1. Introduction

Cavitation is the rapid nucleation, oscillation, and final collapse of tiny air bubbles inside a liquid [1,2]. The collapse of cavitation bubbles gives rise to some particular phenomena, such as localized extreme high temperature [3,4] and pressure [5,6], micro-jet with high velocity [7], and shock wave [8,9]. These phenomena have many applications, such as ultrasonic cleaning [10], ultrasonic extraction [11], and sonochemistry [12]. Besides, the collapse of cavitation bubbles could directly break solid surfaces, such as the erosion of hydraulic structures and hydraulic machinery [13-15].

So far, the knowledge of cavitation is rather rudimentary and qualitative, and it is still difficult to modify and control the cavitation process accurately in industrial applications. Therefore, the cavitation bubble characteristic has been widely studied in recent years for potential scientific and industrial values. The cavitation bubble characteristic inside water has been widely studied because water is transparent [16-22].

Some typical cavitation structures, such as Pit cavitation [16], Smoker cavitation [17], Tailing cavitation [18], conical cavitation [19], and other cavitation structures [20-22], have been discovered and studied. The cavitation characteristic inside a thin water layer has been studied by Moussatov et al. [23] and Bai et al. [24-27]. Moussatov et al. [23] reported that an amplification of acoustic pressure is obtained inside a thin liquid layer, and cavitation could be obtained in a broad frequency range at low power intensity due to this amplification effect. Bai et al. [26] found that the cavitation structures inside a thin layer are stable, and cavitation clouds could return to their original shape and remain stable in the face of large perturbations. Bai et al. [27] also reported some particular cavitation structures, such as the Rod-shaped and Y-branch cavitation structures in the thin liquid layer.

The cavitation inside a liquid metal causes microstructure refinement [28], avoids cast defects [29], mixes composite materials [30], and removes the oxide layer on the substrate during ultrasonic soldering/brazing [31,32]. Furthermore, the cavitation characteristic inside a
liquid metal is different from that in water because of the sharp difference in their physical and chemical properties [33]. Therefore, investigating the cavitation characteristic inside liquid metals is important. Some researchers have used synchrotron X-ray radiography to observe the cavitation characteristic inside liquid metals [34-37]. Xu et al. [34] observed the dynamic behavior of cavitation bubbles in molten Al–10 wt % Cu alloy by synchrotron X-ray radiography and reported that the cavitation bubble exhibits a log-normal size distribution with an average radius of 15.3 ± 0.5 μm under an acoustic intensity of 800 W/cm² and a maximum acoustic pressure of 4.5 MPa. Mirihanage et al. [36] used fast synchrotron radiography to investigate cavitation bubble formation during the liquid metal processing of Al–Cu alloy composites and found that Al₂O₃ nanoparticles act as heterogeneous bubble formation nuclei. However, the cavitation bubble morphology obtained by synchrotron X-ray radiography is a superimposed imaging of multiple cavitation bubbles at a certain region and time. This superimposition raises the difficulty level of studying the characteristic of a single bubble. Besides, synchrotron X-ray radiography can only take images at several dozen frames per second [34,37]. We have reported that most of the cavitation bubbles inside a liquid metal could emerge and collapse within several acoustic periods (T) [33]. Therefore, recording the characteristic change of cavitation bubbles with an acoustic period is difficult when using synchrotron X-ray radiography (30 kHz in the work of Xu et al. [34] and 20 kHz in the present work). High-speed photography can record images at very high frames per second, and this promising feature can record the change characteristics of cavitation bubbles within an extremely short time [38-40].

Therefore, the cavitation characteristic inside the thin liquid metal layer was investigated by a high-speed camera in this work. The effect of cavitation is strongly related to the distance between cavitation bubbles and solid surfaces during ultrasonic cleaning, extraction, or soldering/ brazing processes. Erosion damage can be produced on a solid surface only if a cavitation bubble collapses within a distance smaller than 2 or 3 times the diameter of the bubble to the solid surface [41-43]. Therefore, this work observed the cavitation at the substrate/liquid interface. The cavitation variation process, bubble characteristic, and the effects of experimental parameters on the cavitation characteristic were studied. The influence factors on cavitation characteristic, such as the amplitude on the substrate surface and the acoustic pressure inside the liquid, were also discussed.

