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Investigation of the Focused Ultrasonic Vibration Abrasive Jet Polishing System

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Abstract: This paper presents a novel focused ultrasonic vibration abrasive Jet polishing system. Theoretical analyses of the focusing characteristics, impedance matching properties, and acoustic field propagation characteristics are conducted based on acoustic theory. The effects of key system parameters on the focusing performance and the output sound pressure of the abrasive jet are investigated through simulations and experiments. Based on the analytical results, an optimal structural design method is proposed. Finally, the effectiveness of the proposed system in polishing applications is validated through polishing experiments. The research findings are expected to promote the development of abrasive jet polishing technology.

Keywords: focused ultrasonic; abrasive jet polishing; system optimization;

0 Introduction

Ultrasonic vibration abrasive jet polishing is a novel polishing method that integrates ultrasonic vibration with abrasive jet polishing technology [1,2]. This approach couples high-frequency vibration energy with jet kinetic energy: the ultrasonic vibration system transmits vibrations into the abrasive flow, generating a high-intensity ultrasonic field at the focal region, which acts together with the jet on the workpiece surface to achieve material removal and surface finishing. This technique expands the process applicability of conventional abrasive jet machining and demonstrates significant improvements in both processing efficiency and surface quality, making it particularly suitable for the high-efficiency precision polishing of hard and brittle difficult-to-machine materials and complex curved components [3-6]. Lv et al. [7,8] investigated different ultrasonic vibration modes and confirmed that superimposing ultrasonic energy onto the jet kinetic energy significantly enhances the erosion capability of abrasive particles on the workpiece surface. Jiang et al. [9] applied ultrasonic vibration-assisted CMP polishing to SiC and achieved a material removal rate of 8.44 $\mu\text{m}/\text{h}$ with low surface damage. Ye et al. [10] found that ultrasound promotes and guides the abrasive flow, increasing the material removal rate by 26.9%, thus confirming the positive effect of ultrasonic excitation on polishing efficiency. Meng [11] studied the surface morphology of quadratic cylindrical surfaces in ultrasonic vibration-assisted polishing and confirmed that ultrasonic assistance improves surface performance and reduces mid-to-high frequency errors in the polished surface. Zhang [12], Sun [13], and Geng [14] investigated the effects of various process parameters on surface roughness and quality in ultrasonic polishing, all achieving favorable processing results.

In ultrasonic vibration abrasive jet polishing, in addition to the energy of the abrasive jet itself, the mechanical shock waves and cavitation effects induced by ultrasonic vibration are critical mechanisms that enhance the polishing effect. The sound pressure intensity at the focal point directly determines the intensity of mechanical impact and cavitation. Therefore, the manner in which the ultrasonic vibration system interacts with the abrasive jet and its resultant effects are key factors influencing polishing performance. Conventional longitudinal vibration

ultrasonic transducers require a large radiating surface to effectively transmit ultrasonic vibration energy into the liquid, resulting in low energy density at various points in the liquid and making it difficult to precisely control the polishing position and material removal amount [15,16]. In contrast, spherical focused ultrasonic transducers enable directional concentration of acoustic energy, offering advantages such as good directivity and high working efficiency [17-19], and have been widely applied in the medical field [20]. After the energy is focused at the focal point, the abrasive jet acquires high-intensity ultrasonic vibration energy [21-23], driving efficient and controllable material removal on localized workpiece surfaces and improving polishing effectiveness. Beaucamp et al. [24,25] employed a spherical acoustic lens-focused ultrasonic transducer to achieve efficient polishing by utilizing the ultrasonic cavitation effect of focused ultrasound on the abrasive jet. Under the action of focused ultrasound, the abrasive jet undergoes ultrasonic vibration and converges at the nozzle outlet to form high-intensity ultrasonic vibration, inducing intense cavitation in the abrasive jet. Driven by the cavitation-induced jet, abrasive particles impact the workpiece surface, accomplishing material removal. Experimental results using a 26 kHz Al_2O_3 water-based abrasive jet on BK7 glass and electroless nickel demonstrated that the focused ultrasonic-assisted polishing achieved a processing efficiency 380% higher than that of conventional polishing under the same processing conditions and surface quality requirements. Wei et al. [26] designed a novel concave spherical focused ultrasonic transducer impedance matching structure based on acoustic impedance matching theory and Kirchhoff theory. Using a 1.2 MHz ultrasonic vibration system to measure the sound pressure at the focal point, they found that the maximum sound pressure at the focal point was increased by 72.03% compared to the case without matching.

The focused ultrasonic vibration jet polishing system is the key enabling device for focused ultrasonic vibration abrasive jet polishing (FUJP) technology. Achieving high-amplitude sound pressure at the focal point is essential for fully utilizing the mechanical and cavitation effects of ultrasonic vibration to achieve efficient polishing. However, reports on this system remain relatively limited. To address this gap, this paper proposes a novel focused ultrasonic vibration abrasive jet polishing system incorporating a concave spherical self-focusing piezoelectric ceramic transducer, building upon previous theoretical and experimental studies. The acoustic field characteristics of the system are analyzed, the key structural parameters are optimized through simulations, and the effectiveness of the system is validated through polishing experiments. The findings are expected to further promote the development and application of focused ultrasonic abrasive jet polishing technology.

1. Configuration of the FUJP System

The proposed focused ultrasonic vibration abrasive jet polishing system is illustrated in Fig. 1. The system consists of four main components: an ultrasonic power supply, a focused ultrasonic abrasive jet polishing device, an abrasive supply system, and a circulating cooling water system. The focused ultrasonic abrasive jet polishing device comprises a concave spherical piezoelectric ceramic ultrasonic transducer, a rear reflector, a front conical cavity, a metal diaphragm, and a conical nozzle. A concave spherical reflector is installed inside the rear housing. The spherical piezoelectric ceramic transducer is mounted in the housing bore through an elastic structure with edge support. The gap between the convex surface of the transducer and the concave surface of the reflector serves as the rear matching layer, which enables efficient reflection of the vibration radiated from the rear side of the transducer. An impedance matching material is applied to the concave surface of the piezoelectric ceramic to achieve acoustic

impedance matching between the piezoelectric ceramic and the sound transmission liquid, thereby ensuring efficient transmission of the ultrasonic vibration radiated from the concave surface. The concave surface of the piezoelectric ceramic, together with the front conical cavity and the conical nozzle, forms a conical space, which is divided into upper and lower chambers by a metal diaphragm positioned near the nozzle. During operation, the upper chamber is filled with circulating pure water, while the abrasive flow is directly supplied to the lower conical space through a central supply tube. This configuration forms a triple-layer sound transmission medium consisting of water, the metal diaphragm, and the abrasive jet. The ultrasonic vibration generated by the concave spherical piezoelectric ceramic transducer propagates through the sound transmission liquid, the metal diaphragm, and the abrasive flow, and is eventually focused at the nozzle. Under the combined effect of the focused ultrasonic vibration energy and the jet energy, the abrasive jet is ejected from the nozzle and impinges on the workpiece surface. In this system, the focusing effect of the ultrasonic vibration at the nozzle directly determines the system's performance. The main factors affecting the focusing effect include the parameters of the spherical piezoelectric transducer, the propagation characteristics of the ultrasonic vibration in the transmission medium, and the impedance matching between the transducer and the liquid medium.

