Design of a novel integrated ultrasonic tool holder for friction stir welding

Ju Jianzhong1 · Long Zhili1 · Ye Shuyuan1 · Liu Yongzhi1 · Zhao Heng1

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Abstract
Ultrasonic vibration friction stir welding (UVFSW) has shown advantages in reducing welding defects and improving welding quality in aerospace, automobile, and power electronics. In this study, we design a novel 20-kHz integrated ultrasonic tool holder in FSW. The finite element model of FSW transducer is established, where the elastic modulus is measured by non-destructive acoustic. In the three transducer prototypes with alloy steel, the effect of prestress on resonant frequency is investigated and the ultrasonic vibration is measured. It proves that the resonant frequencies are well consistent between simulation model and the experiment by the elastic modulus testing and the prestress optimization. The ultrasonic amplitude of the pin is up to 24 μm. The experiment also indicates that the vibration is different with the steel material properties. Our findings can have a guidance to the design for a general ultrasonic actuator. The integrated FSW ultrasonic tool has potential to apply in a confined space in general machining equipment.

Keywords Friction stir welding · Ultrasonic transducer · Modal analysis · Pre-tightening force · Material property

1 Introduction
Friction stir welding (FSW), a solid-state welding, has been widely used in a variety of fields such as aerospace, automobile, and power electronics [1–3]. FSW has outstanding advantages in controlling welding defects, improving joint strength and fatigue properties [4, 5]. In FSW process, heat generation and material flow are to achieve the high-quality welded joints, which also cause some issues such as high welding load and sharp tool wear. Nowadays, many optimized approaches such as thermal energy-assisted FSW [6–8] and ultrasonic vibration friction stir welding (UVFSW) [9–11] have been proposed to improve the welding performance.

Ultrasonic vibration used in FSW is beneficial to the plastic flow, mechanical properties of joints, and reduce welding defects by welding experiment [12, 13] and simulation method [14–16]. Currently, researchers and engineers have developed various ultrasonic FSW devices. These devices can be divided into two configurations, where one is that the ultrasonic vibration is applied into the pin along the vertical and horizontal direction, and the other is that the ultrasonic energy is applied into the workpiece. Park et al. [17] applied ultrasonic vibration to the pin through the lateral coupling bearing, which proved that ultrasonic energy could decrease the welding defects and enhance the mechanical properties of the joint. However, the ultrasonic energy was dissipated into other paths. Kumar et al. [18] improved Park’s device to increase the energy transfer efficiency. He et al. [19] developed a UVFSW system that integrated the transducer into the rotating fixture, which could efficiently apply ultrasonic energy to the weld nugget zone through the pin. Amini et al. [20] achieved the same rotary ultrasonic vibration and applied in shorter welding plates by refitting the lathe. In the second configuration, the ultrasonic vibration generated by lateral transducer makes the workpiece vibrate in high frequency. Wu et al. [21] designed an inclined ultrasonic device in which the ultrasonic wave was propagated to the workpiece. Hu et al. [22] accomplished an ultrasonic transmission device which can make ultrasound focus into the bottom of the workpiece. Strass et al. [23] developed an ultrasonic rolling seam oscillator to apply vibration on the advancing side. Tarasov et al. [24] presented that an ultrasonic transducer was directly connected to the workpiece through a bolt. In summary, the first configuration is that the ultrasonic
component is complicated in structure, high mass, and large volume, which cannot meet the confined space requirement. In the second configuration, there is a distance difference between the ultrasonic head and the pin, which can cause the ultrasonic energy dissipation because of the propagation attenuation.

The piezoelectric transducer is a critical component in ultrasonic machining. Small amplitude in resonant frequency is generated by the piezoelectric elements, and then is amplified to the tool tip by a horn. The resonant frequency is determined by the geometric construction and material properties, which is calculated by the mechanical equivalent circuit and finite element [20, 26]. The resonant frequency is determined by the elastic modulus. The increase of elastic modulus can decrease the vibration amplitude. To obtain the high energy conversion efficiency, many optimization approaches, such as changing the position of the piezoelectric element [25, 28], the structure design for flange mounting [29], and fabrication technique, were proposed. The optimal pre-tightening force can significantly improve the frequency and vibration output of the transducer [30], which can avoid the cracks or degradation in piezoelectric stack. In general, the pre-tightening torque is controlled by a digital torque wrench. The optimal torque for transducer varies greatly with the material composition and the size of piezoceramics. However, the optimal prestress of the piezoceramics, which is beneficial to make a precise control to resonant frequency, was not discussed in their investigation.

