Investigation of the longitudinal-flexural resonating spindle in ultrasound-assisted grinding of SiCp/Al composites

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Research Article

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Abstract

Rotary ultrasonic machining is a cost-effective and precise machining method for hard and brittle materials. Aiming at processing SiCp/Al composites, a rotary ultrasonic grinding spindle is proposed in the present study. Expressions were established to calculate the displacement, rotation angle, bending moment, and shear force of the vibrating elements based on the Mindlin moderate plate theory. Combining continuous and boundary conditions of vibrating elements with the proposed expressions, the vibration model and frequency equation of longitudinal-flexural resonating transformer with a large load were established. Then two transformers were designed according to the frequency equation. The resonant characteristics of the transformers were studied using finite element analysis, impedance analysis, and ultrasonic resonance experiments. The obtained results show that the maximum deviation between the resonant frequency and the design frequency of the transformers was 4.95%. Moreover, the maximum deviation of the positions of the pitch circles was 6.51%. It is concluded that the proposed designs have high accuracy. Finally, the orthogonal single-factor experiments of SiCp/Al composites were performed with and without ultrasound. The obtained results show that introducing ultrasonic vibrations significantly reduces the grinding force and the surface roughness while improving the surface quality of the SiCp/Al workpiece. The present study is expected to provide experimental fundamentals to further improve the structure of the grinding spindle, optimize process variables of ultrasound-assisted grinding, and improve the processing efficiency.

1. Introduction

SiCp/Al composites are increasingly used in various engineering applications, such as in military equipment, aero-engines, instrumentation, brakes of high-speed trains, electronic packaging, and numerous high-tech fields thanks to their high hardness, high specific strength, high elastic modulus, low density, low thermal expansion, excellent corrosion and wear resistance [1–3].

Despite the superior characteristics of SiCp/Al composites, the machining property of them is poor due to the reinforced particles existing in matrix. Conventional processing methods have disadvantages such as large cutting force, poor surface quality, and low processing efficiency [4–6]. Meanwhile, many methods such as electrical discharge machining, laser processing, high-pressure water jet processing, and electrochemical processing affect the performance of SiCp/Al composites so that they are not applicable to process SiCp/Al components [7, 8].

Studies show that rotary ultrasonic machining technology is an effective compound processing method for SiCp/Al composites, which has attracted many researchers. Compared with conventional machining methods, it has excellent characteristics [9, 10]. In the ultrasound-assisted grinding method, diamond or cubic boron nitride (CBN) grinding wheels are usually used as the cutting tool. While the tool rotates at a high speed, it also vibrates along the axial direction. This method is an efficient processing technology for metal-matrix composites, which has the advantages of grinding multi-edge cutting and ultrasonic vibration machining simultaneously [11, 12].

Compared with the conventional grinding methods, the ultrasound-assisted grinding method has several advantages such as reducing the grinding force and heat, reducing the machining damage, improving the machining efficiency and accuracy, and prolonging the tool life [13]. In this regard, the machining of hard and brittle materials has been extensively studied experimentally and numerically to assess cutting ability, surface roughness, tool wear, and blockage of the grinding wheel. Li et al. [14] carried out the experiments on rotary ultrasound-assisted drilling of carbon fiber-reinforced polymers under no cooling conditions. The obtained results showed that compared with the common drilling, when the vibration amplitude reached 5.0 and 7.5 mm, the cutting ability of the core drill tool was greatly enhanced so that excellent chip removal efficiency was achieved. Meanwhile, the dimensional accuracy of the machined hole and the rod diameter was improved. Tawakoli et al. [15] carried out an axial ultrasound-assisted dry grinding experiment on

42CrMo4 and avoided the treatment and harm of the coolant. The results showed that ultrasound-assisted dry grinding of 42CrMo4 workpiece reduces wheel wear and burned areas on the workpiece surface. Moreover, it reduces the surface roughness and normal grinding force. Xiang et al. [16] studied the blockage mechanism of the grinding wheel in the conventional grinding process of SiCp/Al composites. It was found that the combination of ultrasonic vibration and conventional grinding significantly reduces the blockage volume of the grinding wheel and improves the service life of the grinding wheel. Jing et al. [17] studied the ceramic-based parts and established mathematical models to estimate the life of the abrasive tool, abrasive particle size, and abrasive concentration in ultrasound-assisted grinding. Through Box-Behnken and validity and significance experiments, various factors affecting the life of abrasive tools were analyzed and the affecting variables of abrasive tools were optimized.