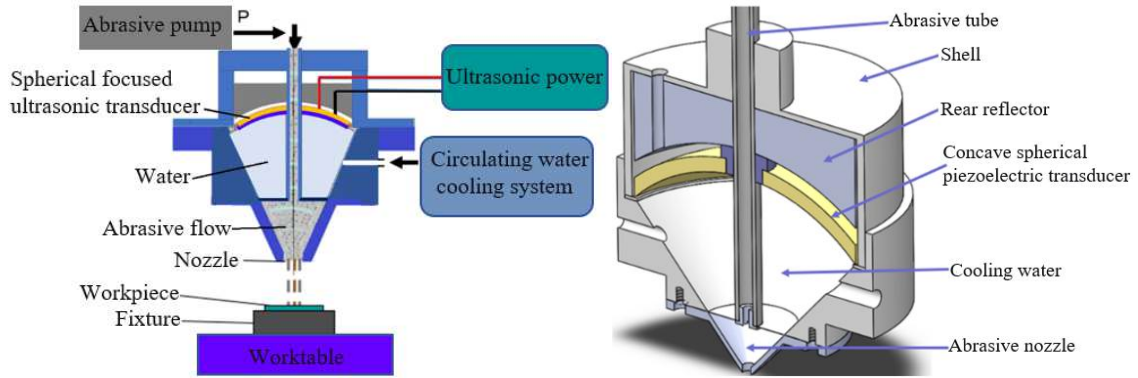


Fig. 1 Configuration of the FUJP system

2. Theoretical Analysis of the FUJP System

2.1 Focusing Characteristics Analysis

In the focused ultrasonic jet polishing device, each point on the concave spherical transducer vibrates uniformly along the radial direction of the spherical surface, radiating ultrasound into the liquid, as shown in Fig. 2. The ultrasonic wave attenuates during propagation in the liquid due to viscous absorption and abrasive scattering losses. As the propagation distance increases, both the sound pressure and amplitude decrease. Neglecting the effect of dispersion, let α_0 be the acoustic attenuation coefficient of the ultrasound in the liquid, with $\alpha = \alpha_0 \omega^2$ being the attenuation in the medium. Studies [22] have shown that α_0 is influenced by the volume concentration of abrasive particles in the medium. The sound pressure at a point P in the liquid in front of the spherical shell can be expressed as:

$$p(r, \theta) = j\rho_0 f u_0 \int_0^{2\pi} \int_0^b \frac{e^{-jkr_1}}{r_1} e^{-\alpha r_1} R_1 dR_1 d\phi \quad (1)$$

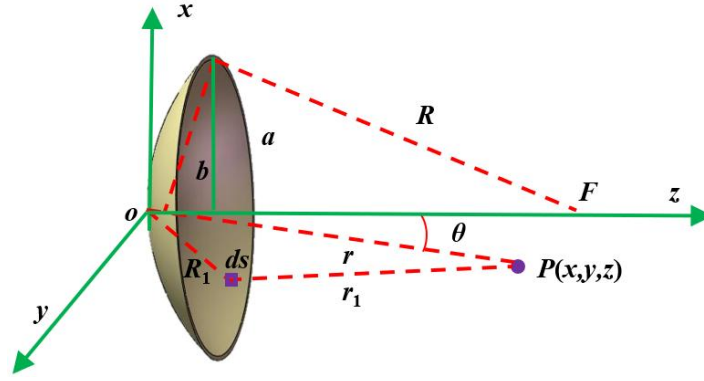


Fig. 2 Sound pressure distribution of the radiated sound field of the concave spherical transducer

where a is the aperture radius of the spherical shell, R is the radius of curvature of the spherical shell, and b is the distance from the vertex O to the edge of the spherical shell. P is a point in the sound field, ds is the area element on the spherical surface, R_1 is the distance from the area element to point O , r_1 is the distance from point P to the area element, and θ is the angle between OP and the Z -axis. r is the distance from point P to point O . Then:

$$r_1 = \left[r^2 - 2rR_1 \sqrt{1 - \frac{R_1^2}{4R^2}} \sin \theta \cos \phi + R_1^2 \left(1 + \frac{r \cos \theta}{R} \right) \right]^{\frac{1}{2}}$$

From Eq. (1), the sound pressure distribution on the acoustic axis can be obtained as:

$$p(z) = j\rho_0 u_0 f \frac{2\lambda}{\left(1 - \frac{z}{R}\right)} \sin \left[\frac{1}{2} K \left(\sqrt{(z-h)^2 + a^2} - z \right) e^{-j\frac{1}{2}K(\sqrt{(z-h)^2 + a^2} + z)} \right] \quad (2)$$

where z is the Z -axis coordinate of the point on the acoustic axis, $\lambda=c/f$ is the ultrasonic wavelength in the polishing liquid, ρ_0 is the density of the medium, $K=k-ja$ is the complex wave number accounting for acoustic attenuation in the medium, and $k=\omega/c$. $h=\sqrt{b^2-a^2}$ is the height of the spherical surface vertex. The sound pressure at each point on the acoustic axis can be obtained by taking the modulus of Eq. (2).

For given transducer parameters, the sound pressure distribution on the acoustic axis of the radiated sound field of the concave spherical focusing transducer can be calculated using Eq. (2). Assume the aperture of the concave spherical transducer is $2a = 60\sim 100$ mm, the radius of curvature is $R = 60\sim 80$ mm, the resonant frequency is $f = 0.5\sim 1.5$ MHz, the acoustic attenuation coefficient in the abrasive flow is $\alpha = 1\sim 3$, the density of the abrasive flow is $\rho_0 = 1 \times 10^3$ kg/m³, the sound velocity is $c = 1480$ m/s, and the normal amplitude on the spherical surface is 0.1 μ m. The sound pressure distribution on the transducer axis is shown in Fig. 3.

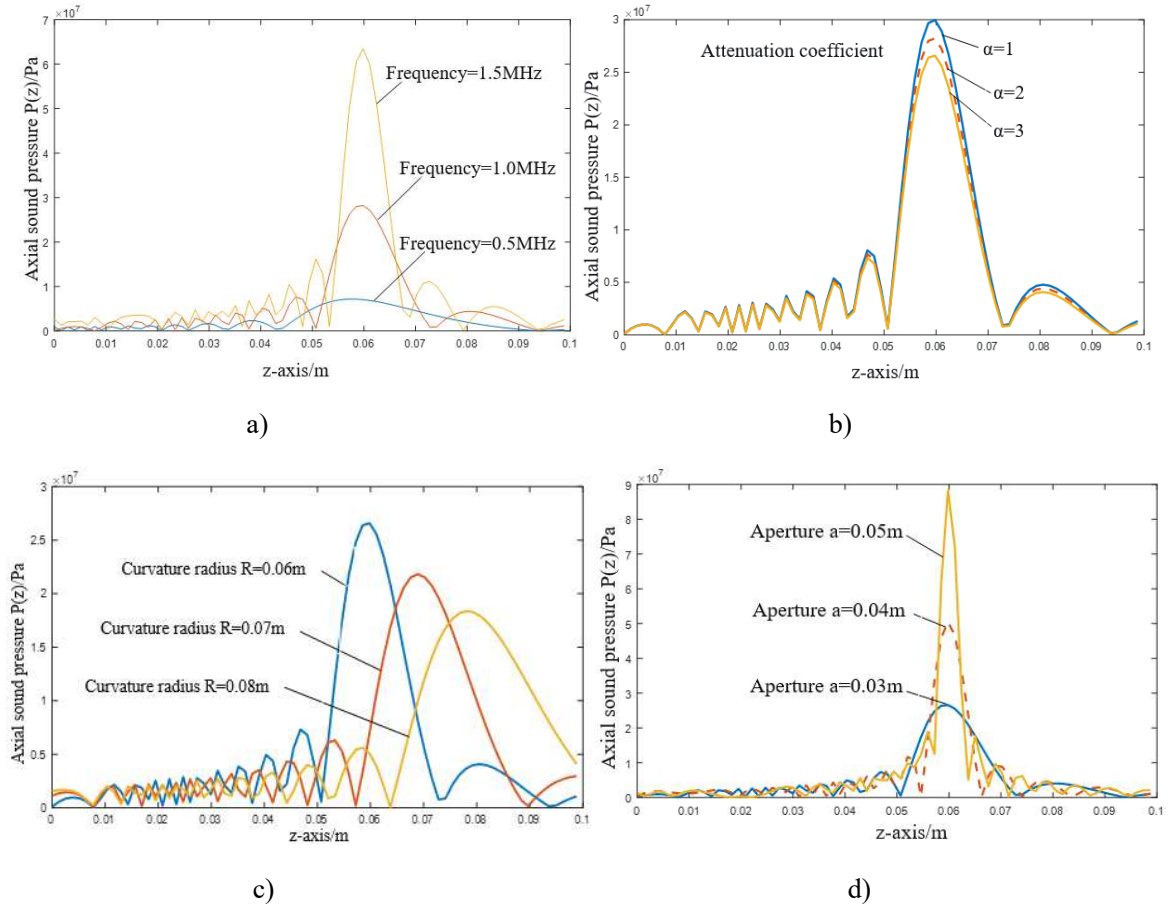


Fig. 3 Sound pressure distribution of the radiated sound field of the concave spherical transducer