In this study, a novel integrated ultrasonic tool holder with advantages of compact structure, low mass, and flexible replacement is developed to meet with the FSW process, which the transmission of ultrasonic energy can be improved into the welding area. Firstly, the structure of ultrasonic transducer is designed, where the elastic modulus of the material is measured by the non-destructive acoustic testing. The structural size of transducer is determined by finite element method using the measured material properties. FSW transducers of three steel alloys are fabricated and tested. The error of designed frequency by non-destructive acoustic is analyzed. On the other hand, the effect of prestress on the resonant frequency and the impedance is investigated to determine the appropriate prestress. Finally, the vibration of transducers with different materials is tested to ensure the machining requirements.

2 Structure design

The configuration of ultrasonic FSW device is designed in Fig. 1. The ultrasonic generator provides 15 to 30 kHz AC excitation signals with 2000 Watt power. The high-frequency electrical signal is transmitted to the transducer through the slip ring. The piezoelectric ceramic stack is excited at the natural frequency of the transducer and amplifies the vibration by the horn. An external flange on the vibration node of the transducer is connected with the BT40 tool holder. Our self-developed ultrasonic generator has the functions such as frequency sweeping and real-time tracking to the dynamic resonant frequency of the transducer.

The FSW transducer includes the back plate, piezoceramics stacks, horn, and pin. The piezoceramics stacks consist of four identical piezoceramics and two sets of copper electrode. These components are clamped by a pre-tightening screw. To realize the flexible replacement of the pin, the front end of the horn and the pin are connected by threads. The structural dimensions of the back plate and the horn are adjusted to determine the final flange position and structure, as shown in Fig. 2. The pin is designed for a 3-mm thick workpiece. In our investigation, the 303 austenitic stainless steel, 3Cr13 martensitic stainless steel, and SKD11 tool steel are selected as the transducer materials to verify the effect of the material on the ultrasonic vibration. H13 is used as the pin material for light metal welding.

3 Elastic modulus measurement

To study the effect of metal material on the vibration characteristics and reduce the error of designed frequency, the material density, sound velocity, and elastic modulus of the transducer are measured. Instead of the static measurement of the tensile machine, the non-destructive acoustic wave method is utilized to measure the elastic modulus of the material based on the principle of sound wave propagation in the solid. The shear velocity and longitudinal velocity of ultrasonic waves in the medium are as follows:

![Fig. 1 Ultrasonic FSW configuration](image)
where $\rho$ is the density, $E$ is the elastic modulus, $G$ is the shear modulus, $\mu$ is the Poisson’s ratio, $V_L$ is the longitudinal wave sound velocity, $V_T$ is the shear wave sound velocity.

By measuring the longitudinal and shear sound velocity of the material, the elastic modulus and Poisson’s ratio equation of the material are obtained [31]:

$$
E = \frac{\rho V_L^2 (1 - \mu)}{\rho (1 + \mu) (1 - 2\mu)}
$$

(1)

$$
V_L = \sqrt{\frac{E(1 - \mu)}{\rho(1 + \mu)(1 - 2\mu)}}
$$

(2)

$$
V_T = \sqrt{\frac{E}{2\rho(1 + \mu)}}
$$

(3)

$$
G = \frac{E}{2(1 + \mu)}
$$

(4)

where $\rho$ is the density, $E$ is the elastic modulus, $G$ is the shear modulus, $\mu$ is the Poisson’s ratio, $V_L$ is the longitudinal wave sound velocity, $V_T$ is the shear wave sound velocity.

According to the above principle, the pulse echo is to measure the elastic modulus in our experiment. By measuring the time interval $\Delta t$ between the reflected echoes and the length of test piece, the equation $v = \frac{2L}{\Delta t}$ is calculated and the ultrasonic propagation velocity in the sample is attained. To reduce the measurement error, the cylindrical specimen is selected in 100 mm length and 20 mm diameter. The same heat treatment is adopted in the machining process. The material quality is measured by an electronic balance and the metal density is attained.

