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Design and Development of a Novel Ultrasonic Field Wetting Angle Measuring Instrument for Researching the Wetting of the Liquid–Solid Interface

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Abstract: A key technical problem in the preparation of Al-Ti-C grain refiner and other composite materials is the poor wetting of the Al-C interface, which greatly restricts the development of the preparation technology of related composite materials. In view of this scientific challenge, a novel ultrasonic field wetting angle measuring instrument has been designed to research the wetting behavior of the liquid–solid interface and ensure that preparation conditions are optimized. The dimensional parameters of the ultrasonic transducer and the horn in the novel ultrasonic wetting angle measuring instrument have been designed by theoretical calculation, and the modal analysis was performed for the ultrasonic horn using the functions of displacement and time. Modal analysis was utilized to optimize the dimension of the ultrasonic horn, and the natural frequency of the longitudinal vibration of the horn was reduced from 22,130 Hz to 22,013 Hz, resulting in an error rate between the actual value (22,013 Hz) and the design value (20 kHz) of less than 1%. In addition, the influence of different transition arc radii on the maximum stress of the optimized ultrasonic horn was analyzed.

Keywords: ultrasonic field; ultrasonic horn; liquid–solid interface; modal analysis; nature frequency

1. Introduction

Liquid–solid interface behavior is a common physicochemical phenomenon in processes of material preparation and chemical synthesis, such as welding, liquid-phase sintering, chemical reactions of solid surfaces in liquid phase, metallurgical processes and interface reactions, and wetting behavior of some composite materials [1–3]. The research of liquid–solid interface behavior has important scientific significance in theory, and it is key in the preparation of composite materials, which determines the possibility of composite preparation, the final microstructure, and properties and production efficiency [4]. However, the liquid–solid interface is difficult to wet during the preparation of some composite materials, which greatly limits the development of composite materials preparation technology. For example, in the in situ synthesis process of Al-Ti-C grain refiner and TiCp-reinforced Al matrix composites, synthesis and preparation are very difficult due to the poor wetting of the Al-C interface [5–8].

Studies have shown that adding alloying elements and increasing the temperature of liquid metal could improve the wetting of the interface [9–11], as while the performance of the prepared material is poor, the wetting effect is not obvious. In order to solve the difficulty of interface wetting, researchers found that a high intensity ultrasonic field could achieve the wetting and dispersion of the reinforcement in the matrix in a very short time [12–14]. Zhao et al. [6] reported that the application of an ultrasonic field in the preparation of Al-Ti-C grain refiner could improve the wetting of the Al-C interface. Sarasua [15] sheds light on how ultrasound can instantly adjust the contact angle by tuning
the vibration amplitude, and a thermodynamic model describing how ultrasound decreases the contact angle in a three-phase wetting system has been developed. Moreover, analytical and experimental research has been carried out in order to demonstrate that ultrasound is an important competitor to surfactants in terms of energy efficiency and environmental friendliness. Shrestha [16] directly address the wetting for membrane-based desalination and separation of oil-saline water mixtures by applying a superhydrophilic and oleophobic coating to a commercial membrane surface. Ezazi [17] developed a water-responsive self-repairing superomniphobic film by utilizing a cross-linked HPC-SiO$_2$ composite treated with a low-surface-energy perfluorosilane. The HPC-SiO$_2$ film can repair a deep scratch and restore its inherent superomniphobic wetting and mechanical hardness upon exposure to water vapor. Lebon [18–20] found that the ultrasonic field can improve the wetting between the reinforcing phase and the metal melt, thereby increasing the strengthening effect of the particles relative to the base metal. The results of previous research show that the application of an ultrasonic field has become an effective technology to regulate the wetting of the liquid–solid interface in the processes of composite materials preparation and chemical synthesis [21–27].