The results show that the sound pressure on the axis of the spherical focusing transducer is affected by the structural parameters of the transducer, the vibration frequency, and the acoustic attenuation characteristics of the liquid medium. Near the geometric center of the spherical transducer, the sound pressure reaches its maximum value, which is the focal point of the focusing transducer. As the resonant frequency of the transducer increases, the spherical radius of curvature decreases, or the transducer aperture increases, the focal sound pressure increases. As the acoustic attenuation coefficient of the liquid increases, the focal sound pressure decreases.

2.2 Impedance Matching Analysis

During operation, the piezoelectric ceramic self-focusing transducer vibrates along its thickness direction, with both its concave and convex surfaces radiating ultrasonic vibration to the adjacent media. As shown in Fig. 4, the vibration energy radiated from the concave surface (front) is transmitted forward through the medium (liquid) and focused at the focal point, while the energy radiated from the convex surface (rear) propagates backward in the medium and dissipates. From an application perspective, it is desirable to maximize the energy transmission efficiency of the front side and minimize the energy loss on the rear side. The acoustic impedance matching characteristics between the transducer radiating surface and the medium directly affect the transmission and reflection of vibration energy. On the front side, due to the significant difference in acoustic impedance between the piezoelectric ceramic material and the liquid medium, an impedance matching layer needs to be added between the transducer and the liquid to achieve impedance matching, thereby improving the transmission rate of vibration energy. On the rear side, an appropriate matching layer is needed to reflect the vibration energy radiated from the

rear side of the transducer back, thereby improving energy efficiency.

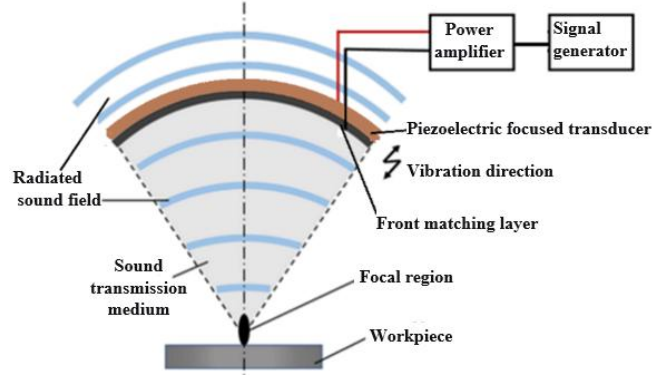


Fig. 4 Radiated sound field of the focused ultrasonic transducer

(1) Front matching layer

After adding a matching layer between the piezoelectric ceramic and the abrasive flow, the transmittance T of the sound wave at the interface between the transducer and the matching layer can be derived as [27]:

$$T = \frac{2Z_3}{[(Z_1 + Z_3)^2 \cos^2 \frac{2\pi d}{\lambda_2} + (Z_2 + \frac{Z_1 Z_3}{Z_2})^2 \sin^2 \frac{2\pi d}{\lambda_2}]^{\frac{1}{2}}} \quad (3)$$

where $\lambda_2 = c_2/f$ is the wavelength in the matching layer, and c_2 is the sound velocity in the matching layer. z_1 , z_2 , and z_3 are the acoustic impedances of the piezoelectric ceramic transducer, the matching layer, and the abrasive flow liquid, respectively, and d is the thickness of the front matching layer. Since the front matching layer of the transducer has uniform thickness, the sound pressure P can be calculated from Eqs. (2) and (3):

$$p = if \rho u_0 \int_0^{2\pi} \int_0^b \frac{e^{-jkr}}{r} R_1 T dR_1 d\phi \quad (4)$$

From Eqs. (3) and (4), the sound pressure distribution on the acoustic axis for different matching layer thicknesses d can be obtained, as shown in Fig. 5. Obviously, when the thickness of the matching layer is an odd multiple of a quarter wavelength, the transmittance of sound pressure in the liquid can be effectively increased, and the maximum sound pressure can be obtained at the focal point.

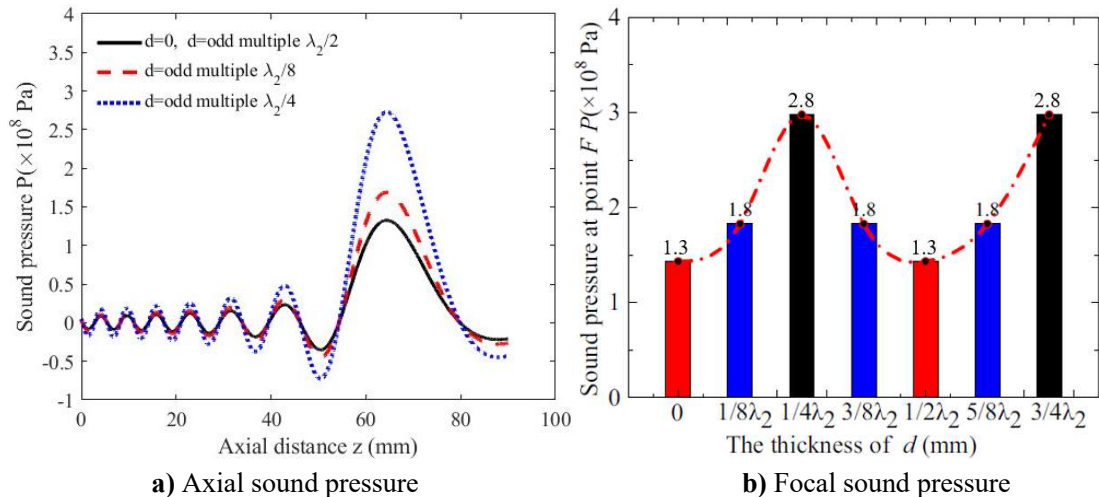


Fig. 5 Relationship between front matching layer and sound pressure($f=430\text{KHz}$, $A=1\mu\text{m}$, $a=45\text{mm}$, $R_0=65\text{mm}$)

(2) Rear matching layer

The function of the rear matching layer is to reflect the vibration radiated from the rear side of the transducer back to the transducer to enhance the vibration. As shown in Fig. 6, a matching material (Layer II) of uniform thickness H_0 is inserted between the piezoelectric ceramic and the metal backing layer. The reflectance R_2 can be obtained as [28]:

$$R_2 = \frac{e^{-2\pi i H_0 / \lambda_5} (Z_4 + Z_5)(Z_5 - Z_6) + e^{2\pi i H_0 / \lambda_5} (Z_4 - Z_5)(Z_5 + Z_6)}{e^{-2\pi i H_0 / \lambda_5} (Z_5 - Z_4)(Z_6 - Z_5) + e^{2\pi i H_0 / \lambda_5} (Z_4 + Z_5)(Z_5 + Z_6)} \quad (5)$$

Where Z_4 , Z_5 , and Z_6 are the acoustic impedances of the piezoelectric ceramic, Layer II, and Layer I, respectively, and $\lambda_5 = c_5 / f$ is the wavelength in Layer II.

