, suppressing the burrs and achieving high quality surface finish and longer tool life [19], [20]. RUEM was turned out to be feasible for carbon fiber reinforced plastic.

In this paper, a novel ultrasonic machining method is proposed. Different from previous RUM, longitudinal-bending hybrid ultrasonic vibration instead of single longitudinal vibration is added to a core drill in order to form an elliptical movement at the cutting edge. This method is also different from RUEM mentioned before since the elliptical movement is vertical to the working surface. This elliptic motion changes the cutting mechanism and thus promotes cutting greatly. Cutting edges impact into the work surface and scratch grooves as the same of RUM. Brittle fracture happens in this process. When scratching, the cutting edge gets a larger linear velocity from bending vibration. Thus, the brittle fracture in RUM is amplified with this velocity. Also, the radial clearance made by bending vibration in RUEM exists in this cutting method. Advantages of RUM and RUEM are combined in this machining method. With these mechanisms, the drill of hard and brittle materials can be speeded up. This kind of ultrasonic machining is called longitudinal-bending hybrid ultrasonic drill (LBUD) in this paper. Cutting mechanism was analyzed and experiments were conducted to verify the effect of LBUD.

II. DESIGN OF THE CUTTING TOOL

As the same in RUM and RUEM, a core drill attached to an ultrasonic transducer is used as the cutting tool in this paper. As shown in Figure 1. Two groups of PZTs were set within the transducer. There are two longitudinal PZTs with reverse polarizations generating longitudinal vibration and four bending PZTs with reverse polarizations each neighboring ones generating bending vibration. Longitudinal and bending vibrations with the same resonance frequency form an elliptical motion trail at the end of the cutting tool eventually. At the same time, the cutting tool rotates with the drive of a motor. A back cylinder with various diameters made of carbon steel is set at the end of the transducer to cut off vibration and connect with the motor. A horn made of aluminum alloy is set in the front of the transducer to decrease cross section and thus amplify the vibration amplitude. Electrodes made of Beryllium bronze are set between PZTs to load voltage on them. Materials used in the transducer and their properties are shown in Table 1.

TABLE 1. Materials used in the cutting tool and their properties.

Part	Horn	Back cylinder	Electrodes
Material	Aluminum alloy	Carbon steel	Beryllium bronze
Density（kg/m^3）	2810	7800	8300
Elasticity Modulus（GPa）	72	206	133
Tensile strength（MPa）	420	600	1000
Poisson's ratio	0.33	0.3	0.35

In order to obtain a certain movement at the end of the cutting tool, the resonance frequencies of the longitudinal and bending vibrations should be agreed. Thus, structural parameters of the transducer should be adjusted accurately. Finite element analysis was used during this process to calculate the resonance frequencies. Structural parameters of the transducer were adjusted to degenerate these two frequencies subsequently. Firstly, a group of initial parameters were applied to the transducer and the resonance frequencies of longitudinal and bending vibrations were obtained by using FEM (ANSYS software). Resonance frequencies of the longitudinal and bending vibrations differed a lot at first. Afterwards, a single parameter was changed and other ones kept constant, modal analysis was conducted repeatedly and the results were drawn into a curve to reveal the effect of that parameter on the resonance frequencies. This procedure was called sensitivity analysis and was conducted for all parameters adjustable. Structural parameters adjusted during design include the length of the horn (L), the diameter of the horn section (d), the diameter of PZTs (D) and the thickness of the back cylinder (H). Curves of sensitivity analyses are shown in Figure 2. Parameters were adjusted based on the sensitivity analysis to degenerate the resonance frequencies. Moreover, when adjusting these parameters, the positions of PZTs and the tail end of the cutting tool should be noticed. In order to get the maximum vibration amplitude at the end of the cutting tool, the longitudinal PZTs should be placed at the wave node of the longitudinal vibration, while the bending PZTs should be placed at the wave loop of the bending vibration and the tail end of the cutting tool should be placed at the wave loop of both vibrations.