The ultrasonic testing device in experiment is illustrated in Fig. 3(a). The narrow pulse is generated by the signal generator (CTS-8077PR), and boosted by a power amplifier. A longitudinal wave probe (SIUI2.5Z14N) with 5 MHz frequency is to receive longitudinal wave echo signals, and a shear wave probe (GE MB2Y) with 5 MHz frequency is to receive shear wave echo signal, as seen in Fig. 3(c). The acoustic signals are monitored by an oscilloscope. Ultrasonic couplant (GW-III) is adopted for longitudinal and shear wave probe, separately. The longitudinal and shear wave velocity of different material were measured 10 times and their average values were obtained.

The measurement results of longitudinal and shear velocity of 303 material are shown in Fig. 4. The wave velocity and elastic modulus of four metals are measured and listed in Table 1. It is shown that the measured elastic modulus is close to the engineering value, which proves the feasibility of non-destructive acoustic wave method. Compared with the engineering value, the maximum error for the elastic modulus is 5.6% from 3Cr13 metal, and the maximum error of density is 1.5% from H13 metal.

In addition, we find that the sound velocity by Eqs. (1), (7) has a significant effect on the sound velocity. If the engineering elastic modulus is calculated by the expression (1) and (7), the sound velocity is compared to the one of the non-destructive acoustic waves. It indicates that the error of sound velocity by Eq. (8) is above 12%; the sound velocity is more accurate by Eq. (1), as listed in Table 2, which is beneficial to the modal design and calculation.
Finite element simulation

Figure 5 shows the designed structure of ultrasonic transducer in our study. The length of the transducer is designed by $\lambda = \frac{V_L}{f}$, and the nodal point is placed in front of the piezoelectric ceramic stack. To meet with the welding workpiece in different thicknesses, the pin is designed into a two-stage section. The structure of the shoulder section can be adjusted to adapt to different workpieces.

The modal analysis is carried out by finite element method (FEM, ANSYS software). During the simulations, the vibration frequency and mode shape are obtained by Block Lanczos solver under free boundary conditions. The material density and elastic modulus by non-destructive acoustic wave in Table 1 are introduced into the FEM model. The PZT-4 with a 7600 kg/m$^3$ density, 64.5 GPa elastic modulus, and 0.3 Poisson’s ratio is selected for the piezoceramics. It is

### Table 1
Measured physical properties of materials

| Material | $\rho$ (kg/m$^3$) | $E$ (GPa) | $\mu$ | $V_L$ (m/s) | $V_T$ (m/s) | $E$ (GPa) | $\mu$ | $\Delta \rho$ (%) | $\Delta E$ (%) |
|----------|-------------------|-----------|-------|-------------|-------------|-----------|-------|-----------------|----------------|
| 303      | 7930              | 193       | 0.3   | 7896.7      | 5734.5      | 3135.8    | 199.8 | -0.42           | +3.52          |
| 3Cr13    | 7760              | 219       | 0.3   | 7751.2      | 5895.6      | 3217.5    | 206.7 | -0.11           | -5.62          |
| SKD11    | 7800              | 214       | 0.3   | 7689.1      | 5975.5      | 3236.4    | 208.2 | -1.42           | -2.71          |
| H13      | 7800              | 210       | 0.3   | 7680.5      | 5995.4      | 3242.7    | 208.9 | -1.53           | -0.52          |

### Table 2
Calculated and measured sound velocity

| Material | $V_{L1}$ (m/s) | $V_L = \sqrt{\frac{E}{\rho}}$ (m/s) | $\Delta V_{L1}$ (%) | $V_L = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}}$ (m/s) | $\Delta V_L$ (%) |
|----------|----------------|----------------------------------|---------------------|---------------------------------------------------------------|-----------------|
| 303      | 5734.5         | 4933.4                           | -13.97              | 5723.9                                                          | -0.19           |
| 3Cr13    | 5895.6         | 5312.4                           | -9.89               | 6163.7                                                          | +4.55           |
| SKD11    | 5975.6         | 5237.9                           | -12.35              | 6077.2                                                          | +1.70           |
| H13      | 5995.4         | 5188.7                           | -13.46              | 6020.2                                                          | +0.41           |