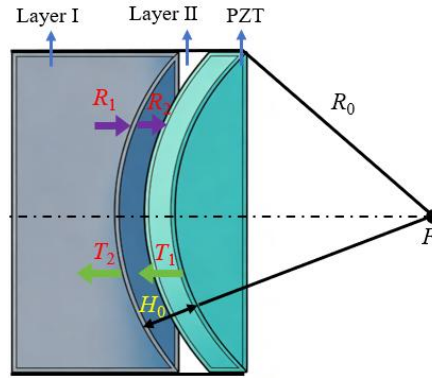


Fig. 6 Analysis of the rear matching layer

The numerical calculation results of the relationship between H_0 and R_2 are shown in Fig. 7. Obviously, compared with the conventional single-layer metal matching layer structure, the double-layer reflection matching structure can significantly change the reflectance of sound pressure. When appropriate materials are used and the thickness of Layer II is an odd multiple of a quarter wavelength, the reflectance can reach its maximum. Compared with water and silicone gel, using air as the material for Layer II can achieve more stable and higher reflectance over a wider thickness range. Since the attenuation of sound waves propagating in air is very large, the thickness of the air matching layer should be minimized while satisfying the above requirements. This allows the vibration energy radiated from the rear side of the piezoelectric ceramic to be reflected back as much as possible, improving the energy output efficiency of the transducer.

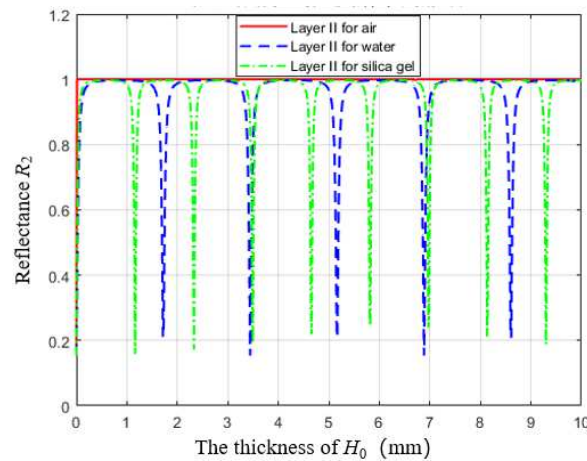


Fig. 7 Effect of rear matching layer II on sound reflectance

2.3 Analysis of Ultrasonic Propagation in FUJP System

From the perspective of ultrasonic propagation, the ultrasonic vibration generated by the spherical focusing piezoelectric ultrasonic transducer should be transmitted and focused using a low-loss liquid medium (such as degassed pure water). On the other hand, from the perspective of polishing processing, the polishing medium is an abrasive fluid containing abrasive particles. The acoustic propagation loss of this medium is greater than that of water. Therefore, from an engineering application perspective, it is necessary to divide the liquid medium into two parts—water and abrasive flow—and separate them with a metal diaphragm, thereby minimizing the propagation distance of sound waves in the abrasive flow. Thus, in the focused ultrasonic vibration abrasive jet polishing head, a triple-layer liquid-solid-liquid sound transmission medium consisting of circulating water, a metal diaphragm, and abrasive flow is formed. According to acoustic theory, when sound waves propagate through different media, reflection and refraction occur at the interfaces.

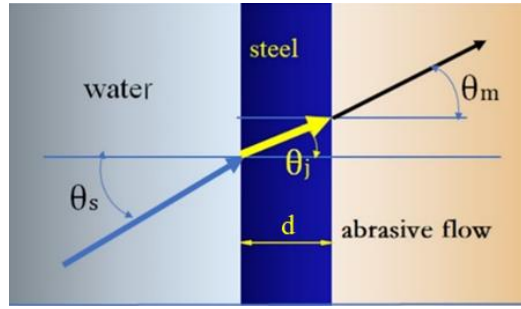


Fig. 8 Analysis of ultrasonic wave propagation in the water-metal-abrasive flow triple-layer medium

Let the acoustic characteristic impedances of water, metal, and abrasive flow be $R_s = \rho_s c_s$, $R_j = \rho_j c_j$, $R_m = \rho_m c_m$ respectively. According to acoustic theory, the transmittance of sound waves from water through the metal layer to the abrasive flow is:

$$t = \frac{4z_s z_j}{(z_s - z_j)(z_j - z_m)e^{jk_j d \cos \theta_j} + (z_s + z_j)(z_j + z_m)e^{-jk_j d \cos \theta_j}} \quad (6)$$

Where: $z_s = R_s / \cos \theta_s$, $z_j = R_j / \cos \theta_j$, $z_m = R_m / \cos \theta_m$, $k_j = 2\pi / \lambda_j$, and λ_j is the wavelength in the metal medium. θ_s , θ_j and θ_m are the incident angle at the water-metal interface, the incident angle at the metal-abrasive flow interface, and the refraction angle in the abrasive flow, respectively. d is the thickness of the metal layer.

The refraction angle of the sound wave in the abrasive flow after passing through the metal diaphragm is:

$$\theta_m = \sin^{-1} \left(\frac{c_m}{c_s} \sin \theta_s \right) \quad (7)$$

From the above analysis:

(1) When the incident angle of the sound wave is zero, or when the thickness of the metal layer is very small compared to the wavelength of the sound wave, the exponential function in Eq. (6) is approximately 1. For example, when $d = 0.1$ mm and $f = 430$ kHz, $e^{jk_j d \cos \theta_j} \leq 1.04$. Therefore, Eq. (6) can be simplified to:

$$t = \frac{2z_s}{(z_s + z_m)} \quad (8)$$

That is, the transmittance of sound waves in the water-metal-abrasive flow medium depends only on the characteristic acoustic impedances of water and the abrasive flow.

(2) The refraction angle of the sound wave in the abrasive flow after passing through the metal diaphragm depends only on the ratio of sound velocities between the abrasive flow and water, and the incident angle of the sound wave from water into the metal diaphragm. When the incident angle is zero, the refraction angle is also zero. Therefore, as long as the interface between water and the metal diaphragm is perpendicular to the incident direction of the sound wave, no refraction occurs.

3. Simulation and Experimental Study of FUJP System

To optimize the structure of the focused ultrasonic vibration abrasive jet polishing System, this paper employs COMSOL software to solve the homogeneous Helmholtz equation in two-dimensional axisymmetric cylindrical coordinates, using a two-dimensional axisymmetric pressure acoustics-frequency domain model for simulation analysis. An experimental system is also constructed to study the effects of transducer matching parameters, nozzle diameter, metal diaphragm position, and standoff distance on the outlet sound pressure. The optimal structure of the focused ultrasonic abrasive flow polishing head is thereby determined.

3.1 Simulation Model

The simulation model structure is shown in Fig. 9. Here, h_1 is the distance from the vertex of the concave spherical surface of the piezoelectric ceramic to the metal diaphragm; d_1 is the thickness of the sound-transmitting diaphragm; d_0 is the nozzle diameter; λ_1 is the wavelength of ultrasound in the sound transmission liquid medium. The parameters of the transducer and focusing device are listed in Table 1.

