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Abstract. A new centerless grinding method without regulating wheel is proposed. Instead of using a regulating wheel, this method employs an ultrasonic vibrating shoe to support the workpiece. The end of the vibrating shoe is in elliptic motion at a high frequency, while the rotational speed of the workpiece is controlled by the elliptic motion of the shoe. An experimental apparatus has been designed and constructed. Tests involving the rotational driving of a workpiece were then conducted on the apparatus, which showed that the workpiece rotational speed depended on the AC voltage and its frequency. Finally, grinding tests involving pin-shaped workpieces with an initial roundness of 20μm were performed. The results showed that the roundness of the workpieces was improved to 1.5μm after grinding using the new apparatus.

Introduction

Centerless grinding is a unique grinding method for the precision machining of a cylindrical workpiece which is held at three points on its circumference by a regulating wheel, a blade, and a grinding wheel during grinding. In this method, the labor required to place the workpieces on and off the chuck or to center them is unnecessary, thus increasing processing efficiency. Furthermore, this method allows high-precision and heavy duty grinding since the workpiece is supported over its overall length by the regulating wheel and the blade.

However, the finish accuracy (i.e. roundness) of the workpiece greatly depends on the roundness and the rotational accuracy of the regulating wheel as the workpiece is held essentially along its periphery [1, 2]. Therefore, a high-precision truing technique for regulating the wheel and a high-rotational accuracy spindle for regulating the wheel axis are strongly required so that high precision machine parts can be easily obtained by centerless grinding. In addition, from the point of view of resource conservation, and energy and space saving, desktop-size machine tools are recently in increasing demand, especially for micro-parts machining [3]. However, it is difficult to build a desktop-size centerless grinder having a regulating wheel since such a machine requires the installation of many apparatuses such as a rotation driving unit and a truing attachment for the regulating wheel. Accordingly, the most valid way to solve this problem would be to develop a new centerless grinding method in which the regulating wheel is not required.

In the present study, a new centerless grinding method is proposed. Instead of using a regulating wheel, this method uses an ultrasonic vibrating shoe to support the workpiece. The end of the vibrating shoe is in elliptical motion at a high frequency, while the workpiece rotational speed is controlled by the elliptic motion of the shoe. An experimental apparatus has been designed and constructed. Grinding tests of pin-shaped workpieces have been carried out. This paper describes in detail the principle of this new method, the construction of the experimental setup, and the grinding tests.

Features of the New Method

The conventional centerless grinding method and the proposed new method are outlined in Figures 1(a) and (b), respectively. The former employs a regulating wheel to support the workpiece together with a blade to feed the workpiece towards the grinding wheel. The rotational speed of the workpiece is controlled by the rotation of the regulating wheel. On the other hand, the latter employs an ultrasonic vibrating shoe to support the workpiece and feed it towards the grinding wheel. The rotational speed of the workpiece is controlled by the elliptic motion of the shoe.

Comparing these two methods, it is evident that desktop-size centerless grinders based upon the new concept could be produced easily because no attachments or apparatuses related to a regulating wheel are needed. Further, this method avoids the risk of roundness errors caused by the regulating wheel or rotary errors of its axis, both of which significantly affect the final roundness of the workpiece when using the conventional method.

Experimental Apparatus

Outline of Experimental Apparatus. Figure 2 illustrates the experimental apparatus. The workpiece is constrained between the ultrasonic vibrating shoe, the blade, and the grinding wheel. The shoe and blade are fixed on their holders by means of bolt. A fine feed unit composed of a linear motion bearing and a ball screw, and the shoe holder is driven by a stepping motor to give the shoe a fine motion forward or backward onto the grinding wheel during grinding. In the meantime, the rotational speed of the workpiece is controlled by the elliptic motion of the shoe. In the present study, a fine feed unit and an ultrasonic vibrating shoe were designed and produced. A conventional centerless grinder was then adapted so that the produced fine feed unit with the shoe could be installed on it.