Although many efforts have been made to improve the wetting of the liquid–solid interface, an ultrasonic field wetting angle measuring instrument has not been developed, and similar devices were limited to the conventional measurement of wetting angle [28,29]. The main reason is that the circulation and turbulence caused by the acoustic streaming effect in the melt form discrete spectrums such as harmonics and sub-harmonics, resulting in the ultrasonic field being difficult to control [30]. Another important reason is that the acoustic cavitation causes cavitation damage during the coupling process between the ultrasonic horn and the melt and a reverberant sound field appears in the melt, which ultimately leads to the drift of system resonant frequency and the reduction of acoustic coupling efficiency. Therefore, a novel ultrasonic field wetting angle measuring instrument has been designed to research the wetting of the liquid–solid interface in the preparation of composite materials.

Generally, the main components of the ultrasonic treatment device are an ultrasonic generator, a transducer, an ultrasonic horn, a tool head, etc. [31,32]. The function of the transducer is to convert the electrical signal generated by the transmitter into mechanical vibration, which provides the amplitude required for the preparation of the composite materials [33,34]. However, the amplitude of vibration produced by the transducer is of order 5–10 µm, which is very low for the preparation of the composite materials [31,35]. As an important part, the ultrasonic horn, also termed as an amplifier, transformer, concentrator, or acoustic coupler, is employed to magnify the amplitude of vibration to a value suitable for the preparation of the composite materials [32,36]. In addition, the frequency of the horn is the same as the frequency of the transducer, which results in the ultrasonic vibration system reaching a resonance state. Therefore, the design of ultrasonic horn is an important aspect for achieving a large amplitude and the resonant state of the system, which achieves the technical requirements of ultrasonic processing on the liquid–solid interface.

The structural diagram of the novel ultrasonic field wetting angle measuring instrument is illustrated in Figure 1. In this paper, the design of the novel ultrasonic field wetting angle measuring instrument was mainly divided into three steps: Firstly, the dimensions of the transducer and horn of the ultrasonic vibration system were theoretically designed. The ultrasonic vibration system was assembled into a conventional wetting angle measuring instrument which could perform the research of improving the wetting of the liquid–solid interface under an ultrasonic field, and the design was an important innovation of the device. Secondly, modal analysis was performed to verify the natural frequency of the ultrasonic horn in longitudinal vibration, and the horn was optimized when combined with the modal analysis. Finally, the influence of different transition arc radiiuses on the maximum stress of the optimized ultrasonic horn was analyzed.
2. Materials and Methods

2.1. Ultrasonic Transducer Design

The frequency of the sandwich piezoelectric ultrasonic transducer designed in this paper was 20 kHz, and the structural diagram is shown in Figure 2. In order to reduce the material used in the transducer, it was necessary to design it as a reasonable size to ensure that the transducer had an ideal vibration state. The most common design methods for a sandwich piezoelectric transducer include the half wavelength method and the quarter wavelength method. The transducer designed by the half wavelength method easily caused the piezoelectric plate to vibrate in an extra direction (the piezoelectric plate requires longitudinal vibration). In this paper, the most common quarter wavelength and piezoelectric ceramic transducer was adopted because the piezoelectric ceramic transducer can generate stable ultrasonic wave when the load changes. Meanwhile, the quarter wavelength transducer also has the characteristics of large amplitude, high electro-acoustic conversion rate, low calorific value, and high reliability. Because of the large electromechanical coupling factors and stable material characteristics of PZT ceramics, the transducer piezoelectric plate adopts PZT-8 piezoelectric ceramic material [37,38]. The number of piezoelectric ceramics must be an even number to ensure that the polarities of the front and rear cover plates are consistent. Two conventional piezoelectric ceramics were difficult to meet the power requirements, therefore we used four circular PZT-8 piezoelectric ceramics with holes.