4 Finite element simulation

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worth noted that the three transducers are designed with the same structure to furtherly analyze the influence of vibration output by different materials. With the modal calculation, the vibration modes of transducer are presented by adjusting the geometric dimensions. As shown in Fig. 6, the resonant frequencies for three transducers are close to the 20 kHz designed frequency, which is 19,698 Hz (303 metal), 19,969 Hz (3Cr13), and 20,049 Hz (SKD11), respectively. The transducer vibrates in the axial shape, where the maximum displacement is located at the pin tip. The vibration vector is in axial direction and one node point is located in transducer, which can be connected to the mounting flange. The mounting flange with 3 mm thickness is designed on the node surface, and the simulation result is shown in Fig. 7. The mounting flange is connected to the BT40 holder by screws. The modal vibration of three transducers with flange structure is shown in Fig. 7(a). Its vibration modes of the transducers are in appropriate vibration, where the vibration of flange is close to zero. Compared to the flangeless structure, the resonant frequency of transducers with flange increases by 200 Hz. It indicates that the structure and location of the mounting flange are designed reasonably and cannot affect the frequency and vibration transmission of the transducer. The final dimensions of the transducer and resonant frequency are listed in Table 3, where the vibration modes are normal when the three transducers are in the same size, same mounting flange, and same node location. The frequencies of transducers designed by 303 steel (TRD-303), 3Cr13 steel (TRD-3Cr13), and SKD11 steel (TRD-SKD11) are 19904 Hz, 20190 Hz, 20273 Hz, respectively. Finally, the modal analysis of the ultrasonic tool holder is carried out by integrating with the ultrasonic transducer, the mounting flange, and the holder, and the result is summarized in Fig. 7(b), (c). It is observed that the vibration displacement is amplified by the horn, and the vibration is concentrated in the pin. The vibration of the tool holder is close to zero, indicating that the ultrasonic vibration is efficiently propagated to the processing area, instead of being transmitted to the tool holder and the spindle.
5 Experiments

5.1 Effect of pre-tightening on the transducer impedance

The FSW ultrasonic tool holders with three metals are fabricated and the prototypes are attained, as shown in Fig. 8. It is reported that the pre-tightening torque for transducer affects the resonant frequency, impedance, electromechanical coupling coefficient, and mechanical quality factor, thereby affecting the ultrasonic energy conversion efficiency and the vibration amplitude of the tip [30]. However, the optimum pre-tightening torque varies with the area of the piezoceramics. In this study, we use the prestress to express the pre-tightening state between the piezoceramics and the screw. To determine the optimal prestress for piezoceramics, the relationship between resonant frequency, impedance, mechanical quality factor, and pre-tightening stress is investigated. A digital torque wrench is used to apply a specific torque to the bolt, and an impedance analyzer (Agilent 4294A) is to measure the resonant frequency, impedance, and electrical parameters of the transducer.

Equations (8) and (9) established the expression of the pre-tightening stress of piezoceramics. Because the torque coefficient ($K$) is related to the pitch diameter, the thread lead angle, the equivalent friction coefficient of the thread, a platform in Fig. 9 with a precise force sensor is to test the torque coefficient. The results of torque coefficients $K$ for

| Table 3 Geometries and frequency of the transducer with flange structure |
|---------------------------------|---------------|----------------|
| Category | Parameters values (mm) | Frequency (Hz) | Vibration mode |
|-----------|------------------------|----------------|----------------|
| TRD-303   | 50 30 12 13 26 6.5 3 44 23 | 19,904 | Normal |
| TRD-3Cr13 | 20 190 | Normal |
| TRD-SKD11 | 20,273 | Normal |
three transducers (303, 3Cr13, SKD11) are 0.199, 0.201, and 0.215, respectively.

\[ T_t = K F_0 d \]  \hspace{1cm} (8)

\[ F_0 = \sigma_{\text{bolt}} A_{\text{bolt}} = \sigma_{\text{piezos}} A_{\text{piezos}} \]  \hspace{1cm} (9)

where \( T_t \) is the pre-tightening torque applied to the screw bolt, \( F_0 \) is the pre-tightening force, \( d \) is the diameter of the bolt, \( K \) is the torque coefficient, \( A_{\text{bolt}} \), \( A_{\text{piezos}} \) is bolt area and the ring area of the piezoelectric ceramic, \( \sigma_{\text{bolt}} \), \( \sigma_{\text{piezos}} \) is the prestress of bolt and piezoelectric ceramics.

Figure 10 presents the measured results of impedance and frequency by the pre-tightening torques from 40 to 240 nm. It is found that with the increasing of torques, the resonant frequency of the transducer increases sharply at low torque region (Fig. 10(a), (d), (g)), and the impedance decreases rapidly (Fig. 10(b), (e), (f)), which is beneficial to increase the electrical current and enhance the vibration amplitude output. As an important indicator reflecting the internal friction consumption of the transducer, the mechanical quality factor \( Q_m \) is improved with the increasing of the torques (Fig. 10(c), (f), (i)), which can improve the energy conversion efficiency. As the pre-tightening torque turns up to a certain level, the resonant frequency, impedance, and mechanical quality factor become into a stable level.