Ultrasonic Vibrating Shoe. Figure 3 shows the structure and the operating principle of the shoe. As shown in Figure 4(a), the shoe is composed of a metal elastic plate (SUS304) and a piezoelectric ceramic device (PZT) with four separated electrodes (a-d). The PZT is bonded onto the plate. Thus, when two alternating current signals (over 20 kHz) with 90 degrees of phase difference to each other produced by a wave function generator are applied to the PZT after being amplified with power amplifiers, ultrasonic vibrations with amplitudes of several micrometer in different direction (see Fig.4(b)), bending vibration (B4 mode), and longitudinal vibration (L1 mode) are excited simultaneously. Hence, the synthesis of vibration displacements in two directions creates an elliptic motion on the end face of the metal elastic plate. Subsequently, the rotation of the workpice is controlled by the friction force between the workpiece and the shoe. The speed of the workpiece at its periphery is supposed to be same as the bending vibration speed, u_B, on the shoe end face. Thus, the workpice rotational speed can be changed by changing the value of such parameters as the amplitude and frequency of the voltage applied to the PZT because the shoe bending speed varies with the variation of the applied voltage [4].

Figures 4(a) and (b) show the schematic drawing and the photograph of the ultrasonic vibrating shoe, respectively. In order to excite the elliptic motion on the shoe end face, the resonance frequencies for both the B4 mode and L1 mode must be same or at least very close to each other [5]. Accordingly, all the dimensions of the PZT and the metal elastic plate were determined using FEM analysis and listed in Figure 4(a). On the other hand, a water proof layer was coated on the shoe surface to prevent grinding fluid used during grinding. Furthermore, the friction coefficient between the shoe and the workpiece should be large enough so that the periphery speed of the workpiece is maintained at the same bending vibration speed u_B of the shoe end face. For this purpose, a thin sheet (0.5mm in thickness) of the same material as for a conventional regulating wheel (A120R) was made and attached to an end face of the shoe.

In order to determine the actual resonant frequencies for both the B4 mode and the L1 mode of the ultrasonic vibrating shoe, the impedance characteristics of the shoe were investigated using an impedance analyzer. Figure 5 shows the obtained results where f_{B4}, f_{L1} represent the resonant frequencies for the B4 mode and L1 mode, respectively. It can be seen that both f_{B4} and f_{L1} agree well with their respective values predicted by an FEM analysis (Fig. 5(a)) at values of f_{B4}=f_{L1}=23.72kHz. In addition, the impedance reached a maximum at f=23.88kHz, indicating that the power consumption would be least when the voltage is applied at frequency f=23.88kHz. This point is called the anti-resonance point [5].

Figure 6 shows how the shoe is supported and fixed on a holder. That is, in order not to restrict the ultrasonic vibration, the shoe is bolted at its central location (i.e., the common node for the L1 mode and B4 mode) to the holder where a spacer (electric insulation) is placed between them. A pre-load is then applied to the shoe in its longitudinal direction using a coil spring in order to prevent the PZT from breaking due to resonance. Under such fixed and supported conditions, the vibration amplitude on the end face of the shoe was measured using a laser doppler vibration meter in order to examine the effect of the applied voltage (amplitude and frequency) on the shoe's bending and longitudinal vibration. Figures 7(a) and (b) show the influence of the frequency of voltage f, the amplitude of voltage $V_{p\text{-}p}$ and the pre-load P on the longitudinal (L direction in Fig. 3) vibration amplitude A_L, and the bending (B direction in Fig. 3) vibration amplitude A_B, respectively while the pre-load was fixed at P=15N. From Figure 7(a), it is obvious that both A_L and A_B initially increase with the increase of frequency, and then decrease after reaching their peak values. The two peaks correspond to the resonance points for the B4 mode and the L1 mode, respectively. The difference between the two resonant frequencies f_{B4}, f_{L1} was due to the difference in the effect of the pre-load (15N) on the two modes. It is thus apparent that A_B and A_L increase with the amplitude of voltage $V_{p\text{-}p}$ (Fig. 7(b)).