The design principle of the ultrasonic transducer was as follows: firstly, the overall length of the transducer was equal to the half wavelength of the fundamental wave, AB was the nodal plane, and the transducer was regarded as two quarter-wavelength vibrators on the left and right. Secondly, the frequency equations of the left and right vibrators were derived. The dimensions of the front and rear covers were obtained according to the number of piezoelectric ceramics and the frequency equation of each vibrator. The AB node plane was the center position of the piezoelectric plate, as shown in Figure 2. \( L_{C1} \) and \( L_{C2} \) were the thickness of the two piezoelectric ceramics; that is, \( L_{C1} \) was equal to \( L_{C2} \). \( L_1 \) and \( L_2 \) were the length of the rear cover and the front cover, respectively. \( D_0 \) was the outer diameter of the piezoelectric ceramic, \( d_0 \) was the inner diameter of the piezoelectric ceramic, and \( D_1 \) was the diameter of the front and rear cover.

![Figure 1. Structural diagram of the novel ultrasonic field wetting angle measuring instrument.](image-url)
transducer. $Z_A$ represents the load impedance of the transmitter and $Z_B$ represents the load impedance of the horn. Normally, the transducer would not be connected to the transmitter and in the no-load state, which resulted in the $Z_A$ being zero. When the transducer was connected to different horns, $Z_B$ had different values, which was also regarded as the no-load state. According to the boundary conditions, the displacement and force of each component of the transducer were continuous, and the equivalent circuit of each component could be connected in series. Therefore, Figure 3a can be converted into a composite equivalent circuit diagram containing load impedance $Z_{m1}$ and $Z_{m2}$, as shown in Figure 3b. The left vibrator consists of two PZT-8 piezoelectric ceramics and a rear cover, and the rear cover was regarded as the load of piezoelectric ceramics. Combined with Figure 3b, the equivalent circuit diagram of the left vibrator can be obtained, as shown in Figure 3c.

![Figure 2. Schematic diagram of the ultrasonic transducer.](image)

![Figure 3. Equivalent circuit diagram of ultrasonic transducer, (a) the equivalent circuit of each component of transducer, (b) ultrasonic transducer composite equivalent circuit, (c) the equivalent circuit diagram of the left vibrator.](image)

The equations of $Z_{1p}$ and $Z_{2p}$ can be expressed as:

$$Z_{1p} = j\rho c S \tan \left( \frac{k c L_{c1}}{2} \right)$$

(1)
\[ Z_{2p} = \frac{\rho c_e S}{j \sin(k_e L_{c1})} \]  

(2)

The load impedance of piezoelectric ceramics is defined as:

\[ Z_{m1} = R_{m1} + jX_{m1} \]  

(3)

Assuming that the transducer and the rear cover have no loss, \( R_{m1} = 0 \), the load impedance of the piezoelectric ceramic can be simplified as:

\[ Z_{m1} = jX_{m1} = j\rho_1 c_1 S_1 \tan(k_1 L_1) \]  

(4)

Because the displacement at the AB node plane was zero, the right of the equivalent circuit of the vibrator in Figure 3c was open circuit. According to the total impedance of the circuit of zero, the frequency equation of the left vibrator can be expressed as:

\[ Z_{1p} + Z_{2p} + Z_{m1} = 0 \]  

(5)

Substituting Equations (1), (2), and (4) into Equation (5), the frequency equation of the left vibrator can be described as:

\[ j\rho c_e \tan \left( \frac{k_e L_{c1}}{2} \right) + \frac{\rho c_e S}{j \sin(k_e L_{c1})} + j\rho_1 c_1 S_1 \tan(k_1 L_1) = 0 \]  

(6)

Derivation and transformation of the equation can be obtained as follows:

\[ \frac{j\rho c_e S \left( \frac{1}{\sin(k_e L_{c1})} - \tan \left( \frac{k_e L_{c1}}{2} \right) \right)}{j\rho_1 c_1 S_1 \tan(k_1 L_1)} = 1 \]  

(7)

\[ \frac{j\rho c_e S \left( \frac{1}{2 \sin \left( \frac{k_e L_{c1}}{2} \right) \cos \left( \frac{k_e L_{c1}}{2} \right)} - \frac{2 \left( \sin \left( \frac{k_e L_{c1}}{2} \right) \right)^2}{2 \sin \left( \frac{k_e L_{c1}}{2} \right) \cos \left( \frac{k_e L_{c1}}{2} \right)} \right)}{j\rho_1 c_1 S_1 \tan(k_1 L_1)} = 1 \]  