The performed literature survey reveals that ultrasound-assisted grinding is an effective method for machining hard and brittle materials. However, the ultrasonic vibration of many devices is superimposed on the workpiece, which is lack of process universality [18–22]. Even if the ultrasonic vibration is superimposed on the abrasive tools, the maximum diameter of abrasive tools is only 50mm [23–27]. The small size of abrasive tools limits the processing efficiency.

Therefore, design of the ultrasonic vibration system has attracted many scholars. Based on the longitudinal vibration theory of the horn and the vibration theory of the thin plate, Ma et al. [28] established the displacement and stress expressions for vibration elements. The frequency equation was deduced by combining the proposed expressions with the boundary conditions. A typical ultrasonic grinding system consisting of an ultrasonic horn and a cupped tool was designed. She et al. [29] proposed a method to design ultrasonic polishing systems based on the thin plate vibration theory and considered the longitudinal-flexural resonating between the transducer, horn, and mode-conversion plate. Xu and Lin [30] designed a hollow cylinder-type ultrasonic vibration system based on the thin plate flexural vibration theory and the coupled vibration theory.

It is noted that, these scholars use the thin plate theory to establish the vibration model of the plate. However, the grinding wheel with a large load should be simulated using the moderately thick plate theory as the increase of its ratio of thick to diameter. Previous research has shown that moderately thick plates can not be driven in the single longitudinal mode [31]. So it complicates the design of the resonant system. Meanwhile, the resonant characteristics can be hardly controlled. It is essential to make parallel grinding wheel vibrate in the flexural mode with only circle nodal lines, a symmetrical mode to ensure the machining homogeneity [32]. Therefore, it is of significant importance to investigate the design methods of the ultrasonic vibration spindle with a large-load grinding wheel in ultrasound-assisted grinding.

The main objective of the present study was to design an ultrasound-assisted grinding spindle with a large-load and multi-material grinding wheel. To achieve this, the frequency equation and the expression of the amplitude of the longitudinal-flexural resonating transformer were established based on the Mindlin theory. Moreover, the resonant characteristics were studied. Then, the single factor orthogonal grinding experiments of SiCp/Al composites with and without ultrasound were performed. The machinability parameters, including grinding forces, surface roughness and topography, and size of wear debris of the two techniques were compared to reveal the advantages of machining with ultrasonic vibration.

2. Design Of Longitudinal-flexural Resonating Transformer

The longitudinal-flexural resonating and multi-material transformer in ultrasound-assisted grinding mainly consists of a transverse and flexural-vibrating large-load grinding wheel and a longitudinal-vibrating conical horn, as shown in Fig. 1. In the present study, the grinding wheel is simplified into a matrix annular plate and an abrasive layer annular plate. To simplify the analysis, the size of the nut is ignored compared with the size of the transformer.

A cylindrical coordinate system (r, θ, z) is established, where R_1 , R_2 , and L are the wide end radius, the narrow end radius, and the length of the conical horn, respectively. Moreover, R_3 , R_4 , and R_5 are the inner radius of the matrix annular plate, inner radius, and outer radius of the grinding wheel, respectively. t denotes the thickness of the grinding wheel.

2.1. Frequency equation

When the transformer resonates in a longitudinal-flexural mode, the transducer generates longitudinal vibration and transmits it directly to the horn. Equation (1) denotes the longitudinal displacement ξ of the conical horn at frequency f [33]:

$$\xi = (z - \frac{1}{\alpha})^{-1} [C_1 \cos(kz) + C_2 \sin(kz)]$$

1

Where $\alpha = (R_1 - R_2)/R_1 L$; C_1 and C_2 are constants that depend on the boundary conditions. $k = \omega/c$, $\omega = 2\pi f$, and $c = (E_1/\rho_1)^{1/2}$ denote the wavenumber, the circular frequency and the velocity of the longitudinal wave, respectively. Moreover, E_1 and ρ_1 are Young's modulus and density of the conical horn, respectively.