Furthermore, a test involving the rotational driving of a cylindrical workpiece (SK4 with sizes of 5mm in diameter and 18mm in length) using the produced vibrating shoe was conducted. In the test, the voltage frequency and the pre-load were fixed while the voltage amplitude was varied within a given range. The workpiece rotation speed was measured using a digital tachometer. The test results showed that the rotational speed of the workpiece grows as the voltage amplitude increases. This is because the bending vibration amplitude of shoe A_B, to which the periphery speed of the workpiece is subject, increases with increasing voltage.

Fine Feed Unit. For the finish grinding of micro parts with sizes of less than 1 mm in diameter, the depth of cut must be less than 1 μm in order to make the grinding force small. For this reason, a fine feed unit composed of a shoe holder, a linear guide, a ball screw, and a stepping motor has been designed and produced that carries the shoe toward the grinding wheel at a feed rate of less than 1μm/s. The photograph and specifications of the produced unit are shown in Figure 8. As the step angle of the stepping motor was set at 0.012° per pulse and the lead of the ball screw was 2mm, the shoe feed is supposed to be around 0.067μm per pulse, resulting in a minimum shoe feed rate of 0.67μm/s. Figure 9 shows the performance of the fine feed unit in terms of the shoe feed rate as measured using a laser displacement meter. The feed per step (5 pulses) was around 0.3μm, resulting in an actual feed rate of 0.6μm/s and having a good temporal linearity. These results meet the design requirements.

Grinding Tests

In order to confirm the validity of the proposed new method, grinding tests involving cylindrical workpieces were carried out on the constructed apparatus. During the tests, the pre-load, the voltage amplitude and frequency were set up at P=15N, $V_{p\text{-}p}$=100V (in table 1, it is 50V), and f=24.5kHz, respectively. As the workpieces to be used in tests, 15 pin-shaped cylinders (3 for each diameter) with 5 different diameters of 1mm, 2mm, 3mm, 4mm, 5mm, and a common length of 18mm were prepared from long cylinders (SK4, 1,2,3,4,5mm in diameter). A flat with a radius depth of 20μm was made on the workpiece circumference by surface grinding to be the initial roundness error.

The grinding test was performed as follows: First, the grinding wheel was moved toward the blade and stopped right before they interfere with each other. Next, the shoe was fed forward to carry the workpiece toward the grinding wheel at a feed rate of V_f=0.2mm/min and ground under the grinding conditions listed in Table 1. The shoe then retracted from the grinding wheel after the stock removal had been completed. By repeating this cycle, grinding operations continued until all the 15 workpieces have been ground.

The roundness and cross section profile of the ground workpieces were measured using a roundness measurement instrument. Figure10 shows the measured results. It was found that the roundness of the workpieces with initial diameters of 2mm to 5mm improved much from the initial error of 20μm to less than 4μm. The minimum roundness was 1.5μm. However, of the 3 workpieces with initial diameters of 1mm, one (No.2) improved in roundness while the other two (No.1 and No.3) deteriorated. This is apparently due to the lightness of the workpiece, which allowed it to vibrate vertically during grinding, in the same manner as the through-feed centerless grinding for light workpieces [6]. Based on the triangle cross section profile of the workpiece (upper left in Fig.10), the vibration peaks 3 times per workpiece revolution. This indicates that for the high precision grinding of pin-shaped workpieces with small size using the new method, the workpiece instability problem must be solved first. A detailed investigation of this problem will be reported later.

Conclusions

A new centerless grinding method has been proposed in which an ultrasonic vibrating shoe instead of a regulating wheel is employed for supporting the workpiece and controlling the speed of the workpiece rotation. An experimental apparatus has been constructed by installing the new shoe and fine workpiece feed unit on a conventional centerless grinder. The tests of workpiece rotational speed control and grinding were performed. The obtained results can be summarized as follows:

(1) The speed of the workpieces rotation depends on the bending vibration velocity of the shoe end face.
(2) By changing the voltage amplitude and frequency applied to the shoe, the rotation speed of the workpiece is changed.
(3) The results of grinding tests showed that the roundness of pin-shaped workpieces with diameters of 2-5mmm were improved from an initial value of 20μm to a final value of less than 4μm. However, of the three workpieces with diameters of 1mm, two deteriorated due to their lightness that allowed vertical vibration during the grinding operation.