(8)

\[ \frac{j\rho c_e S \left( \frac{\cos(k_1 L_1)}{2 \sin \left( \frac{k_1 L_1}{2} \right) \cos \left( \frac{k_1 L_1}{2} \right)} \right)}{j\rho_1 c_1 S_1 \tan(k_1 L_1)} = 1 \]  

(9)

Therefore, the final frequency equation of the left vibrator was expressed as:

\[ \rho c_e S = X_{m1} \tan(k_e L_{c1}) = \frac{\rho_1 c_1 S_1 \tan(k_e L_{c1})}{\cot(k_1 L_1)} \]  

(10)

Similarly, the frequency equation of the right vibrator was expressed as:

\[ \rho c_e S = X_{m2} \tan(k_e L_{c2}) = \frac{\rho_2 c_2 S_2 \tan(k_e L_{c2})}{\cot(k_2 L_2)} \]  

(11)

where, \( \rho \), \( \rho_1 \), and \( \rho_2 \) were the density of piezoelectric ceramics, rear cover, and front cover, respectively; \( c_e \), \( c_1 \), and \( c_2 \) were the sound velocity of piezoelectric ceramics, rear cover, and front cover, respectively; \( k_e \), \( k_1 \), and \( k_2 \) were the wave number of piezoelectric ceramics, rear cover, and front cover, respectively; \( S \), \( S_1 \), and \( S_2 \) were the cross sectional area of piezoelectric ceramics, rear cover, and front cover, respectively.

The frequency of the ultrasonic equipment transmitter was 20 kHz. Because the ultrasonic energy was transmitted from the front cover to the horn, 2A12 duralumin with high transmission efficiency was selected for the front cover. The rear cover was connected to the transmitter and 45# steel with low transmission efficiency was selected to prevent the overflow of ultrasonic energy [39]. The material parameters used in ultrasonic transducer are shown in Table 1.
By transforming Equation (10), the frequency equation of the left vibrator can be expressed as:
\[
\tan(k_1 L_1) = \frac{\rho c e S}{\rho_1 c_1 S_1 \tan(k_1 L_{c1})}
\]  
(12)

Substituting the above parameters into Equation (12), the length dimension of the rear and front cover can be obtained: the length dimension \( L_1 \) of the rear cover was 29 mm and the length dimension \( L_2 \) of the front cover was 53 mm. Moreover, there was an electrode (thickness of 0.2 mm) between each piece of piezoelectric ceramic and the resulting length dimension of the piezoelectric ceramics stack was 20.8 mm.

2.2. Ultrasonic Horn Design

In this paper, the stepped horn with the highest amplitude amplification coefficient and succinctly designed dimensions was selected, and the 45# steel was employed in the manufacture of the ultrasonic horn. Figure 4 shows the structural schematic of the stepped ultrasonic horn.

![Figure 4. Structural schematic of the stepped ultrasonic horn.](image)

When the simple harmonic vibration was applied on the stepped ultrasonic horn, the longitudinal wave vibration equation at the variable cross-section can be described as follows [31,40]:
\[
\frac{\partial^2 \xi}{\partial x^2} + \frac{1}{S} \times \frac{\partial S}{\partial x} \times \frac{\partial^2 \xi}{\partial x^2} + K^2 \xi = 0
\]  
(13)

where \( K \) was the circular wavenumber, \( K = \omega/c; \omega \) is the ultrasonic circular frequency, rad/s; \( c \) was the longitudinal wave propagation velocity, \( c = \sqrt{E/\rho} \), \( E \) and \( \rho \) were the young’s modulus and density of the ultrasonic horn material; \( \xi \) was the displacement function of the particle, \( \xi = \xi(x) \); \( S \) was the cross-sectional area function of the ultrasonic horn, \( S = S(x) \).
For the stepped ultrasonic horn, $S(x)$ is a constant, the longitudinal wave vibration equation can be simplified as follows:

\[
\frac{\partial^2 \xi}{\partial x^2} + K^2 \xi = 0 \quad (14)
\]