The flexural vibration of the grinding wheel is generated by the longitudinal vibration of the horn. According to the Mindlin theory, transverse displacement w and the rotation β_r of the grinding wheel along the r -direction can be mathematically expressed as the following [34, 35]:

$$\begin{cases} w_i = A_{1i} J_0(\delta_{1i} r) + B_{1i} Y_0(\delta_{1i} r) + A_{2i} J_0(\delta_{2i} r) + B_{2i} Y_0(\delta_{2i} r) \\ \beta_{ri} = (\sigma_{1i} - 1) [A_{1i} J'_0(\delta_{1i} r) + B_{1i} Y'_0(\delta_{1i} r)] \\ \quad + (\sigma_{2i} - 1) [A_{2i} J'_0(\delta_{2i} r) + B_{2i} Y'_0(\delta_{2i} r)] \end{cases}$$

2

Where

$$\begin{cases} \delta_{1i}^2, \delta_{2i}^2 = \frac{\delta_{0i}^4}{2} \left\{ (R_i + S_i) \pm \left[(R_i - S_i)^2 + \frac{4}{\delta_{0i}^4} \right]^{\frac{1}{2}} \right\} \\ \sigma_{1i} = \frac{\delta_{2i}^2}{R_i \delta_{0i}^4 - S_i^{-1}}, \sigma_{2i} = \frac{\delta_{1i}^2}{R_i \delta_{0i}^4 - S_i^{-1}} \\ \delta_{0i}^4 = \frac{\rho_i t_i}{D_i} \omega^2, \delta_{Hi}^2 = \frac{2[R_i \delta_{0i}^4 - S_i^{-1}]}{1 - \mu_i}, R_i = \frac{t_i^2}{12}, S_i = \frac{k_\tau D_i}{G_i t_i} \end{cases}$$

3

Where i ($i=1,2$) is the matrix annular plate and abrasive layer annular plate. A_{ji} and B_{ji} ($j=1,2; i=2,3$) are constants determined by the boundary conditions; $J_n(\cdot)$ and $Y_n(\cdot)$ are the first and second kind Bessel functions of order n , respectively. Moreover, n is the number of pitch diameters of the grinding wheel. In the grinding experiment, there are

transverse and flexural vibrations with pitch circles in the grinding wheel to acquire uniform amplitude of the outer edge of the grinding wheel and improve the process. Accordingly, n is set to zero.

According to the dynamic analysis of the annular plate [36–38], the bending moment per length unit M_r and the transverse shear force per unit length Q_r of the grinding wheel can be expressed as the following:

$$\left\{ \begin{aligned} M_{ri} &= D_i(\sigma_{1i} - 1) \left[J'_0(\delta_{1i}r) + \frac{\mu_i}{r} J_0(\delta_{1i}r) \right] A_{1i} \\ &+ D_i(\sigma_{2i} - 1) \left[J'_0(\delta_{2i}r) + \frac{\mu_i}{r} J_0(\delta_{2i}r) \right] A_{2i} \\ &+ D_i(\sigma_{1i} - 1) \left[Y''_0(\delta_{1i}r) + \frac{\mu_i}{r} Y'_0(\delta_{1i}r) \right] B_{1i} \\ &+ D_i(\sigma_{2i} - 1) \left[Y''_0(\delta_{2i}r) + \frac{\mu_i}{r} Y'_0(\delta_{2i}r) \right] B_{2i} \\ Q_{ri} &= \frac{G_i t_i}{k_\tau} \sigma_{1i} J'_0(\delta_{1i}r) A_{1i} + \frac{G_i t_i}{k_\tau} \sigma_{2i} J'_0(\delta_{2i}r) A_{2i} \\ &+ \frac{G_i t_i}{k_\tau} \sigma_{1i} Y'_0(\delta_{1i}r) B_{1i} + \frac{G_i t_i}{k_\tau} \sigma_{2i} Y'_0(\delta_{2i}r) B_{2i} \end{aligned} \right.$$

4

Where $D_i = E_i t_i^3 / [12(1 - \mu_i^2)]$ and $G_i = E_i / [2(1 + \mu_i)]$ are flexural rigidity and shear modulus of the grinding wheel, respectively. Moreover, ρ_1 , ρ_2 , and ρ_3 are densities of the conical horn, matrix annular plate, and abrasive layer annular plate, respectively. E_1 , E_2 , and E_3 denote the Young's modulus of the three components, respectively. μ_1 , μ_2 , μ_3 are Poisson's ratios of the three components, respectively. $k_\tau = 12/\pi^2$ is the shear correction factor.

In order to establish the vibratory mathematical model of the longitudinal-flexural resonating transformer, it is necessary to analyze the boundary conditions of the two ends of the transformer and the coupling conditions of the contact surface between the various parts.