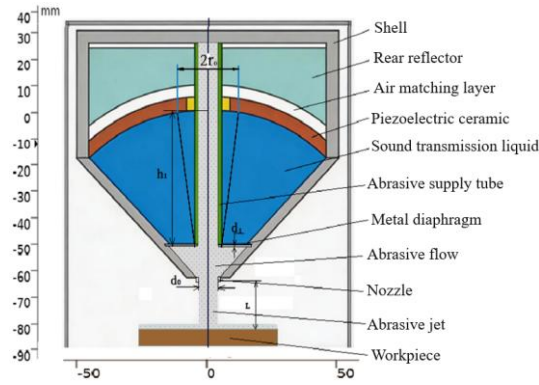


Fig. 9 Simulation model structure

Table 1 Simulation model parameters

Component	Material	Parameter
Concave spherical piezoelectric ceramic shell	PZT-8	Aperture radius $a = 45$ mm, thickness = 5 mm, spherical radius of curvature $R_0 = 65$ mm
Rear reflector block	45steel	Spherical radius $R_b = 69$ mm
Rear matching layer	Air	thickness = 4 mm
Front matching layer	Silicone	
Metal diaphragm	316L	$d_1 = 0.1$ mm
Ultrasonic parameters		$A = 0.5 \mu\text{m}$, $f = 430$ kHz

3.2 Experimental System

The experimental system adopts the same structural parameters as the simulation system, as shown in Fig. 10. A piezoelectric force sensor is used to measure the pressure per unit area on the workpiece surface. The outlet pressure is measured by varying the nozzle diameter and the standoff distance (distance from the nozzle to the workpiece surface).

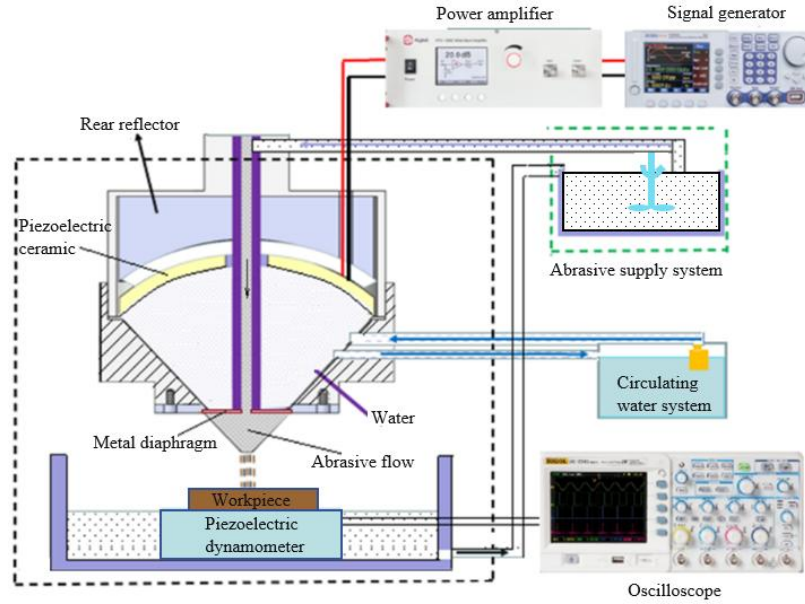


Fig. 10 Experimental system for structural optimization of the focused ultrasonic polishing head

3.3 Simulation and Experimental Results and Analysis

3.3.1 Analysis of Matching Layer Effects

Simulations were conducted for the concave spherical transducer with and without the front matching layer. The simulation conditions were: standoff distance of 20 mm, metal diaphragm of 0.1 mm thick 316L stainless steel positioned at 50.58 mm from the concave spherical center, nozzle diameter of 4 mm, and front matching layer of epoxy resin with a thickness of 0.1 mm. The simulation results with and without the front matching layer are shown in Fig. 11. To obtain the optimal front matching layer thickness, simulations were performed for thicknesses ranging from 0 to 1 mm, and the effects on outlet sound pressure were analyzed, as shown in Fig. 12.

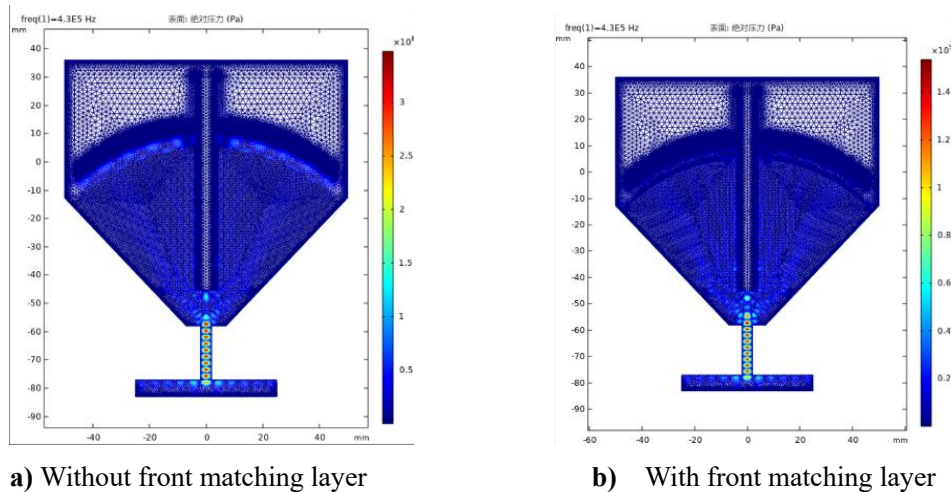


Fig. 11 Simulation analysis of the effect of front matching layer on outlet sound pressure
($d_0 = 0.1$ mm, standoff distance = 20 mm, $h_1 = 50.58$ mm)

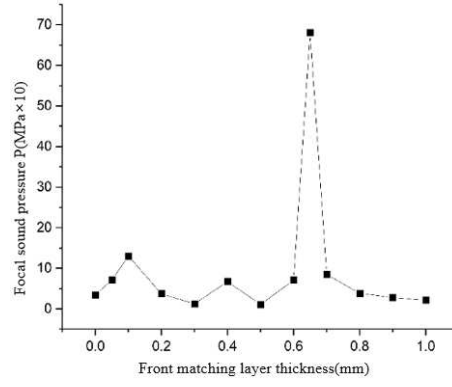


Fig. 12 Analysis of outlet sound pressure at different front matching layer thicknesses

3.3.2 Analysis of Metal Diaphragm Effects

(1) Effect of metal diaphragm position

From an application perspective, 0.1 mm thick 316L stainless steel was selected as the metal diaphragm material. The axial position of the diaphragm relative to the concave spherical transducer was varied to analyze the sound field characteristics at different positions. The simulation results are shown in Fig. 13. The outlet sound pressure was simulated for the diaphragm positioned at quarter-wavelength and half-wavelength locations, with results shown in Fig. 14.

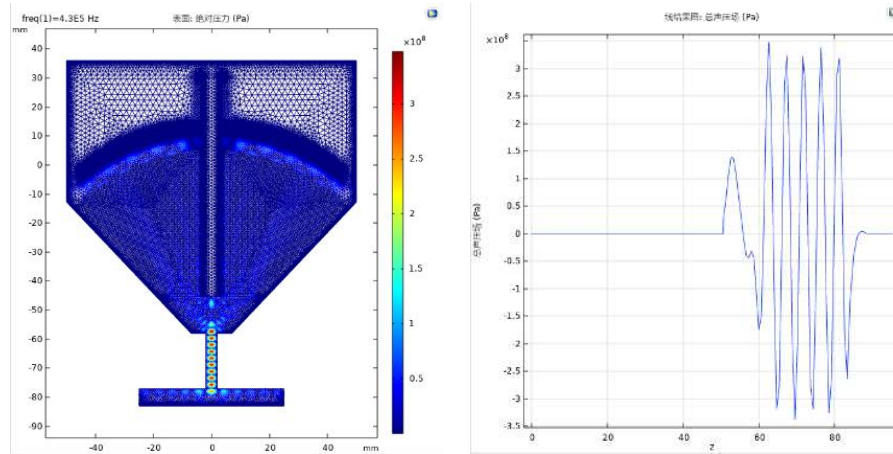


Fig. 13 Simulation analysis of the effect of metal diaphragm axial position on outlet sound pressure