After repeated modal analyses and adjustment, structural parameters were finally determined. The resonance frequencies were 22.499 kHz for longitudinal vibration and 22.494 kHz for bending vibration. These two frequencies are close enough so that a uniform frequency could be used to excite both longitudinal and bending vibrations. Figure 3 shows the vibration modes and resonance frequencies of longitudinal and bending vibrations. Besides the resonance frequencies, vibration modes and positions of PZTs and tail end are also satisfying as shown in Figure 3. Vibration displacements were obtained by FEM transient analysis and the results were shown in Figure 4. During the calculation, sine and cosine signals with voltage of 400V and frequency of 22.496 kHz were applied. The maximum displacements after stabilizing at the end of the cutting tool were 5.46 μm in axial direction and 2.30 μm in radial direction. Also the motion trail of a point at the edge of the drill's end was calculated in this process, as shown in Figure 5. In Figure 5, UY indicate the displacement along OY direction, whereas UZ is the displacement along OZ direction. The maximum displacements change with the amplitude of the exacting voltage applied to the PZT elements and the direction of the motion trail can be adjusted by changing the phase difference of the exciting voltages. Longitudinal and bending vibrations can be excited separately in this cutting tool. When the longitudinal vibration is excited solely, the cutting tool is the same as that of RUM. Thus both RUM and LBUD can be conducted by using the same experimental facilities.

III. DISCUSSION OF THE CUTTING MECHANISM

Longitudinal-bending hybrid mode ultrasonic drill combines the advantages of RUM and RUEM. In this section, the cutting mechanism of LBUD is analyzed. Figure 6 shows the cutting mechanism of LBUD briefly. There are two typical kinds of particle at the end of the cutting tool: particle A where the bending vibration share the same direction with the linear velocity of rotation and particle B where the vibration speed of bending vibration is perpendicular to the rotating speed. Cutting mechanism at particle A is an enhancement of that of RUM while the cutting mechanism at particle B is similar to that of RUEM mentioned before.

As for particle A, the bending vibration increases the linear speed of the cutting edge in the horizontal plane and thus enhances the brittle fracture. Studies concentrated on RUM were conducted for years and indicated that the cutting mechanism is mainly brittle fracture. With longitudinal vibration in RUM, the cutting edges move up and down with the longitudinal vibration and contact with the workpiece intermittently. A great stress would be generated when cutting edges contact with the working surface with the action of longitudinal vibration. When moving down, the cutting edge impacts the workpiece, at the same time it rotates and scratches a groove on the working surface. For hard and brittle materials, brittle fracture occurs in this process and cutting chips generate. With bending vibration, LBUD speeds up this process. At particle A, the bending vibration has the same direction with the rotating speed, these two speeds add and form a higher linear velocity. Thus a shaper locus is acquired in LBUD compared with that of RUM. Figure 6(b) shows the locus of LBUD and RUM in YOZ plane. When the cutting tool moves down with the longitudinal vibration, it moves forward with the synthetic velocity which is much larger than the linear velocity of rotation. As the transient analysis mentioned before, the maximum displacement of the bending vibration was 2.3 μm corresponding to a maximum