When the natural frequency of the transformer is calculated, it is assumed that the transformer is not affected by external forces [39]. Therefore, the wide end of the horn is free and the normal stress is equal to zero. This can be mathematically expressed as follows:

$$\left. \frac{\partial \xi}{\partial z} \right|_{z=0} = 0$$

5

It is worth noting that the grinding wheel is mounted on the mandrel of the narrow end of the horn and tightly connected by the nut so that it can be regarded as a rigid connection. Therefore, the longitudinal displacement and normal force are continuous. Since the grinding wheel is fixed on the horn by a nut, it cannot rotate radially around the horn. Therefore, the radial rotation angle of the matrix annular plate is zero. This can be mathematically expressed as follows:

$$\left\{ \begin{array}{l} \pi(R_3^2 - R_2^2)E_1 \frac{\partial \xi}{\partial z} \Big|_{z=L, r=R_2} = 2\pi R_3 Q_{r2} \Big|_{r=R_3} \\ \xi|_{z=L} = w_2 \Big|_{r=R_3} \\ \beta_{r2} \Big|_{r=R_3} = 0 \end{array} \right.$$

6

It should be indicated that deflection $w_{\bar{r}}$, angle $\beta_{r\bar{r}}$, bending moment $M_{r\bar{r}}$ and shear force $Q_{r\bar{r}}$ are continuous on the contact surface of two annular plates.

$$\left\{ \begin{array}{l} w_2 \Big|_{r=R_4} = w_3 \Big|_{r=R_4} \\ \beta_{r2} \Big|_{r=R_4} = \beta_{r3} \Big|_{r=R_4} \\ Q_{r2} \Big|_{r=R_4} = Q_{r3} \Big|_{r=R_4} \\ M_{r2} \Big|_{r=R_4} = M_{r3} \Big|_{r=R_4} \end{array} \right.$$

7

When the natural frequency of the transformer is calculated, the outer edge of the grinding wheel is regarded as a free boundary:

$$\left\{ \begin{array}{l} M_{r3} \Big|_{r=R_5} = 0 \\ Q_{r3} \Big|_{r=R_5} = 0 \end{array} \right.$$

8

Substituting Eqs. (1)-(3) into Eqs. (5)-(8), a homogeneous system of equations can be derived as follows:

$$\Delta_{10 \times 10} \zeta_{10 \times 1} = 0_{10 \times 1}$$

9

Where

$$\Delta_{10 \times 10} = \begin{bmatrix} D_{11} & D_{12} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ D_{21} & D_{22} & D_{23} & D_{24} & D_{25} & D_{26} & 0 & 0 & 0 & 0 \\ D_{31} & D_{32} & D_{33} & D_{34} & D_{35} & D_{36} & 0 & 0 & 0 & 0 \\ 0 & 0 & D_{43} & D_{44} & D_{45} & D_{46} & 0 & 0 & 0 & 0 \\ 0 & 0 & D_{53} & D_{54} & D_{55} & D_{56} & D_{57} & D_{58} & D_{59} & D_{510} \\ 0 & 0 & D_{63} & D_{64} & D_{65} & D_{66} & D_{67} & D_{68} & D_{69} & D_{610} \\ 0 & 0 & D_{73} & D_{74} & D_{75} & D_{76} & D_{77} & D_{78} & D_{79} & D_{710} \\ 0 & 0 & D_{83} & D_{84} & D_{85} & D_{86} & D_{87} & D_{88} & D_{89} & D_{810} \\ 0 & 0 & 0 & 0 & 0 & 0 & D_{97} & D_{98} & D_{99} & D_{910} \\ 0 & 0 & 0 & 0 & 0 & 0 & D_{107} & D_{108} & D_{109} & D_{1010} \end{bmatrix}$$

10

$$\zeta_{10 \times 1} = [C_1 \ C_2 \ A_{12} \ A_{22} \ B_{12} \ B_{22} \ A_{13} \ A_{23} \ B_{13} \ B_{23}]^T$$

11

Where D_{pq} ($p, q=1,2,3,\dots,10$) is the coefficient of the undetermined constants A_{ji} , B_{ji} , C_j ($j=1,2;i=2,3$). These coefficients can be calculated for known geometric dimensions, material parameters, and the longitudinal-flexural resonating frequency of the transformer.

It is found that when the solution of matrix Eq. (9) is zero, the transformer is at rest, which is not in conformity with the actual situation. Therefore, Eq. (9) should have a non-zero solution. The necessary and sufficient condition is:

$$|\Delta_{10 \times 10}| = 0$$

12

Eq. (12) is the frequency equation of ultrasound-assisted grinding -flexural resonating transformer. If the geometric dimensions, material parameters, and design frequency of the transformer are known, an unknown parameter of the transformer can be calculated to meet the processing requirements. Similarly, when all the geometric dimensions of the transformer are known, the resonance frequency can be calculated using the frequency equation.