The particle displacement of Equation (14) can be derived as follows:

\[
\begin{align*}
\xi_a &= (A_1 \cos kx + B_1 \sin kx), \quad (-a < x < 0) \\
\xi_b &= (A_2 \cos kx + B_2 \sin kx), \quad (0 < x < b)
\end{align*} \quad (15)
\]

According to the boundary conditions, $A_1, B_1, A_2$ and $B_2$ were expressed as:

\[
\begin{align*}
A_1 &= \xi_1 \cos ka \\
B_1 &= -\xi_1 \sin ka \\
A_2 &= -\xi_2 \cos kb + F_2 \frac{\sin kb}{Eks_2} \\
B_2 &= -\xi_2 \sin kb - F_2 \frac{\cos kb}{Eks_2} = -\xi_2 \left( \sin kb + j \frac{Z_0}{Z_02} \cos kb \right)
\end{align*} \quad (16-19)
\]

Substituting Equations (17)–(20) into Equation (15), the final particle displacement equation can be rewritten as:

\[
\begin{align*}
\xi_a &= \xi_1 \cos K(a + x) \\
\xi_b &= \xi_1 \left[ j \frac{Z_0}{Z_02} \sin K(b - x) - \cos K(b - x) \right]
\end{align*} \quad (20)
\]

When the displacement node was $x = 0$, the horn was in the resonant state and the amplification of the horn was a function of the ratio of the squared radius. At this time, $a = b = \lambda/4$, and the length of the ultrasonic horn could be expressed as:

\[
L = a + b = 2a = \lambda/2 \quad (21)
\]

Structural steel was used for ultrasonic horn analysis (the velocity of sound wave on structural steel is 5760 m/s) and the length of the horn was calculated according to Equation (21). Table 2 shows the parameters of the ultrasonic horn.

**Table 2. Parameters of the ultrasonic horn.**

| Horn   | E (Gpa) | $\rho$ (kg/m$^3$) | $c$ (m/s) | $a$ (mm) | $b$ (mm) | $L$ (mm) |
|--------|---------|-------------------|-----------|-----------|-----------|-----------|
| Value  | 209     | 7.84              | 5760      | 72        | 72        | 144       |

### 2.3. Modal Analysis of the Ultrasonic Horn

The modal analysis of the ultrasonic horn allows for knowing the natural frequencies of each mode and the deformations that the model has in each of these frequencies. The modal analysis of the horn adopts the relationship between displacement and time function, and the dynamic equilibrium equation in matrix form is expressed as [31]:

\[
[M] \{x''\} + [C] \{x'\} + [K] \{x\} = \{F(t)\} \quad (22)
\]

where $[M]$, $[C]$, and $[K]$ denote mass matrix, damping matrix, and stiffness matrix, respectively, and $\{x''\}$, $\{x'\}$, and $\{x\}$ denote acceleration, velocity, and displacement of vibrating body, respectively. Mode is an inherent property of any mechanical system, and each mode
corresponds to a natural frequency, mode shape, and damping. The dynamic equilibrium equation of undamped free vibration can be simplified as:

\[
[M] \{x''\} + [K] \{x\} = \{0\}
\]  (23)

The modal properties of ultrasonic horn are evaluated by solving the eigenvalue problem as follows [31,32]:

\[
\{ [K] - \omega_i^2 [M] \} \{x_i\} = \{0\}
\]  (24)

where \(\omega_i\) denotes natural frequency of \(i\)th mode shape and \(x_i\) – \(i\)th denote eigenvector (mode shape) [31].