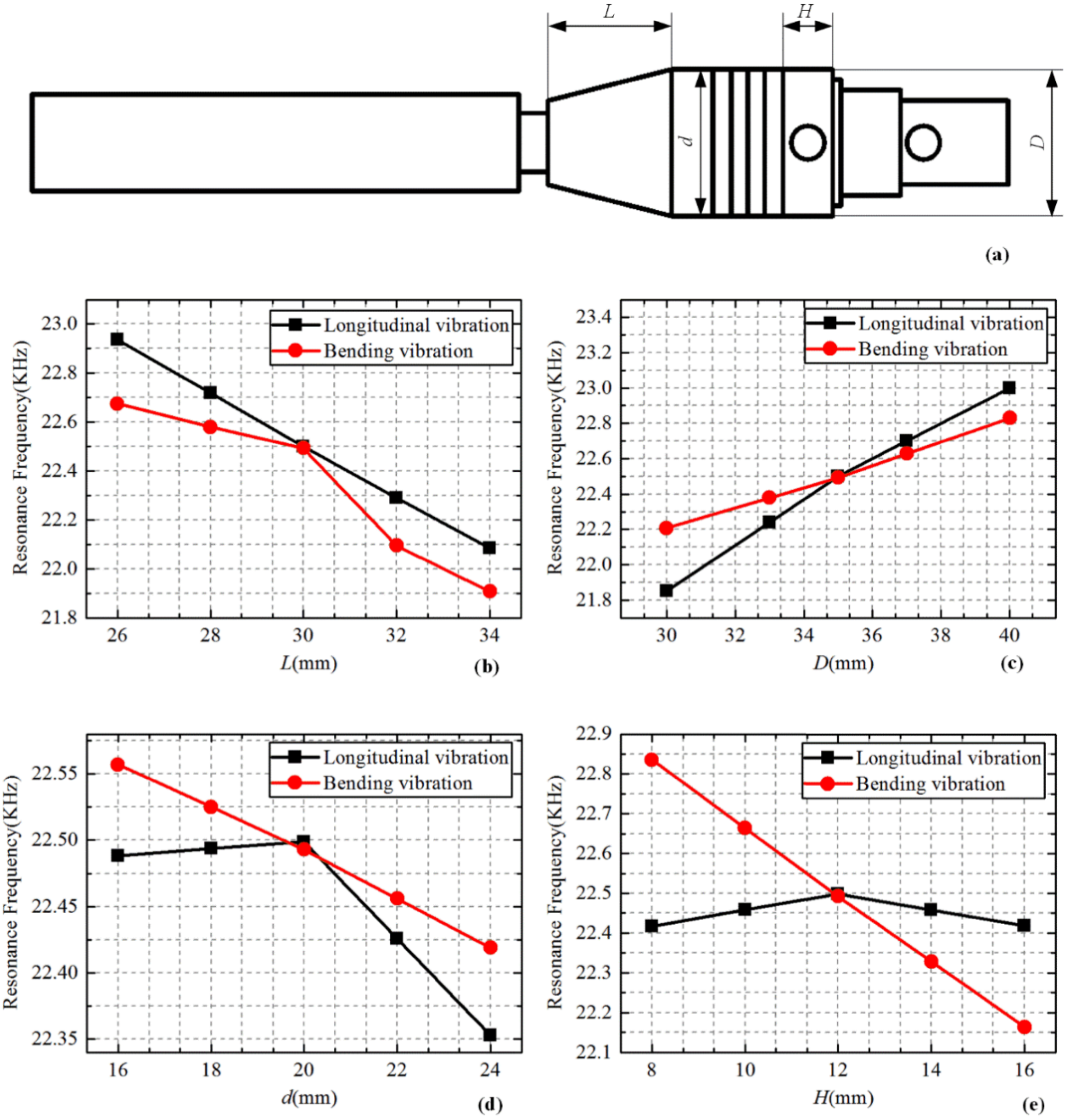

FIGURE 2. **Sensitive analyses of the cutting tool: (a) structural parameters, (b) the length of the horn, (c) the diameter of PZTs, (d) the diameter of the horn section, (e) the thickness of the back cylinder.**

linear velocity of 0.32 m/s. While the linear speed of rotation used in this paper is about 0.48 m/s. Thus a synthetic speed of 0.8 m/s was obtained at cutting edges. When cutting edges impact the cutting surface of the workpiece, the larger relative velocity speeds up the scratching and thus speeds up the brittle fracture and amplifies the brittle fracture region. As a result, the cutting get easier in LBUD compared with RUM.

As for particle B, with the action of the bending vibration, the cutting tool contact with and cut the side surface of the hole intermittently, as shown in Figure 6(e). This action makes a clearance between the cutting tool and the hole [14]. Thus the friction between the cutting tool and the side surface of the workpiece would decrease. Moreover, the big clearance makes it easier to remove the cutting chips so that chip jamming is avoided. Thus, the cutting would get easier and the cutting speed increases. Advantages including reduced tool wear, enhanced surface quality of holes and prevention of delamination at the hole exit surface may be provided by the bending vibration.