It is worth noting that Eq. (9) is a homogeneous system of equations with non-unique solution vectors. The ultrasonic vibration in the horn is transmitted by the transducer. Let the amplitude of the wide end of the conical horn be ξ_0 . There is a boundary condition of longitudinal displacement as follows:

$$\xi|_{z=0} = \xi_0$$

13

A Group of special solutions of $\zeta_{10 \times 1}$ can be obtained by substituting Eq. (13) into Eq. (9). Then, the amplitude of the end face of the grinding wheel can be obtained by substituting the special solutions into Eq. (2).

2.2. Finite element analysis and the impedance characteristic experiment

According to Eq. (12), two longitudinal-flexural resonating transformers in ultrasound-assisted grinding were designed as shown in Fig. 2. They were designed to resonate in the tuned longitudinal-flexural composite mode at about 20 kHz. Tables 1 and 2 present the geometrical dimensions and material of the transformers, respectively. The abrasive concentration and grain size of diamond grinding wheels are 100% and 100#, respectively. Table 3 presents the material parameters.

The finite element modal analysis of the two transformers is carried out using ANSYS software. Fig. 3 shows the results of the modal analysis, indicating that the resonance frequencies corresponding to the transformers A and B are 19243 Hz and 19654 Hz, respectively.

The impedance characteristics of the ultrasound-assisted grinding spindle consisting of a transformer, a slip ring, a sleeve, and a transducer (Fycg YP-5520-4Z, China) were tested using an impedance analyzer (Bandera PV70A, China). Fig. 5 illustrates the obtained results from Transformer B.

The frequencies obtained from the finite element simulation, the impedance analysis experiment, and the design frequency are shown in Table 4. It is observed that compared with the design frequency of the transformers, the maximum deviation of finite element simulation and experiment are 3.79% and 3.29%, respectively. This analysis demonstrates that the designed transformers using the proposed method meet the resonance requirements.

2.3. Ultrasonic resonance experiment

The output displacement of the 20 kHz transducer is 6 μm . Therefore, the input displacement ξ_0 at the wide end of the conical horn is 6 μm . Then ξ_0 can be introduced into Eq. (9) to obtain the column vector $\bar{Z}_{10 \times 1}$ by solving the displacement characteristic equation. It should be indicated that all calculations were carried out in the MATLAB environment. Then the calculated $\bar{Z}_{10 \times 1}$ is substituted into Eq. (2). The amplitude curves along the radius direction of the grinding wheels are shown in Fig. 6. It is observed that positions of pitch circles are located at $r_{11}=24\text{mm}$, $r_{12}=64.72\text{mm}$, $r_{21}=26.76\text{mm}$, and $r_{22}=44.86\text{mm}$.

The amplitudes of the ultrasound-assisted grinding spindle were measured by a scanning laser vibrometer (Polytec PSV500, Germany) as shown in Fig. 7. SiC particles are evenly sprinkled on the surface of the grinding wheel. When the output frequency of the ultrasonic generator (Fycg ZJS-2000, China) is set to $f_1=20985\text{Hz}$ and $f_2=19651\text{Hz}$, SiC particles immediately aggregate into two rings, respectively, which are the locations of pitch circles shown in Fig. 8. It is concluded that the grinding wheels vibrate in the transverse and flexural mode with only circle nodal lines. The maximum relative deviation between experiment results and design frequency is 4.93%.

Figure 9 shows the amplitude of end surfaces of two grinding wheels obtained by theoretical calculations and ultrasonic resonance experiments. Accordingly, it is found that positions of pitch circles of two transformers are at $r'_{11}=25.56\text{mm}$, $r'_{12}=63.8\text{mm}$, $r'_{21}=25.65\text{mm}$, and $r'_{22}=44.82\text{mm}$. Moreover, outer edge amplitudes of the grinding wheels are $\xi_{E1} = 13.50\mu\text{m}$, and $\xi_{E2} = 10.02\mu\text{m}$, respectively. Consequently, amplification factors of the transformers are $M_{pE1} = \xi_{E1}/\xi_0 \approx 2.25$, and $M_{pE2} = \xi_{E2}/\xi_0 \approx 1.67$. It is found that the experimental curves are consistent with the theoretical calculations. The positions of pitch circles of the two transformers have a relative deviation of 6.51%.

In summary, the results of finite element simulation and ultrasonic resonance experiment show that two longitudinal-flexural resonating transformers in ultrasound-assisted grinding, which are designed using the Mindlin theory, meet the

expected requirements. The outer edge amplitudes of the grinding wheels are large enough and have amplification factors of 2.25 and 1.67, respectively. Accordingly, these wheels can be used in the ultrasound-assisted grinding experiment.