Considering the actual situation of the device, the diameters of the large and small ends of the horn have been kept at 38 mm and 13 mm, respectively. The parameters in Table 1 and ABAQUS software were used for modal analysis of the ultrasonic horn, and 25 modes were output from the calculation results. The solution can contain more than one natural frequency and corresponding mode shape in a given frequency range.

3. Results and Discussion

3.1. Modal Analysis Results

To verify the frequency value of the horn, the frequency extraction range was set to 10~30 kHz in the modal analysis of the horn, and the modal analysis results are shown in Table 3.

Table 3. The modal analysis results of ultrasonic horn.

| Modes | 9 Mode | 10 Mode | 11 Mode | 12 Mode | 13 Mode | 14 Mode |
|-------|--------|---------|---------|---------|---------|---------|
| Frequency (Hz) | 14,303 | 20,424 | 20,428 | 22,130 | 27,938 | 27,939 |

In the ideal resonant state, the frequency of the horn is the same as that of the ultrasonic transducer (20 kHz). It can be seen from Table 3 that there are three groups of natural frequencies close to 20 kHz: the frequencies are 20,424 Hz, 20,428 Hz, and 22,130 Hz, respectively. The frequency values of 10–13 modes were input into the model for the vibration mode verification of the horn, and the cloud diagram of the horn vibration mode is shown in Figure 5. It can be clearly seen from Figure 5a,b,d that the horn bends and vibrates along different coordinate axes when the natural frequency of the horn is 20,424 Hz, 20,428 Hz, and 27,938 Hz, respectively. Figure 5c shows the vibration mode of the horn with the natural frequency of 22,130 Hz, and the vibration mode is the longitudinal vibration along the X-axis, which achieves the design requirements of the stepped ultrasonic horn.

3.2. Ultrasonic Horn Optimization

When the working frequency of the transducer is consistent with the natural frequency of the horn, the entire ultrasonic vibration system reaches a resonance state. As described in the previous section, the modal analysis results of the ultrasonic horn show that the natural frequency of the ultrasonic horn in longitudinal vibration is 22,130 Hz, which is about 10.6% different from the design value of 20 kHz. For the best vibration form, it is necessary to optimize the size of the horn to make the error rate of frequency less than 1%. According to the modal analysis, the natural frequency of the ultrasonic horn in longitudinal vibration is higher than the design frequency. Therefore, the length size of the horn should be increased to reduce frequency, which achieving the natural frequency close to the design frequency. In order to improve the correction efficiency, the length of the three-dimensional model of the horn was changed and the modal analysis was carried out, and the modal analysis results were used to guide the correction process. Figure 6 shows the vibration mode cloud diagram of the 10–13 modes after the large end of the horn is increased by 1 mm. After the large end of the horn increased by 1 mm, the natural frequency of the horn in longitudinal vibration is reduced to 22,032 Hz, which indicates
that the design principle of increasing the size of the horn to reduce the natural frequency close to the design value is accurate, as shown in Figure 6c.

According to the principle of horn optimization, increasing the length of the large and small ends of the horn in turn leads to the change of the natural frequency of the horn. Table 4 shows the change of the natural frequency after increasing different lengths of the horn. As shown in Table 4, when the length of the large end increased by 1 mm, the natural frequency of the horn in longitudinal vibration (12 mode) decreased by 98 Hz, and when the length increased by 2 mm, the natural frequency decreased by 259 Hz; when the length of the small end increased by 1 mm, the natural frequency decreased by 102 Hz, and when the length increased by 2 mm, the natural frequency decreased by 213 Hz; and when the length of the large and small ends of the horn simultaneously increased by 1 mm, the natural frequency reduced by 269 Hz. The following conclusions can be drawn: in the optimization process, increasing the large end and small end of the horn by the same length has similar effects on the frequency. Basically, as the length of the large end or small end of the horn increased by 1 mm, the frequency reduced by approximately 100 Hz. Compared

![Figure 5](image1.jpg)  
**Figure 5.** Cloud diagram of horn vibration mode of the 10–13 modes, (a) 10 mode, (b) 11 mode, (c) 12 mode, (d) 13 mode.