Compared with RUM, bending vibration is added in LBUD. Thus, a higher horizontal velocity is obtained. This horizontal velocity helps to amplify the brittle fracture and thus speed up cutting. Meanwhile, similar with RUEM, the bending vibration makes a radial clearance between the cutting tool and the workpiece decreasing cutting force and promoting chip removal. These mechanisms increase the processing speed and cut down the cutting force of hard brittle materials.

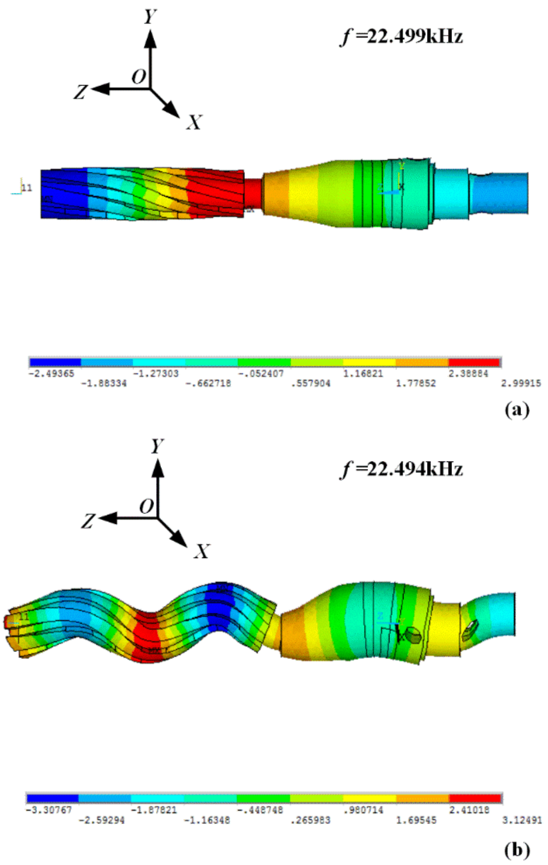

FIGURE 3. **Vibration modes and resonance frequencies of the cutting tool: (a) longitudinal vibration mode, (b) bending vibration mode.**

IV. EXPERIMENT AND RESULT

In order to verify the effect of LBUD, experiments were carried out. Marble which is a representative of hard and brittle materials was chosen as the workpiece in this experiment. Contrast experiments among traditional core drill, RUM and LBUD were conducted.

In addition to the cutting tool, an experiment set-up which provides rotational movement and feed movement for the cutting tool was designed and manufactured. As shown in Figure 7, the experiment set-up mainly consists of a motor, a guide rail, a group of holders and a mass block. The cutting tool was connected to a motor via a group of couplers. In order to reduce the constraint of the coupler to the cutting tool which changes the resonance frequencies and hinders the vibration, elastic couplings are used here. An electrical slip ring was used between the motor and the cutting tool to avoid the coil of wire when rotating. A group of holders is used to keep the cutting tool being coaxial with the motor. The motor is fixed in the holder and the cutting tool is restrained by a bearing in the holder. The holder is placed on the guide rails along the feed direction. The motor and the cutting tool along with the holder can move freely on the guide rails. A mass block pulls the holder through a rope whose direction is changed by a pulley so as to provide constant cutting force for the cutting tool. By changing the mass of the block, the cutting force could be adjusted. The workpiece was clamped by a clamp placed at the edge of the experiment table.