3. Experimental Setup And Methodology

An ultrasound-assisted grinding spindle system mainly consists of an ultrasonic generator, a spindle flange, a slip ring, a sleeve, a transducer, a horn, and a grinding wheel. Furthermore, the grinding force measuring system consists of a three-dimensional dynamic piezoelectric dynamometer (Kistler Type 9272, Switzerland), a charge amplifier (Kistler Type 5073, Switzerland), and a data acquisition board. Fig. 10 illustrates the schematic of the test setup. Fig. 11 indicates that the two systems were installed on a vertical CNC machine tool (Hanland HCZK1340A, China). Table 5 shows the material parameters of SiCp/Al composites. During the experiment, variable factors include the grinding speed V_s , feed rate V_w , and the depth-of-grind a_p . On the other hand, the grinding force, surface roughness, and surface micro-morphology were studied using single factor orthogonal experiments with and without ultrasonic vibration under the same grinding conditions. Experimental parameters are listed in Table 6.

4. Experiment Results And Discussions

4.1. Grinding forces

During ultrasound-assisted grinding, force components along three orthogonal directions, including tangential, axial, and radial directions, were measured. Due to the use of circumferential grinding of the grinding wheel in the experiment, the reference value of the axial force F_z is not significant so that it can be ignored.

Machining was conducted with a feed rate V_w of 150 mm/min and a depth-of-grind a_p of 0.2 mm. Fig. 12 shows the correlation between the grinding speed and the grinding force. It is observed that at the same grinding parameters, the radial force F_x is much greater than the tangential force F_y . It is worth noting that the grinding force in ultrasonic vibration is significantly less than that of ordinary grinding. It is found that as the grinding speed increases, the corresponding grinding force decreases gradually in both processing modes. This may be attributed to the constant feed rate and depth of grind. Therefore, the work done by a single abrasive grain in a certain period of time does not change during the grinding process. However, the grinding path becomes longer, thereby decreasing the grinding force. Moreover, as the grinding speed increases, the temperature of the grinding process increases too. The softening degree is especially more pronounced in Al parts. This phenomenon may reduce friction and debris deformation, thereby reducing the grinding force. Consequently, for a constant grinding force, ultrasound-assisted grinding can meet machining requirements at lower speeds, which facilitates the process.

Figure 13 shows the distribution of the feed rate against the grinding force when machining was conducted with a grinding speed V_s of 650 m/min and a depth-of-grind a_p of 0.2 mm. It is observed that at the same grinding parameters, the radial force F_x is much greater than the tangential force F_y . It should be indicated that the grinding force with ultrasonic vibration is significantly less than that of ordinary grinding. Moreover, in a constant tangential force F_y , a larger feed rate can be set with ultrasonic vibration to improve the processing efficiency. As the feed rate increases, the grinding force increases in both processing modes. This may be attributed to the longer processing length of single abrasive grain on the diamond grinding wheel is longer so that more material is worn out and the grinding force increases.

Figure 14 shows the distribution of the feed rate against the grinding force in machining with a grinding speed V_s of 650 m/min, and feed rate V_w of 150 mm/min. It is observed that at the same grinding parameters, the grinding force with ultrasonic vibration is significantly less than that of ordinary grinding. It is found that as the depth-of-grind increases, the corresponding grinding force increases in both processing modes. This may be attributed to the increase of the maximum grinding thickness of a single abrasive grain, which increases the grinding force. Furthermore, the length of the contact arc between the diamond grinding wheel and the workpiece increases so abrasive grains are involved in grinding per unit time. Subsequently, the grinding force and efficiency increase.

4.2. Surface roughness

In the present study, the surface roughness and 3D topography of processed SiCp/Al composites were measured using a 3D measuring laser microscope (Company OLS5000, Country). The 3D topography of the grinding surface under the two processing methods was analyzed after machining with a feed rate V_w of 100 mm/min and a depth-of-grind a_p of 0.2 mm. The obtained results are presented in Table. 7.

Table 7 reveals that the difference between the peak height and valley depth of workpiece surface profile in ordinary grinding is about 23 μ m, while the height difference in ultrasound-assisted grinding is about 15 μ m. It is concluded that the axial vibration of abrasive particles in ultrasonic assisted grinding increases the interference and cutting between abrasive particles and the workpiece. Therefore, the contour peak is removed by cutting to obtain a relatively smooth machining surface and improve the surface quality.