According to the measured torque coefficient (0.199, 0.201, and 0.215), the prestress of piezoelectric ceramic plate is obtained. The maximum prestress of the piezoceramics in this study is 50 MPa, and the piezoceramics is not depolarized and cracked under this prestress. Figure 10 shows that the impedance and frequency of transducer changes sharply with the increase of prestress in range of 0–20 MPa. This phenomenon indicates that at the low prestress range, the piezoelectric components of the transducer are not in good connection, resulting in relative large impedance and low quality factor when it is in vibrating. When the prestress exceeds to 30 MPa, the impedance and frequency of the transducer gradually become stable, meaning that the acoustic coupling between the transducer components is significantly improved. In Fig. 10, we can control the prestress of the transducer within the range of 35–45 Mpa.

### 5.2 Impedance and frequency of transducer

After the assembled transducer was aged for a long time, the impedance-phase-frequency curves of the transducers are presented in Fig. 11. The measured results demonstrate that the impedance curves of the three transducers are smooth with no parasitic resonant frequency, indicating that the longitudinal vibration can be excited well at the resonant frequency. The resonant frequency of the TRD-303 is 19900 Hz and the impedance is 4.34 Ω; the resonant frequency of TRD-3Cr13 is 20130 Hz and the impedance is 4.77Ω; the resonant frequency of the TRD-SKD11 is 20230 Hz and the impedance is 4.25 Ω. The internal resistance for three transducers is relatively low, indicating that the pre-tightening force has made good acoustic connection between the components of the transducer. The electromechanical coupling coefficient \( k_{\text{eff}} \), which evaluates the energy conversion efficiency from electrical energy to mechanical vibration, can be calculated from Eq. (10). The electromechanical coupling coefficients of TRD-303, TRD-3Cr13, and TRD-SKD11 are attained as 33.6%, 37.5%, and 36.1%, respectively.

\[ k_{\text{eff}} = \sqrt{\frac{f_p^2 - f_s^2}{f_p^2}} \]  \hspace{1cm} (10)
where $f_p$ is the antiresonant frequency, $f_s$ is the resonant frequency.

In Fig. 10, with the pre-tightening torque from 40 to 240 nm, the resonant frequency is increased to about 5%. As listed in Table 4, $\Delta f_E$ is the error between the simulation frequency by engineering value and testing frequency ($\Delta f_E = |f_E - f_s|$), $\Delta f_A$ is the error between the simulation frequency by non-destructive acoustic wave and testing frequency ($\Delta f_A = |f_A - f_s|$). Under the appropriate pre-tightening force and the elastic modulus obtained by the non-destructive acoustic wave, the resonant frequency transducers are in a maximum error of 0.3% and within 60 Hz in frequencies. However, the maximum error of the resonant frequency calculated by the engineering value is 1.87% (377 Hz).

The resonant frequency and modal shape of the transducer are parameterized according to the dynamic equation of a beam. The axial vibrations along $x$ axis are expressed by the beam equation, as

$$\frac{\partial}{\partial x} \left( EA(x) \frac{\partial \xi(x,t)}{\partial x} \right) = \rho A(x) \frac{\partial^2 \xi(x,t)}{\partial t^2}$$

(11)

where $E$ is elastic modulus, $A$ is the cross-sectional area, $\xi$ is the displacement along $x$ axis, $\rho$ is the mass density, and $L$ is the length of the beam. The resonant frequency is obtained under free boundary.

$$\omega = n \frac{\pi}{L} \sqrt{\frac{E}{\rho}}, \quad n = 1, 2, 3,...$$

(12)

It can be seen that the resonant frequency is proportional to the elastic modulus under the same structure. The resonant frequency of the ultrasonic transducer is more accurate when the elastic modulus is close to the actual value, because the elastic modulus of the transducer material is tested by acoustic method to attain a sufficiently accurate
value, which can ensure the resonant frequency of the FEM can be possible close to the experiment result.