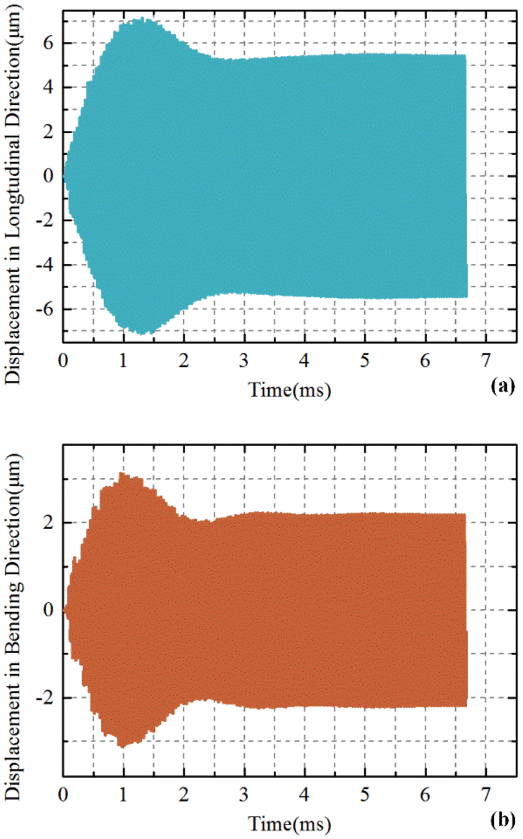

FIGURE 4. **Output displacement at the tail end of the cutting tool in the time domain: (a) displacement in axial direction, (b) displacement in radial direction.**

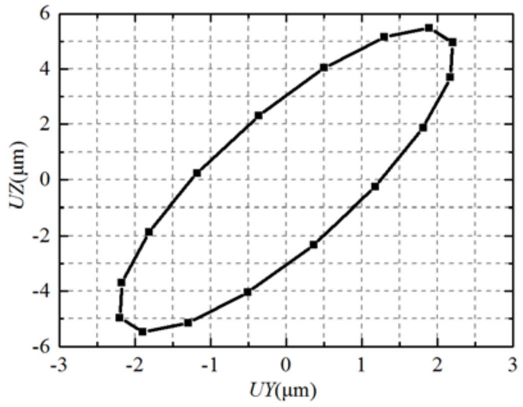

FIGURE 5. **Elliptical locus of the end of the cutting tool.**

The core drill used in this experiment has 6 cutting edges made of hard alloy. The inner diameter of the core drill is 15mm and the outer diameter is 23 mm. The core drill was attached to the ultrasonic transducer by thread to form a cutting tool and then glued to avoid loosening.