Figure 15 shows the distribution of the grinding speed against the surface roughness. It is observed that at the same grinding parameters, the surface roughness of the workpiece with ultrasonic vibration is less than that of ordinary grinding. As the grinding speed of the grinding wheel increases, the surface roughness of the workpiece decreases rapidly. This phenomenon may be attributed to the volume reduction of the material removed by abrasive particles while other processing parameters remain constant, which can mitigate the grinding force. Moreover, trajectories of abrasive particles are more complex, which smoothens the envelope surface and decreases the surface roughness of the workpiece. It is concluded that adding ultrasonic vibration to the grinding wheel is an effective way to reduce the surface roughness and improve the surface quality of the workpiece.

Figure 16 shows the distribution of the feed rate against the surface roughness. It is observed that at the same grinding parameters, the surface roughness of the workpiece processed with ultrasonic vibration is less than that using ordinary grinding. It is found that as the feed rate of the machine tool worktable increases, the surface roughness of the workpiece increases slowly. This is because when the feed rate increases, the material removed by grinding increases too. Moreover, as the force between the grinding wheel and the workpiece increases, the torsional moment also increases. Subsequently, the stability of the whole resonant system decreases, thereby increasing the surface roughness of the workpiece.

Figure 17 presents the distribution of the depth-of-grind against the surface roughness. It is observed that at the same grinding parameters, the surface roughness of the workpiece processed with ultrasonic vibration is less than that of ordinary grinding. Moreover, Figure 17 indicates that as the depth-of-grind increases, the surface roughness of SiCp/Al composites increases. This phenomenon mainly originates from the correlation between surface roughness and the feed rate.

4.3. Size of the wear debris

After machining with a feed rate V_w of 100 mm/min and a depth-of-grind a_p of 0.2 mm, wear debris was collected with and without ultrasound. Then the size of wear debris was analyzed using a 3D measuring laser microscope (Olympus OLS5000, Japan) with 114x magnification. The results are presented in Table. 8. It is found that at the same grinding

parameters, applying the ultrasonic vibration results in a more uniform size of wear debris. Moreover, the wear debris is finer and smaller in the case where ultrasonic vibration was used. On the other hand, the high-frequency hammering effect of ultrasonic vibration makes the debris easier to be removed and cut off. It is inferred that using ultrasonic vibration in the process results in higher surface quality and improves the processing accuracy.

4.4. Surface topography

After machining with a feed rate V_w of 100 mm/min and a depth-of-grind a_p of 0.2 mm, the surface topography was observed using a 3D measuring laser microscope with 227x magnification. The obtained results are presented in Table 9.

It is observed that after ordinary grinding, regular parallel linear grinding marks appear on the workpiece surface. The scratching is obvious. Moreover, a large number of grooves appear on the workpiece surface. However, the grinding trace of the workpiece surface after ultrasound-assisted grinding has a sinusoidal form, which originates from the superposition of the scratching grains in the conventional grinding and the grains in the up-down vibration of the ultrasound-assisted grinding. The effect of strong scratching of the conventional grinding is weakened and the grooves left by the scratch between diamond abrasive particles and the workpiece surface become more obscure. This is because the axial ultrasonic vibration of the grinding wheel causes the abrasive grain to cut off the track left through scratching of the abrasive particles and the workpiece before cutting. The trajectories of abrasive particles become complicated, which improves the smoothness of the grinding surface and the surface morphology of the workpiece. Furthermore, the reduction of the scratching effect reduces the processing temperature and reduces the wear of the grinding wheel.

The amplitude of sinusoidal trajectories of the workpiece surface after ultrasound-assisted grinding is about 8.05 μm , which is slightly smaller than the edge amplitude of the grinding wheel obtained from the ultrasonic resonance experiment. Some pits appear on the surface of the workpiece because the SiC particles are pulled out after processing. Some SiC particles may not break or remove. It is observed that after ultrasound-assisted grinding, ragged regions of the workpiece surface are less than that of ordinary grinding, indicating that using ultrasonic vibration in the grinding process improves the surface morphology of the workpiece.

5. Conclusions

In the present study, a longitudinal-flexural resonating spindle in ultrasound-assisted grinding was investigated. Based on the performed analyses and the obtained results, the main achievements and conclusions can be summarized as follows:

(1) Based on the Mindlin moderate plate theory, expressions were established to calculate the displacement, rotation angle, bending moment, and shear force of the vibration elements. Combining continuous and boundary conditions of vibrating elements with the above expressions, the vibration model and equations of longitudinal-flexural resonating transformer with a large load in ultrasound-assisted grinding were established.