5.3 Vibration characteristics of the transducer

The vibration measurement platform of the ultrasonic transducer is shown in Fig. 12. An excitation signal is generated from a self-developed ultrasonic generator to drive the transducers. A Laser Doppler Vibrometer (HSV-700) is to capture the vibration amplitude at the end of the pin. Oscilloscope (Tektronix MDO3024) is to collect and record voltage, current, and vibration signal. A hand-held infrared thermometer is to monitor the temperature of the transducer.

The voltage, current, and vibration displacement curves of the TRD-303 transducer at 50% duty are recorded. The result is in Fig. 13(a), (b), (c), showing that the voltage, current, and displacement are in a good and stable sinusoidal waveform. The PP (peak-to-peak) amplitude of the transducers along the RMS (root mean square) current is presented in Fig. 14 at different duties. It is found that when the RMS current reaches to 3 A, the PP amplitude of TRD-303, TRD-3Cr13, and TRD-SKD11 is up to 30 μm, 24.0 μm, and 24 μm, respectively. The linear fitting curve shows a good linearity between the amplitude and current.

5.4 Vibration characteristics of different material

As the abovementioned, the three steel transducers are designed in the same structure and same dimension, fabricated by the same prestress (40 MPa). It is shown that the resonant frequency of the three transducers is within 0.33 kHz range from 19.9 to 20.23 kHz. Then, we evaluate the effect of the different materials on the amplitude output of the transducers. From the amplitude linear fitting curve in Fig. 13, it is found that TRD-303 can output the maximal amplitude at the same RMS current. The vibration of TRD-303 is much higher (25.9%) than the one of TRD-3Cr13 and TRD-SKD11. However, the amplitude curves of TRD-3Cr13 and TRD-SKD11 are in almost coincide, meaning that both of them have the same vibration output capacity. Therefore, the integrated ultrasonic tool holder made in 303 stainless material increases the vibration amplitude in the welding area, improving the ultrasonic processing quality of FSW. It is validated that the amplitude of the transducer increases when the elastic modulus decreases. The rooted reason is that the

![The impedance-phase-frequency curves. a TRD-303. b TRD-3Cr13. c TRD-SKD11](image)

**Table 4** Comparison of the two different simulation test resonant frequency

| Category   | Test $f_s$(Hz) | Simulation frequency $f_E$(Hz) | Simulation frequency $f_A$(Hz) | Error Δ$f_E$(%) | Error Δ$f_A$(%) |
|------------|----------------|-------------------------------|-------------------------------|-----------------|-----------------|
| TRD-303    | 19,900         | 19,687                        | 19,904                        | 1.07            | 0.02            |
| TRD-3Cr13  | 20,130         | 20,507                        | 20,190                        | 1.87            | 0.30            |
| TRD-SKD11  | 20,230         | 20,353                        | 20,273                        | 0.61            | 0.21            |
bonding force between atoms becomes weaker when the elastic modulus turns lower, which the ultrasonic energy causes alloys with lower interatomic forces to exhibit higher amplitudes [27].

As shown in Table 1, we can see that the elastic modulus and density of 3Cr13, SKD11 are close in the physical properties. Therefore, we can conclude that the amplitude output capacity of the transducer in 3Cr13 and SKD11 is in the same level. On the contrary, the elastic modulus and density of 303 steel are different from the ones of 3Cr13 and SKD11, which leads to higher amplitude output. Experimental results confirm that the material physical properties and material selection of the transducer have a significant effect on the amplitude output capacity of the transducer.

6 Conclusion

To improve the transmission ultrasonic energy to welding area, a new integrated ultrasonic tool holder with compact structure, low mass is proposed and designed. The influence of prestress on the resonant frequency and impedance of transducer is investigated. The vibration amplitude with difference material transducers is measured and compared. The results show that the prestress can increase resonant frequency and reduce mechanical impedance of the transducer, where the optimal prestress is ranged from 35 to 45 MPa. Based on the elastic modulus measured by the acoustic testing, the maximum frequency design error can be controlled within 0.3%. The amplitudes of pin can reach more than 24 μm, which meet with the FSW requirements. The transducer with 303 steel exhibits higher vibration capability among the three transducers.

The findings in this study can provide a guidance for the design and technical assembly for an ultrasonic actuator, especially the prestress control to the piezoceramics and the more accurate resonant frequency. Due to the compact structure, low mass, and flexible replacement, the proposed ultrasonic tool can be applied in a confined space and integrated in a rotating spindle, which has potential in a general FSW machining equipment.

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Declarations

Competing interests The authors declare no competing interests.

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