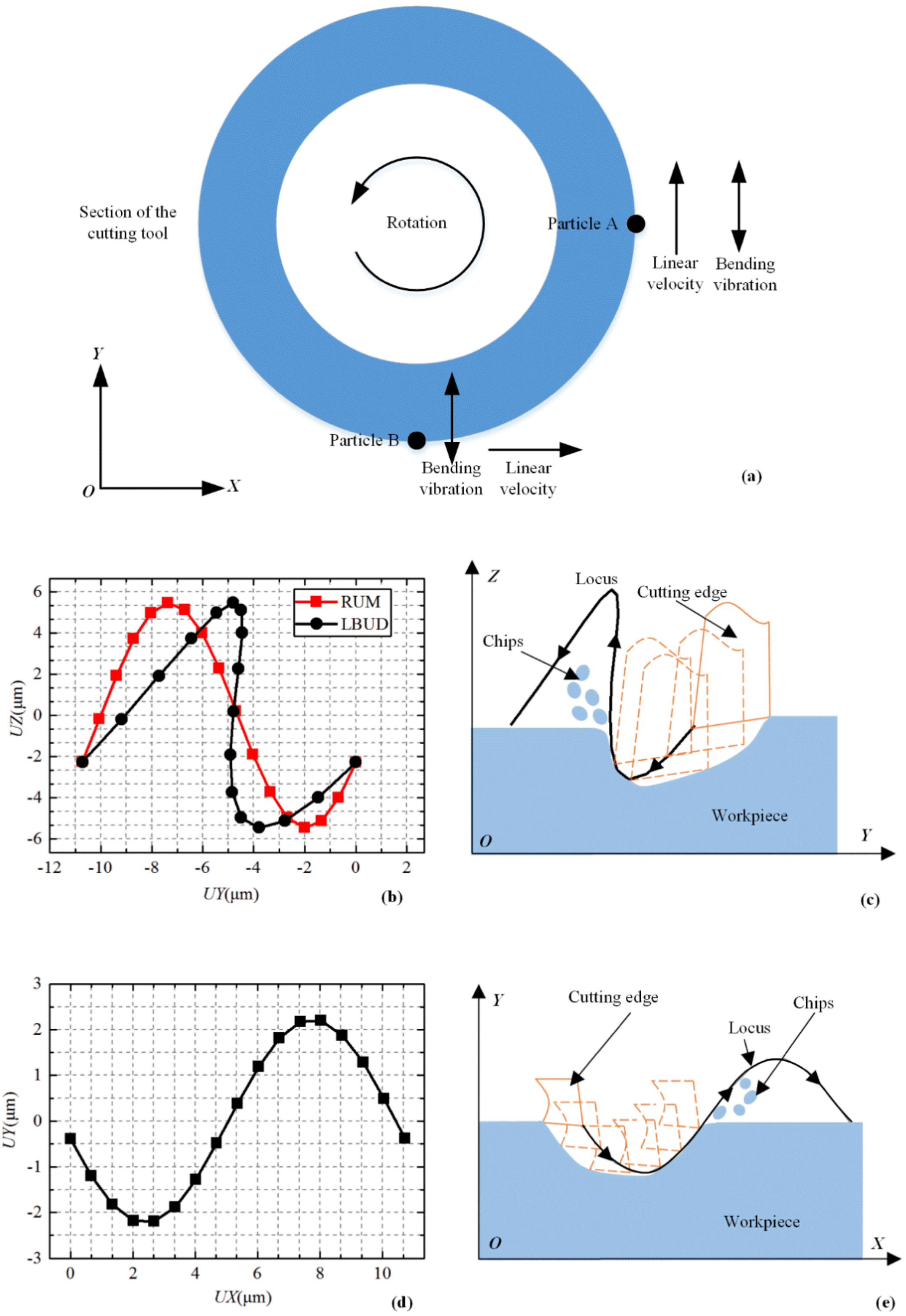

FIGURE 6. Cutting mechanism of LBUD: (a) the section of the cutting tool, (b) motion trail of particle A in the *YOZ* plane within a single cycle of vibration, (c) the cutting edge contact with the workpiece, (d) motion trail of particle B in *XOY* plane within a single cycle of vibration, (e) the cutting tool contact with the side surface of the workpiece.

Performance of the cutting tool was tested by using laser scanning vibrometer (PSV-400-M2, Polytec, Germany), and the frequency response of the cutting tool was shown in Figure 8. It should be noted that these frequency respond curves were measured under free boundary conditions of the cutting edges. In the cutting process, cutting edges contact with the workpiece, which may change the frequency response characteristics. It can be recognized that the

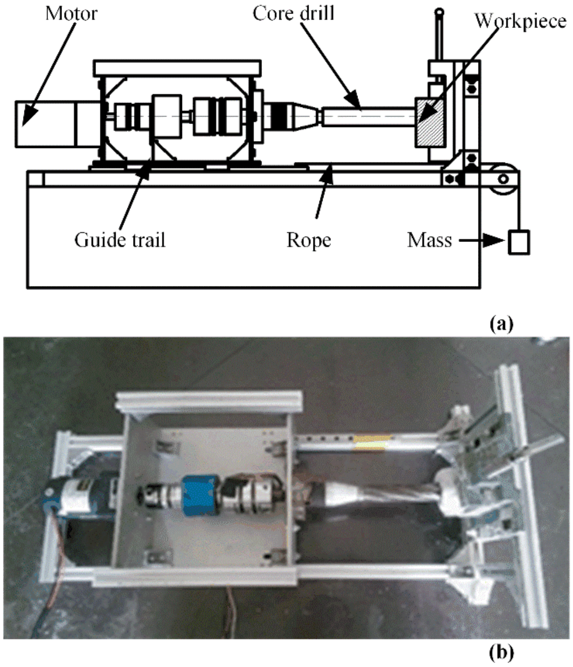

FIGURE 7. The experiment set-up of LBUD. (a) The schematic diagram, (b) the photo.