![Figure 6](image2.jpg)  
**Figure 6.** Cloud diagram of horn vibration mode of the 10–13 modes after the large end was increased 1 mm, (a) 10 mode, (b) 11 mode, (c) 12 mode, (d) 13 mode.
with solely increasing the large end or small end by 2 mm, the frequency decreased more fleetly when the large and small end simultaneously increased by 1 mm.

**Table 4.** The change of the natural frequency after increasing different lengths of the horn (Hz).

| Correction Scheme                  | 10 Mode | 11 Mode | 12 Mode | 13 Mode |
|------------------------------------|---------|---------|---------|---------|
| Before amendment                   | 20,424  | 20,428  | 22,130  | 27,938  |
| Large end increase 1 mm            | 20,213  | 20,218  | 22,032  | 27,978  |
| Small end increase 1 mm            | 20,404  | 20,409  | 22,028  | 27,532  |
| Large end increase 2 mm            | 19,903  | 19,904  | 21,871  | 27,892  |
| Small end increase 2 mm            | 20,313  | 20,319  | 21,917  | 27,042  |
| large and small end simultaneously increase 1 mm | 20,099  | 20,105  | 21,861  | 27,439  |

By testing the influence of a length change of the large and small ends on the natural frequency, the optimization principle of the horn can be summarized: the corrected length of the large and small ends can be appropriately increased, which reduces more frequency in the early stage of the horn optimization; when the frequency was reduced too close to the design frequency, the length of the horn requires a slight increase, which results in the frequency being steadily and accurately close to the design value. Based on the above analysis results, the optimization scheme of the ultrasonic horn was designed. Combined with the modal analysis results, the optimization scheme and the frequency change results of the horn were drawn, as shown in Figure 7. After several optimizations, the natural frequency of the horn in longitudinal vibration reached 20,013 Hz, which was very close to the design frequency of 20 kHz, and it was not necessary to correct the horn.

![Figure 7](image-url)  
*Figure 7. Frequency change during ultrasonic horn optimization, Step 0: before optimization, Step 1: the length of the large and small end simultaneously increased 5 mm, Step 2: the length of the large and small ends simultaneously increased 1 mm again, Step 3: the length of the large and small ends simultaneously increased 1 mm again, Step 4: the length of the large and small ends simultaneously increased 0.5 mm again.*

Figure 8 was the cloud diagram of stress and strain in longitudinal vibration before and after optimization of the ultrasonic horn. After the horn optimization, the maximum stress of the horn was reduced from the original 123 MPa to 81.4 MPa, and the maximum stress was reduced by 41.6 MPa, as shown in Figure 8a,b. In addition, the maximum strain of the horn was also reduced after optimization, as shown in Figure 8c,d. Obviously,
the maximum stress of the horn was reduced after optimization, resulting in the stress concentration of the horn being reduced, thereby improving the stability performance and service life of the horn.

Figure 8. Cloud diagram of the maximum stress and strain in longitudinal vibration, (a) stress before optimization, (b) stress after optimization, (c) strain before optimization, (d) strain after optimization.

3.3. Transition Arc Radius

After optimizing the size of the horn, it was also necessary to consider whether the initial transition arc radius matched the optimized horn. The transition arc radius of the horn before optimization was 9 mm. Therefore, the application of model analysis was performed to verify whether the transition arc radius was consistent with the optimized horn. Figure 9 shows the maximum stress of the horn obtained by modal analysis with the transition arc radius of 7–12 mm (radius is an integer). Clearly, the maximum stress reached the minimum value of 81.4 MPa when the transition arc radius was 9 mm in 12 mode, indicating that the transition arc radius of 9 mm was still suitable for the optimized horn.