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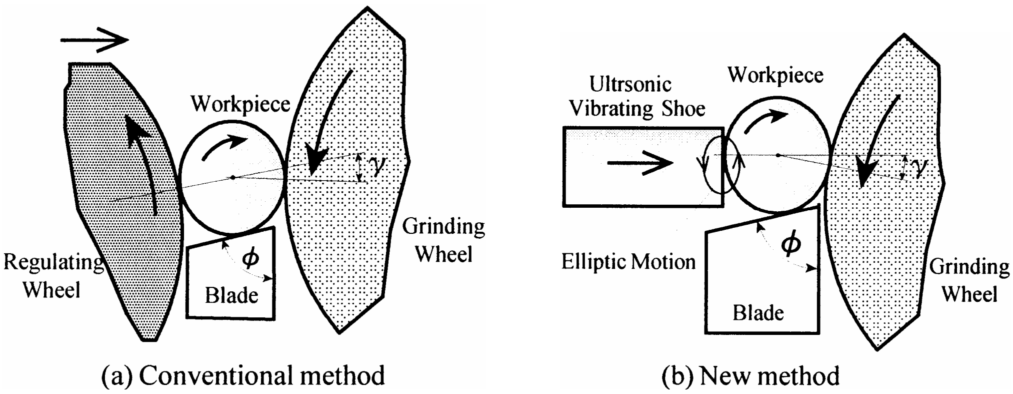


Fig.1 Schematic of conventional and new centerless grinding, method

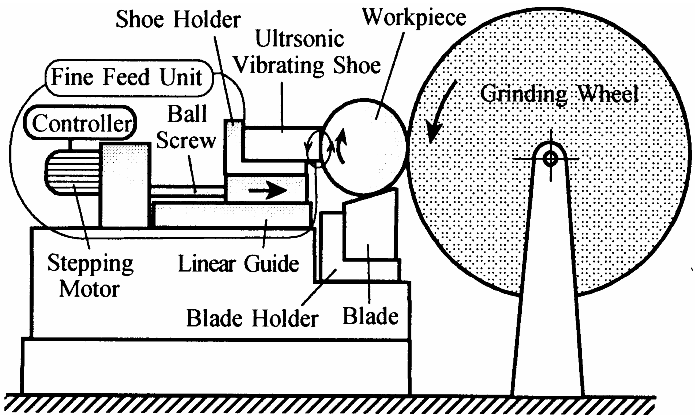
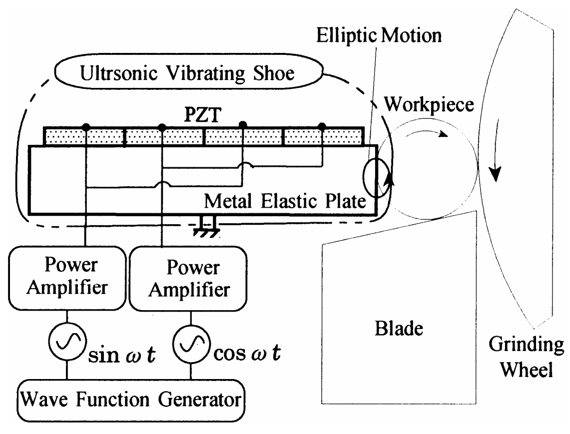
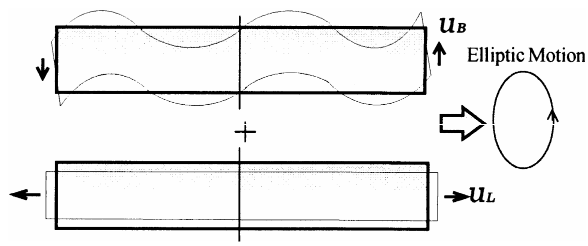