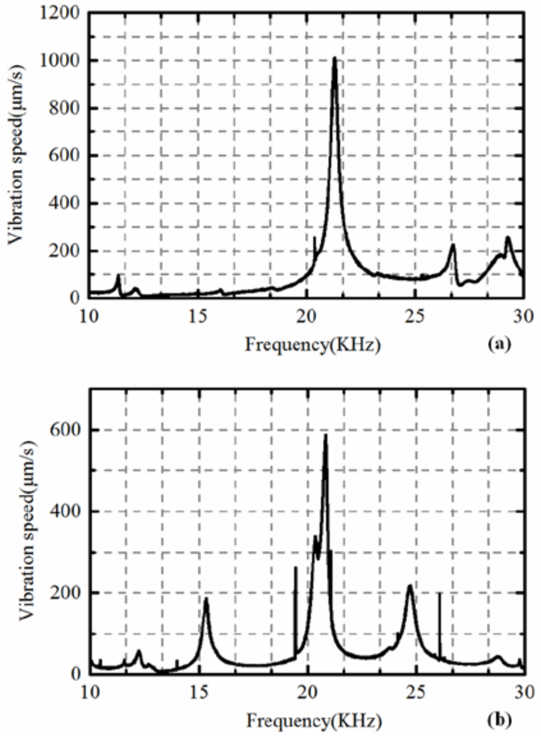

FIGURE 8. Frequency respond curve of the cutting tool, (a) the longitudinal vibration, (b) the bending vibration.

resonance frequencies of the longitudinal and bending vibrations are 21.289 kHz and 20.836 kHz, respectively.

Also, the processing speed versus exciting frequency was tested as shown in Figure 9. These data were measured under the following conditions: the amplitudes of the exciting voltages were 300V, the phase shift of the two voltages was 90 degree, the rotation speed of the drill was 300 rpm and the external force was 100N. It was found that the prototype got the maximum processing speed of 1.87 mm/min under the frequency of 21.3 kHz, which had a little deviation comparing with the resonance frequencies shown in Figure 8.

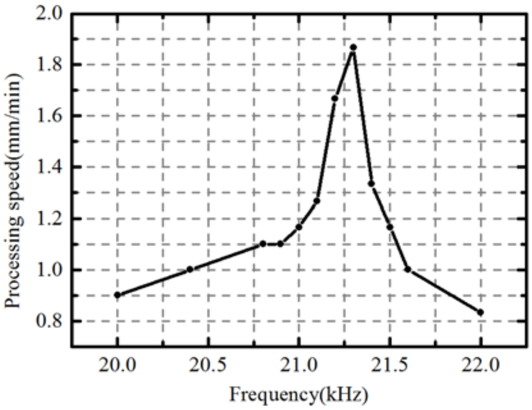

FIGURE 9. Plot of the processing speed versus exciting frequency.

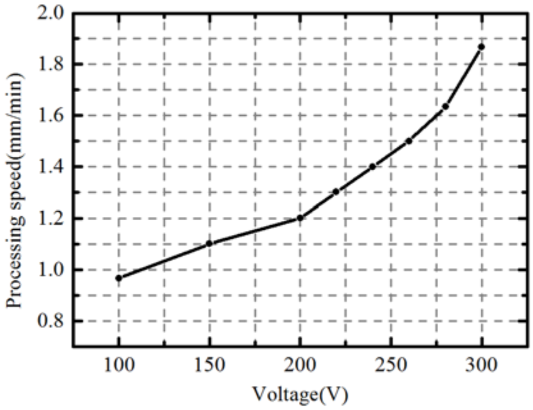

FIGURE 10. Plot of the processing speed versus the exciting voltage.

Then, the frequency was set as 21.3 kHz in the following experiments. The impact of the exciting voltage on the processing speed were measured under phase shift of 90 degree, rotation speed of 300 rpm and external force of 100N, as shown in Figure 10. It shows that the processing speed increases almost linearly with the exciting voltage. Figure 11 shows the relationship between the phase shift of the exciting voltages and the processing speed (the exciting voltage was 200 V, the rotation speed was 300 rpm and the external force was 100N.), which states that impact is very weak.