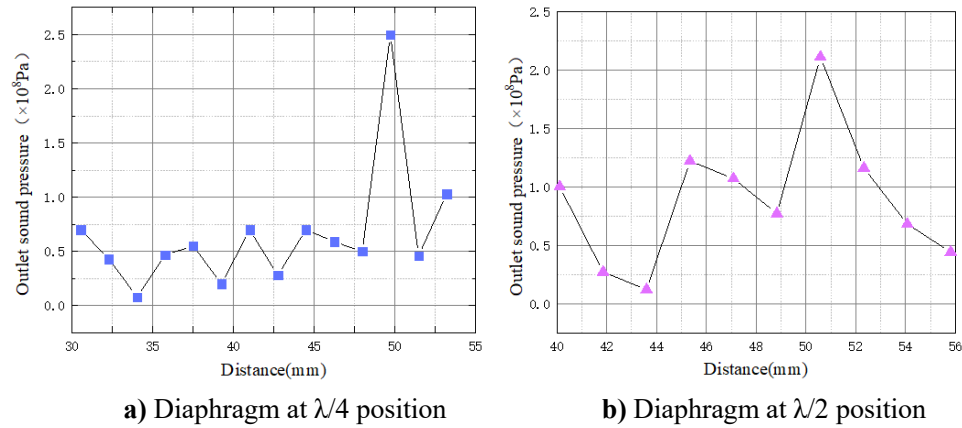


Fig. 14 Outlet sound pressure at different wavelength multiples
(standoff distance 20 mm, nozzle diameter 4 mm)

The analysis results show that when the metal diaphragm is positioned at $h_1 = 49.7$ mm, which corresponds to $h_1 = 57 \times \lambda_2 / 4$ (an odd multiple of quarter wavelength), the ultrasound can effectively transmit through the metal

diaphragm, and the maximum sound pressure is obtained at the focal point.

The position of the metal diaphragm has both positive and negative effects on the focal sound pressure. On one hand, since the acoustic impedance of the abrasive flow is greater than that of pure water, the loss and attenuation of sound waves in the abrasive flow are larger. The closer the metal diaphragm is to the spherical shell, the longer the propagation path of sound waves in the abrasive flow, leading to increased propagation attenuation. On the other hand, the central abrasive supply tube has a certain diameter, which reduces the effective radiation area of the spherical surface. Moreover, due to the abrasive tube, the ultrasonic vibration radiated from points within a circle of diameter $2r_0$ on the spherical surface is blocked by the tube, causing energy loss. Reducing the distance from the metal diaphragm to the spherical shell vertex helps to reduce the effect of the abrasive tube and increase the ultrasonic energy at the focal point. Therefore, there exists an optimal position for the metal diaphragm in the focused ultrasonic vibration device, which is influenced by factors such as the diameter of the abrasive flow supply tube and the acoustic impedance of the abrasive flow.

(2) Effect of metal diaphragm thickness

With the metal diaphragm position unchanged (at $57 \times \lambda_2/4$), the diaphragm thickness was varied to simulate the change in outlet sound pressure. The results are shown in Fig. 15. Clearly, as the metal diaphragm thickness increases, the outlet sound pressure decreases, with the maximum focal sound pressure occurring at a thickness of 0.1 mm. Theoretical analysis shows that when the diaphragm thickness is very small, its effect on transmittance can be neglected. As the thickness increases, the transmittance decreases, and the outlet sound pressure correspondingly decreases.

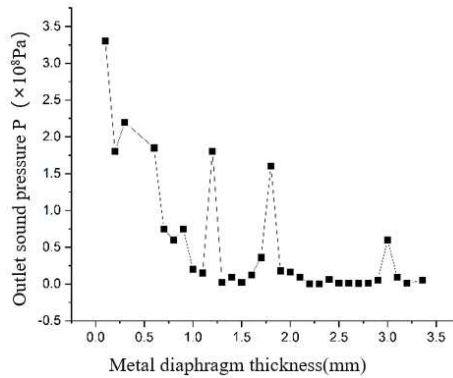


Fig. 15 Effect of metal diaphragm thickness on outlet sound pressure

3.3.3 Analysis of Metal Diaphragm Position

Using a 0.1 mm thick stainless steel metal diaphragm, the effect of standoff distance on outlet sound pressure was analyzed. The simulation results are shown in Fig. 16, and the experimental results are shown in Fig. 17. It can be observed that the standoff distance significantly affects the outlet sound pressure. As the standoff distance increases, the outlet sound pressure generally shows a periodic decreasing trend. Within a certain range, there exists an optimal standoff distance at which the focal sound pressure reaches its maximum. The simulation results show that the outlet sound pressure reaches its maximum at a standoff distance of 6 mm. In the experimental results, no peak was observed at a standoff distance of 22 mm, primarily due to the kinetic energy attenuation of the jet as it moves away from the nozzle.

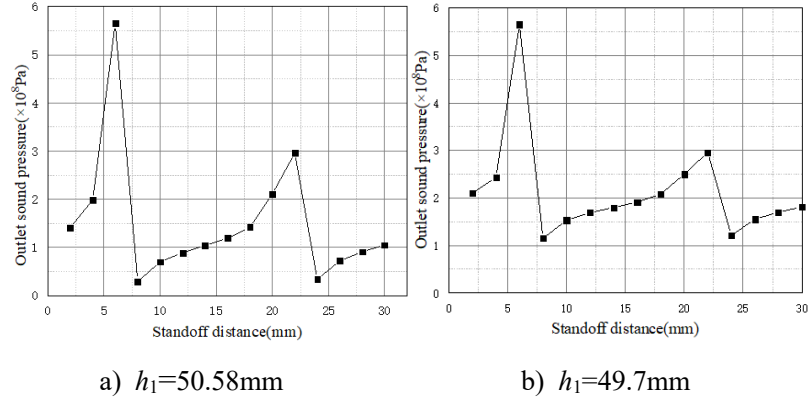


Fig. 16 Simulation analysis of the effect of standoff distance on nozzle outlet sound pressure (Metal diaphragm thickness $d_0=0.1\text{mm}$)

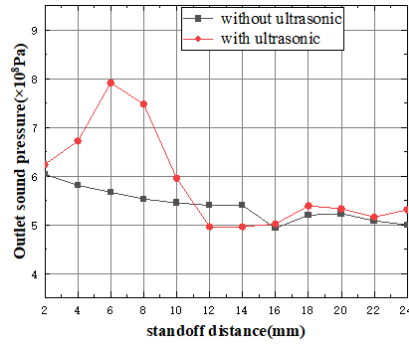


Fig. 17 Experimental results of the effect of standoff distance on nozzle outlet sound pressure (Experimental conditions: $h_1=50.58\text{mm}$)

3.3.4 Analysis of Jet Nozzle Diameter Effects

Simulation and experimental studies were conducted to analyze the change in outlet sound pressure at different nozzle diameters, with results shown in Figs. 18 and 19, respectively. It can be seen that the nozzle diameter significantly affects the outlet sound pressure. Under the experimental conditions of this study, the outlet sound pressure reaches its maximum at a nozzle diameter of $d_0 = 4\text{ mm}$, which corresponds to the focal spot diameter at the focal point. When the nozzle diameter is too small, sound wave reflection occurs on the inner wall of the nozzle, causing some acoustic energy to dissipate within the nozzle and reducing the focusing energy at the outlet. When the nozzle diameter is too large, the outlet cross-sectional area increases, reducing the outlet pressure and jet velocity, which affects the removal efficiency of the abrasive flow on the workpiece surface.