Fig. 2 Illustration of experimental apparatus

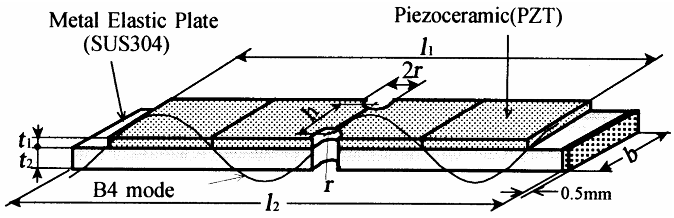


(a) Shoe structure and power application method



(b) Generation principle of elliptic motion

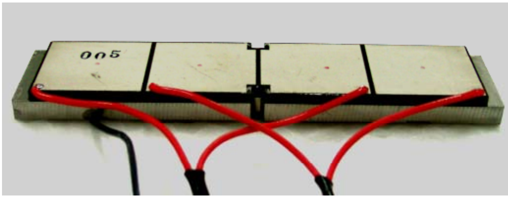
Fig.3 Structure and operating principle of ultrasonic vibrating shoe



(a) Dimensions

Dimensions [mm] and resonance frequencies [kHz]

B=20	t_1=2	t_2=4.44	l_1=88.6	l_2=96.5
R=1.25	H=16.4	f_{B4}=23.72	f_{L1}=23.72	



(b) Photograph

Fig. 4 Dimensions and photograph of the produced shoe

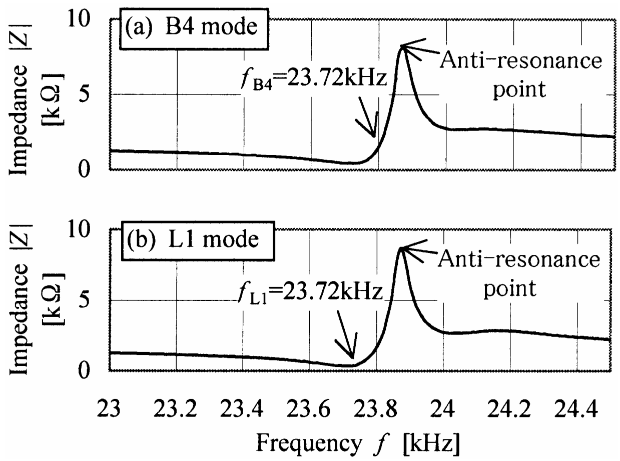


Fig. 5 Impedance characteristics of shoe

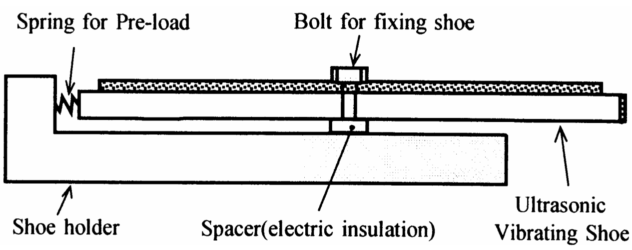
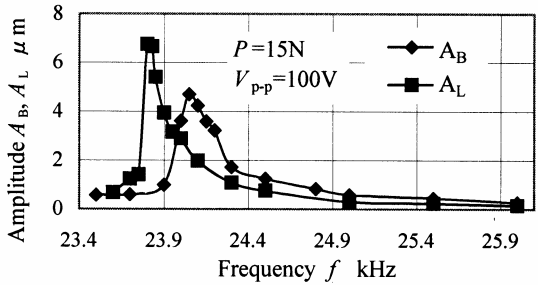
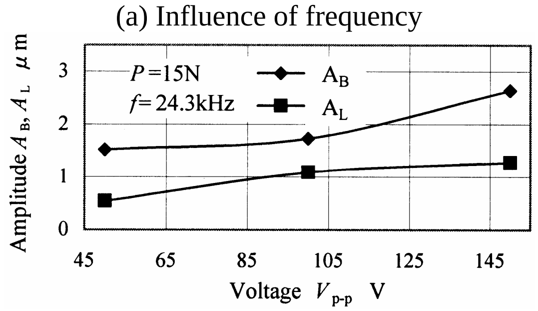