To compare the cutting speed of traditional core drill, RUM and LBUD, three holes were drilled using each method. The exciting frequency was 21.3 kHz, which was the best frequency due to Figure 8. The exciting voltage was 300 V, the rotation was 300 rpm and the cutting force was fixed at 100 N. The cutting depth was recorded every minute and

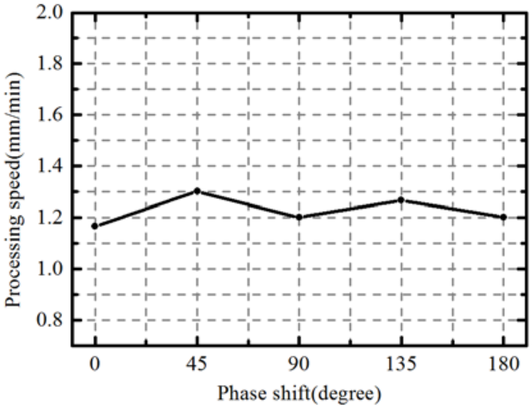

FIGURE 11. Plot of the processing speed versus the phase shift.

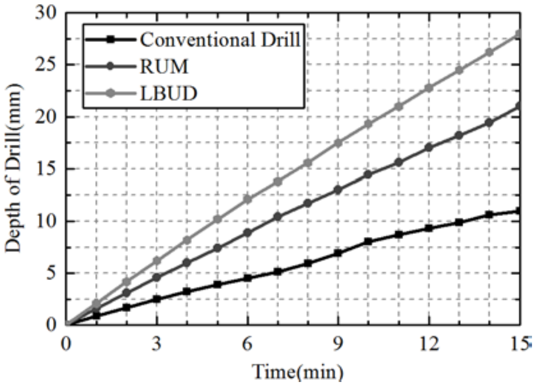

FIGURE 12. The cutting speeds of different methods

each experiment lasted for 15 minutes. Finally, data obtained were drawn to a curve as shown in Figure 12. The result indicates that the processing speeds of the conventional drill, RUM and LBUD increase in turn. In this experiment, cutting processes of the three cutting methods are almost linear. Processing speeds of the three methods are approximately 0.8 mm/min, 1.4 mm/min and 1.87 mm/min respectively. The processing speed of LBUD is 2.34 times of conventional drill and 1.34. times of RUM. Moreover, jamming which usually occurs in conventional and sometimes happens in RUM has never been observed in LBUD, which implies that bending vibration contribute to the avoidance of jamming. Although it is not showed in this experiment that how the bending vibration promote the cutting, it is clear that LBUD is a more effective method to cut hard and brittle materials.

V. CONCLUSION

A novel cutting method to the drill of hard and brittle materials was proposed in this paper. Instead of single longitudinal vibration which is usually used in ultrasonic drill, longitudinal-bending hybrid mode vibration was used in this work. Thus an elliptical locus was formed at the end of the cutting tool to improve the cutting mechanism. LBUD was expected to increase the cutting speed of the drill of hard brittle materials. Cutting mechanism of LBUD was analyzed. A cutting tool and an experiment set-up for LBUD were designed and manufactured. Experiments were conducted to verify the effect of longitudinal bending hybrid ultrasonic drill. Also some characteristics of LBUD were studied through experiment. Results showed that the LBUD increased the cutting speed of hard brittle materials observably by comparing with RUM using single longitudinal vibration.

The following conclusions are drawn from this study:

(a) Bending vibration in LBUD increases the linear velocity of the cutting edge and thus amplifies the brittle fracture on the cutting surface.

(b) The cutting tool cuts the side surface of the workpiece and makes a radial clearance between the cutting tool and the workpiece under the bending vibration.

(c) LBUD is a feasible method for the drilling of hard and brittle materials which speeds up the cutting.

(d) The processing speed of LBUD increases with the increase of the exciting voltage.

(e) The processing speed of LBUD changes with the exciting frequency and reaches a peak near the mechanical resonance frequency of the drill.

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