(2) Two transformers were designed according to the frequency equation. Then the resonant characteristics of the vibration spindles were studied using the finite element analysis, impedance experiments, and ultrasonic resonance experiments. The obtained results show that the maximum deviation between the resonant frequency and the design frequency of the transformers was 4.95%. The overall shape of the calculated and measured amplitude curves of the transformers was consistent. Moreover, the maximum deviation of the positions of the pitch circles was 6.51%. The amplification factors of the two cases were set to 2.25 and 1.67, respectively. It is concluded that the proposed designs have high accuracy.

(3) The orthogonal single factor experiments of SiCp/Al composites were performed with and without ultrasound. It was found that introducing the ultrasonic vibration significantly reduces the grinding force and the surface roughness. Meanwhile, the surface quality of the SiCp/Al workpiece was improved.

(4) The present study is expected to provide experimental fundamentals to further improve the structure of the grinding spindle, optimize process variables of ultrasound-assisted grinding, and improve the process efficiency.

Declarations

Author contribution WX contributed significantly to the conception of the study and wrote the manuscript. QHB revised the manuscript. ZXJ contributed to the data analysis of the manuscript. FY and ZRF designed and performed the experiments. YLZ helped to perform the analysis with constructive discussions.

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Tables

Table 1
Geometrical dimensions of transformers.

Transformer	R_1/mm	R_2/mm	R_3/mm	R_4/mm	R_5/mm	t/mm	L/mm
A	28	14	10	65	75	20	160.6
B	28	14	5	40	50	5	133.2

Table 2
Materials of transformers

Transformer	A	B
Conical horn	Steel	Steel
Matrix annular plate	Aluminum	Aluminum
Abrasive layer annular plate	Diamond grains	Diamond grains

Table 3
Material parameters of transformers

Material	Density $\rho/\text{kg/m}^3$	Young's modulus E/GPa	Poisson ratio μ
Steel	7890	210	0.3
Aluminum	2700	70	0.33
Diamond grains	2900	13	0.33

Table 4
The comparison of experiment and simulation frequencies

Transformer	A	B
Design frequency f_D/Hz	20000	20000
Simulation frequency f_A/Hz	19243	19654
Experiment frequency f_E/Hz	20658	19460
Simulation error $\Delta_A/\%$	3.79	1.73
Experiment error $\Delta_E/\%$	3.29	2.70

Table 5
Material parameters of SiCp/Al composites

Density(g/cm^3)	Young's modulus(GPa)	Yield strength(MPa)	Thermal conductivity(W/m·k)	Rockwell hardness(HRC)	Poisson ratio	Volume fraction
2.94	213	330	235	35	0.23	20%

Table 6
Settings of parameters in the orthogonal experiments

Grinding speed $V_s/(\text{m/min})$	Feed rate $V_w/(\text{mm/min})$	Depth-of-grind a_p/mm
250	50	0.05
350	75	0.1
450	100	0.15
550	125	0.2
650	150	0.25

Tables 7-9 are available in the Supplementary Files section.

Figures

Figure 1

Structure of the longitudinal-flexural resonating transformer

Figure 2

Longitudinal-flexural resonating transformers in ultrasound-assisted grinding: **a** Transformer A and **b** Transformer B

Figure 3
 Modal analysis of the transformers: **a** Transformer A and **b** Transformer B

Figure 4
 Set-up of the impedance characteristic test

Figure 5

Impedance characteristic of the transformer B

Figure 6

Amplitude of the grinding wheels: **a** Transformer A and **b** Transformer B

Figure 7

Experimental set-up of the ultrasonic resonance test

Figure 8

Experiment results of ultrasonic resonance: **a** Transformer A and **b** Transformer B

Figure 9

Amplitude curves of the two grinding wheels: **a** Transformer A and **b** Transformer B

Figure 10

Schematic of the force measurement system

Figure 11

Ultrasound-assisted grinding process system

Figure 12

Distribution of the grinding speed against: **a** radial force F_x and **b** tangential force F_y

Figure 13

The distribution of the feed rate against: **a** radial force F_x and **b** tangential force F_y

Figure 14

Distribution of the depth-of-grind against: **a** radial force F_x and **b** tangential force F_y

Figure 15

Distribution of the grinding speed against the surface roughness

Figure 16

Distribution of the feed rate against the surface roughness

Figure 17

Distribution of the depth-of-grind and the surface roughness

Supplementary Files

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