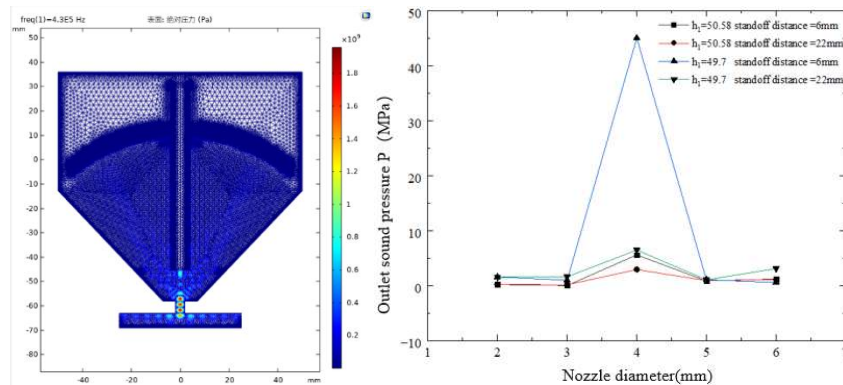


Fig. 18 Simulation analysis of the effect of nozzle diameter on outlet sound pressure (Experimental conditions: diaphragm thickness 0.1 mm , $h_1 = 50.58\text{ mm}$, standoff distance 6 mm)

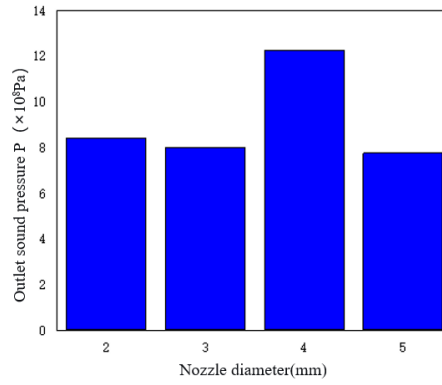


Fig. 19 Experimental results of the effect of nozzle diameter on outlet sound pressure

4. Confirmatory Polishing Experiment of the FUJP System

Based on the above analysis results, a spherical self-focusing transducer with a frequency of 430 kHz was selected to construct a polishing experimental system, and verification polishing experiments were conducted. The experimental system is shown in Fig. 20. In the experiments, 6061 aluminum alloy and monocrystalline silicon were selected as workpiece materials. The polishing effects of focused ultrasonic vibration abrasive jet polishing and conventional abrasive jet polishing were compared. The workpiece specimens were cylindrical surfaces ($\phi 10 \times 10$ mm) and spherical crown surfaces (diameter 20 mm, radius of curvature 82 mm). The surface morphology after processing was examined using a Keyence VHX-700 0 ultra-depth-of-field microscope and a Bruker ContourGT-K0 white light interferometer. The experimental conditions are listed in Table 2.

Table 2 Polishing experimental conditions

Parameter	Experimental conditions			
	6061Aluminum alloy polishing		Monocrystalline silicon polishing	
Ultrasonic frequency	430kHz			
Power output	35%	35%	40%	40%
Abrasive particle size	5μm	0.5μm	2.5μm	0.5μm
Abrasive concentration	10%			
Abrasive material	Al ₂ O ₃		SiC	
Abrasive pump pressure	0.3MPa			
Standoff distance	6mm			
Jet angle	90°			

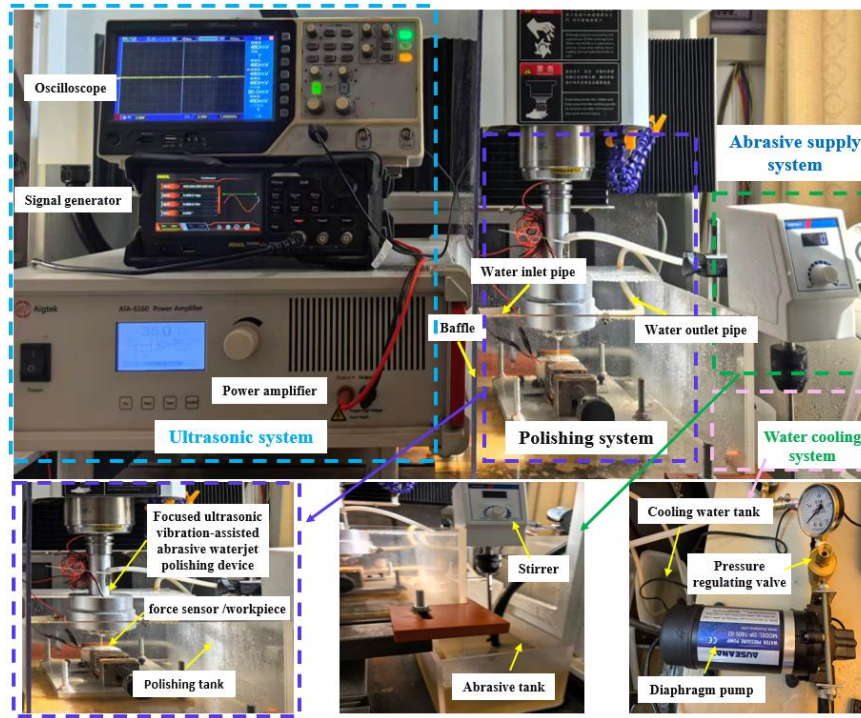


Fig. 20 Polishing experimental system

(1) Polishing of ductile metal surfaces

Aluminum alloy specimens were polished using both conventional abrasive jet polishing and focused ultrasonic vibration abrasive jet polishing for 10 min each, with a power output of 35%. The original surface and polished surfaces are shown in Fig. 21, and the white light interferometer measurement results are shown in Fig. 22. It can be seen that after 10 min of polishing, surface scratches and other defects were significantly removed. However, the surface polished with focused ultrasonic assistance showed more thorough removal of scratches and a smoother, more uniform surface. The surface roughness of the aluminum alloy was $0.639 \mu\text{m}$ for the original surface, decreased to $0.445 \mu\text{m}$ without ultrasound, and decreased to $0.239 \mu\text{m}$ with ultrasonic vibration, significantly outperforming the case without ultrasound.



(a) Original surface

(b) AJP

(c) FUJP

Fig. 21 Polished surfaces of aluminum alloy

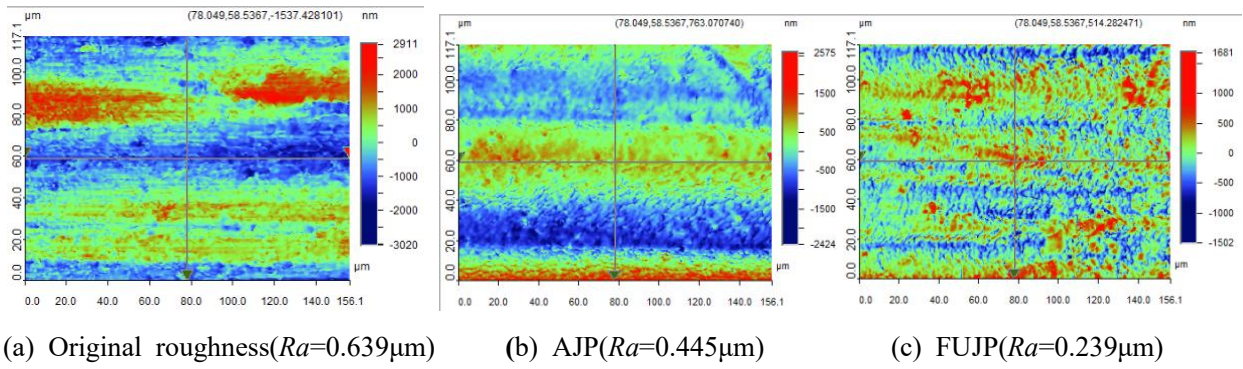


Fig. 22 Surface roughness of aluminum alloy

After polishing with W5 Al_2O_3 for 10 min, polishing was continued using W0.5 abrasive particles. After 30 min, the surface roughness of the aluminum alloy decreased from 0.239 μm to 47.66 nm. The polished specimens are shown in Fig. 23.