Fig. 6 Holding method for shoe

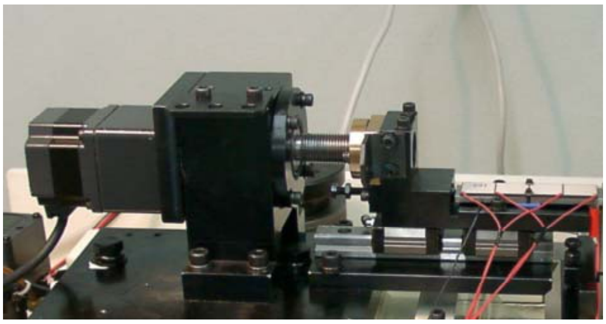


(a) Influence of frequency



(b) Influence of voltage

Fig. 7 Influence of frequency and voltage on vibration amplitude



Motor	Type: 5 phase stepping motor unit Step angle of output axis: 0.012°/step Speed range: 10～30000 steps/s (0.02～60rpm)
Ball screw	Lead: 2mm
Feed rate	(0.02～60)×2=0.04～120mm/min =0.67～2000 μ m/s
Stroke	100mm

Fig. 8 Photograph and specifications of the fine feed unit

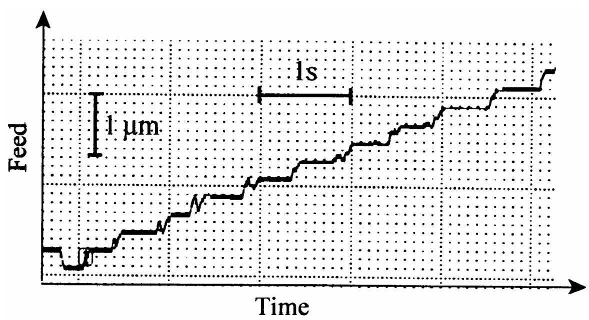


Fig. 9 Performance of the fine feed unit

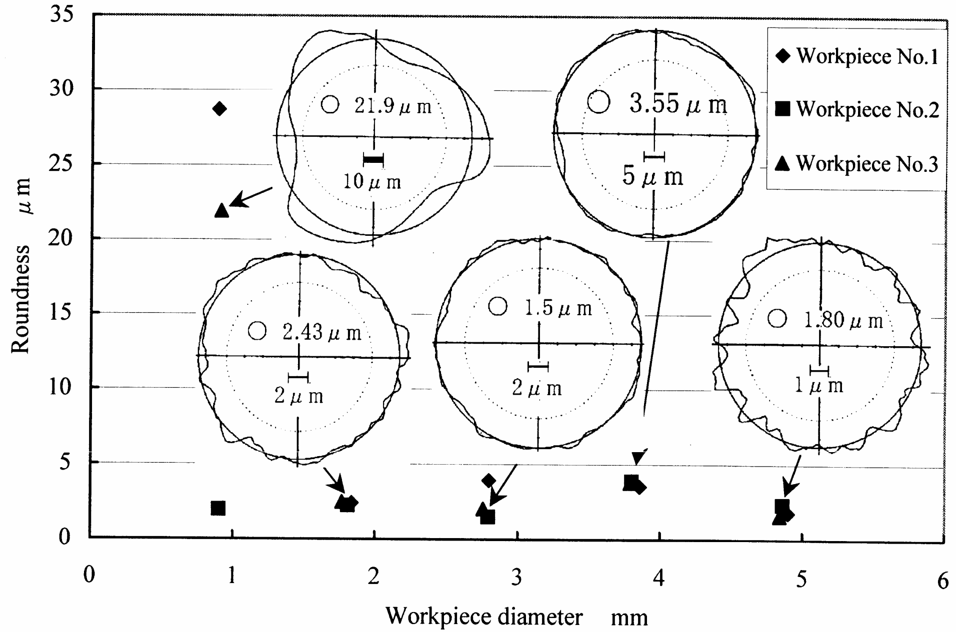


Fig. 10 Results of grinding tests

Table 1 Experimental conditions

Grinding wheel	NX80IV150×20×76.2,1A1	
Workpiece	SK4 ϕ 2×L18 [mm]	
Coolant	Solution type	
Power supplying to PZT	Amplitude	$V_{p\text{-}p}$=50 [V]
	Frequency	f=24.5 [kHz]
Grinding wheel speed	V_g=30 [m/s]	
Infeed rate of shoe	V_f =0.2 [mm/min]	