3.4. Reliability Verification of the Device

The addition of Al-Ti-C grain refiners is an effective and economical method to refine the grain of aluminum alloy. However, the preparation of Al-Ti-C grain refiners is difficult due to the poor wetting of the Al-C interface [41–43]. The wetting of the Al-C interface in the preparation of Al-Ti-C grain refiner was studied by using the ultrasonic field wetting angle measuring instrument, to verify the reliability and effectiveness of the novel device. The sessile drop method was used, and a specially designed experimental system was constructed [44–48] that was suitable for ultrasonic field wetting angle measuring instrument. The graphite substrate was put on the supporting platform with a solid Al sample laying in the center of the top surface of the substrate. In order to improve the wetting, the special molten salt, potassium fluorotitanate (K₂TiF₆), was evenly spread around the Al block [7]. Finally, the ultrasonic field was applied to the samples for 0–25 min and the sample was heated to various temperatures to analyze the effect of the ultrasonic field on the Al-C wetting.

The Al-C interface morphology of the sample was observed and analyzed, as shown in Figure 10. The structure of the Al-C interface can be roughly divided into three layers: Al layer, salt layer, and C layer. The Ti atoms provided by K₂TiF₆ could react with Al and C to form Al₃Ti and TiC particles, respectively. Obviously, the EDS analysis shows that the white block in the Al layer was Al₃Ti, and the area A near the interface can be enlarged to observe the dispersed TiC particles, as shown in Figure 10c. The ultrasonic field improves the wetting of the Al-C interface and can be summarized as follows: the salt layer at the interface provides a large number of Ti atoms that disperse and adsorb
around the graphite, which facilitates the wetting [49]. The surface activity of graphite is improved by cavitation and TiC is formed between C and Ti, achieving the infiltration of the Al melt and graphite. Simultaneously, TiC particles move away from the carbon interface with the ultrasonic standing wave to achieve favorable reactive wetting behavior and mass transfer. In addition, the cavitation reduces the surface tension and increases the fluidity of the Al melt, which could facilitate the wetting of Al-C interface. The explanation of these phenomena has been reported in a previous research work [6]. The wetting of Al-C experiment under the ultrasonic field shows that the ultrasonic field can effectively improve the wetting of the Al-C interface.

Figure 9. Relationship diagram between transition arc radius and maximum stress.

Figure 10. The Al-C interface morphology of the sample, (a) the SEM of sample, (b) the SEM of Al₃Ti, (c) the enlarged SEM of the area A.
4. Conclusions

In this paper, a novel ultrasonic field wetting angle measuring instrument has been designed for the wetting of the liquid–solid interface of composite materials. The new device can be used to study the wetting of the liquid–solid interface during the preparation of composite materials, and the specific conclusions are summarized as follows:

(1) The dimensional parameters of the ultrasonic transducer and the horn were designed by theoretical calculation, and a modal analysis was performed for the ultrasonic horn, which achieved the vibration mode and natural frequency of the horn in the range of 10 kHz–30 kHz. The natural frequency of the ultrasonic horn in longitudinal vibration was 22,310 Hz, sufficing the requirements of the device.

(2) Modal analysis was utilized to optimize the ultrasonic horn, reducing the natural frequency of the ultrasonic horn in longitudinal vibration to 22,013 Hz, which resulted in an error rate between the natural frequency (22,013 Hz) and the design frequency (20 kHz) of less than 1%. Simultaneously, the maximum stress of the horn was reduced from 123 Mpa to 81.4 Mpa by optimizing the ultrasonic horn, which increased the safety and service life of the horn.

(3) The influence of different transition arc radiuses on the maximum stress of the optimized ultrasonic horn was analyzed. The results demonstrated that the maximum stress reached the minimum value of 81.40 MPa when the transition arc radius was 9 mm in 12 mode, indicating that the transition arc radius of 9 mm was still suitable for the optimized horn.

(4) To verify the rationality and effectiveness of the novel device, the Al-C wetting experiments were performed under an ultrasonic field. The results indicate that the design of the novel ultrasonic field wetting angle measuring instrument was reasonable and effective, and the ultrasonic field provided by the novel device was conducive to the improvement of the Al-C interface wetting.

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