Fig. 23 Photographs of polished aluminum alloy specimens

(2) Polishing of brittle material surfaces

Monocrystalline silicon specimens were polished using both conventional abrasive jet polishing and focused ultrasonic vibration abrasive jet polishing for 16 min each, with a power output of 40%. The original surface and polished surfaces are shown in Fig. 24, and the white light interferometer roughness measurement results are shown in Fig. 25. It can be seen that after 16 min of polishing, surface scratches and other defects were significantly removed. However, the surface polished with focused ultrasonic assistance showed more thorough removal of scratches and a smoother, more uniform surface. The surface roughness of the original specimen was 0.956 μm , decreased to 0.636 μm without ultrasound, and decreased to 0.479 μm with ultrasonic vibration, significantly outperforming the case without ultrasound.

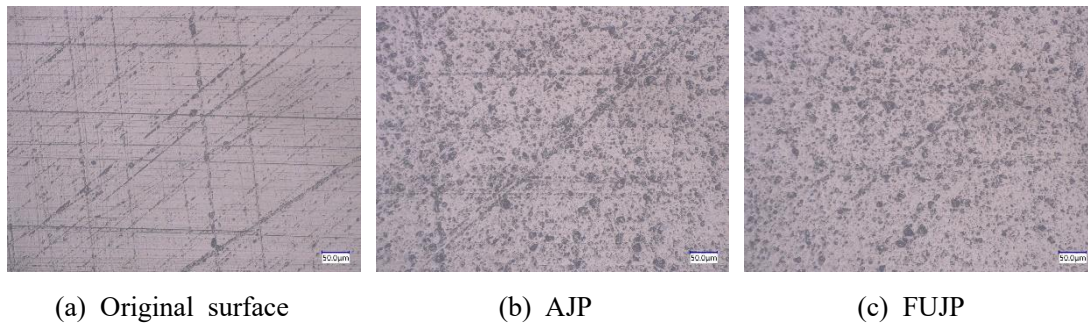


Fig. 24 Polished surfaces of monocrystalline silicon

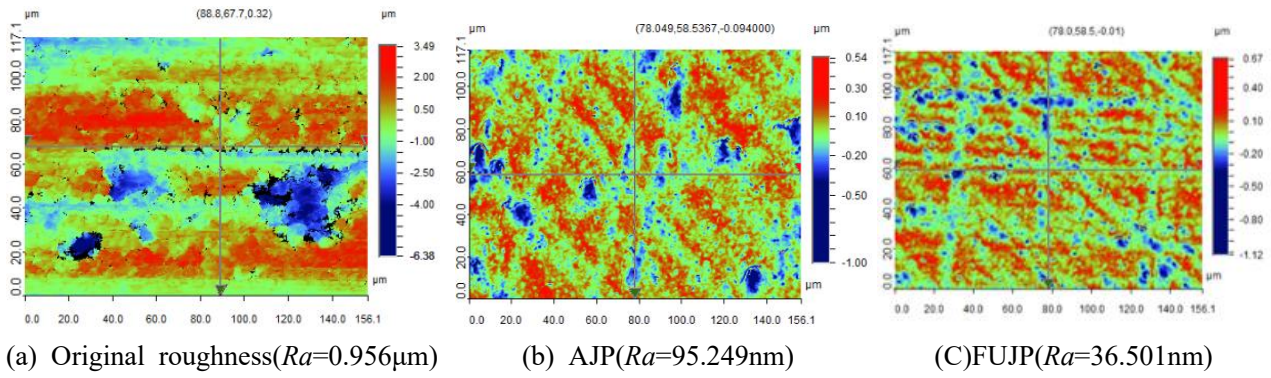


Fig. 25 Surface roughness of monocrystalline silicon

After polishing with W2.5 SiC for 16 min, polishing was continued using W0.5 abrasive particles for 40 min. The surface roughness of the monocrystalline silicon cylindrical surface decreased from $0.479\mu m$ to $38.588nm$, and the spherical surface decreased from $0.901\mu m$ to $36.501nm$. The polished specimens are shown in Fig. 26.

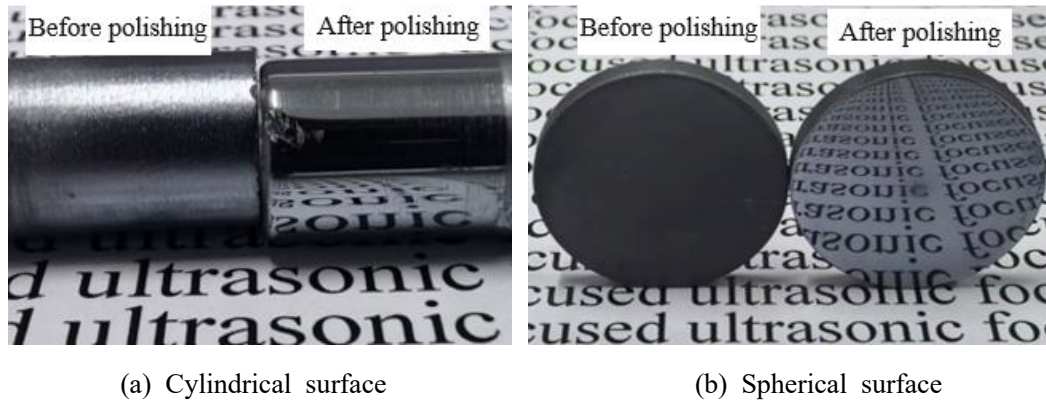


Fig. 26 Photographs of polished monocrystalline silicon specimens

5 Conclusions

This paper proposes a focused ultrasonic vibration abrasive jet polishing system based on spherical self-focusing. Through theoretical analysis, the focusing characteristics, matching characteristics, and acoustic field propagation characteristics of the system are elucidated. Through simulations and experiments, the effects of the main structural parameters on the focusing performance are analyzed. The effectiveness of the system is verified through polishing experiments. The main conclusions are as follows:

1. The ultrasonic vibration frequency affects both the focal spot size and sound pressure, as well as the ultrasonic cavitation threshold. Increasing the frequency reduces the focal spot size and increases the sound pressure, which can enhance the intensity of ultrasonic mechanical impact. However, increasing the frequency also raises the ultrasonic cavitation threshold, affecting the cavitation effect. Therefore, the ultrasonic frequency should be reasonably selected based on the acoustic impedance parameters of the abrasive fluid to facilitate the combined effects of ultrasonic mechanical impact and cavitation jet action.

2. To improve the utilization efficiency of ultrasonic vibration energy from the piezoelectric transducer, the rear side of the transducer should be matched with an air matching layer and a metal reflector, while the front side should be matched with a silicone matching layer.

3.The position of the metal diaphragm in the polishing head, the nozzle outlet diameter, and the standoff distance (distance from the nozzle to the workpiece surface) significantly affect the outlet sound pressure, and optimal values exist. The metal diaphragm should be positioned at a distance of a quarter wavelength from the spherical surface vertex, and its thickness should be minimized. For the polishing head structure adopted in this study, the optimal nozzle diameter is 4 mm, and the optimal standoff distance is 6 mm.

4.Polishing experiments on aluminum and monocrystalline silicon specimen surfaces demonstrate that the novel focused ultrasonic abrasive jet polishing system proposed in this paper can significantly improve the surface quality of the specimens.

Author contribution Kun Ren: conceptualization, investigation, method-ology, and writing original draft preparation. Hua Li: investigation and writing original draft preparation. Dong Wei, Li Wei, Peixiang Zhou, Julong Yuan: validation.

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Declarations

Ethics approval Not applicable.

Consent for publication All authors have read and agreed to the published version of the manuscript.

Competing interests The authors declare no competing interests.

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