2. Experimental

The substrates in this work were pure Al and Q235B alloy with dimensions of 90 mm × 40 mm × 3 mm. A transient glass having a 10 mm × 10 mm pool in its center was fixed on the substrate. The schematic of the cavitation-observing system is shown in Fig. 1. The liquid alloy used in this work is an eutectic Ga–In alloy with a ratio of 3:1. The liquid alloy had a melting point of approximately 16 °C. Therefore, we were able to observe the cavitation characteristic at room temperature. The liquid alloy was placed in the glass pool manually by an injector before the experiment. The liquid layer had a thickness of 2–3 mm. A self-made ultrasonic system (UPM-U-P1010A01) with a TC4 sonotrode was used. This system had a frequency of 20 kHz and a max output power of 1000 W. Three output modes, namely, Mode I (1/3 × 1000 W), Mode II (2/3 × 1000 W), and Mode III (1000 W) were used in this work. The sonotrode is made of TC4 alloy and has a diameter of 20 mm. A high-speed camera (Phantom VEO 719L) equipped with a macro lens (Canon MP-E, 65 mm f/2.8 1–5x) was used. The images were taken using acquisition rates of 5000 to 120,000 fps at resolutions of 512 × 512 and 128 × 128 dpi. The exposure times of 50 and 100 μs were used to provide the best combination of large view field, image resolution, and contrast.

3. Results

3.1. Bubble characteristic within 1 T

The bubble characteristics within 1 T at the glass/liquid interface were first studied in Fig. 2 to reveal the bubble formation–collapse process. These images were obtained at an acquisition rate of 120,000 fps. Fig. 2a shows the end of the last T, and few bubbles were observed in the sight. We assumed this moment as t₀. Some tiny bubbles appeared in regions A and B at t₀ + 1/6 T (Fig. 2b). These tiny bubbles grew into larger sizes after t₀ + 2/6 T, and some new bubbles appeared (Fig. 2c). The bubble sizes in region B were larger than those in region A probably because of the stronger acoustic intensity or higher air content in region B. Plenty of cavitation bubbles with different sizes were observed in the sight at t₀ + 3/6 T (Fig. 2d). The bubble characteristic at t₀ + 4/6 T in Fig. 2e shows that most of the bubbles in region A collapsed and disappeared. The bubbles in region B contracted obviously. These phenomena occurred because the sound wave evolved into a positive half wave and the liquid underwent a large positive pressure. Most of the bubbles in region B collapsed and only several bubbles existed and further contracted after another 1/6 T (Fig. 2f). All the cavitation bubbles collapsed and disappeared after 1 T (Fig. 2g). The sound wave entered into another negative half wave, and some new cavitation bubbles appeared (Fig. 2h).

Fig. 2 shows that the bubbles had a very fast growth rate during the negative-pressure period. As shown in Fig. 2b, the newborn bubbles were approximately 50 μm and grew to approximately 300 μm within 1/3 T. Thus, the calculated bubble growth rate was 16.8 m/s. The growth of cavitation bubbles have been well documented by other researchers as well [34,37,44,45]. Ida et al. [44] directly observed cavitation bubbles in liquid mercury under the action of mechanical impacts and calculated the growth of cavitation bubbles as 1 m/s. Huang et al. [37] observed the cavitation bubble characteristic in Al–10 wt% Cu liquid and obtained a bubble growth rate of approximately 7 m/s. The main difference between these systems is that a very small volume of liquid metal is used in our work. So, we deduce that the significantly high acoustic intensity generated in the thin liquid layer was mainly responsible for the high bubble growth rate, which will be discussed in the following section.

3.2. Cavitation characteristic evolution process

Fig. 3 shows the cavitation characteristic evolution process with time. The ultrasonication power was Mode III, and the liquid layer was 3 mm thick. The images were obtained at an acquisition rate of 5000 fps. As shown in Fig. 3a, some tiny cavitation bubbles were observed at the glass/liquid interface at 4 T after ultrasonication started. Then, the cavitation process evolved into a violent cavitation stage, which lasted for approximately 370 T. Numerous cavitation bubbles with different
Fig. 2. Bubble evolution characteristic within 1 T: (a) few bubbles appeared in sight at $t_0$, (b) bubbles emerged at $t_0 + 1/6$ T, (c) bubbles grew at $t_0 + 2/6$ T, (d) bubbles at their maximum sizes at $t_0 + 3/6$ T, (e) large bubbles shrank and tiny bubbles collapsed at $t_0 + 4/6$ T, (f) bubbles collapsed at $t_0 + 5/6$ T, (g) most of the bubbles collapsed after 1 T, and (h) new bubbles appeared at another T.

Fig. 3. Cavitation evolution process with time: (a) 4 T, (b) 12 T, (c) 376 T, (d) 380 T, (e) 9280 T, and (f) 17,316 T.
sizes were observed during the violent cavitation stage, and the bubble densities were higher than 30%. Fig. 3b shows the cavitation characteristic at 12 T when the cavitation bubbles were distributed almost everywhere in the sight. The cavitation intensity began to decrease at 376 T, and only some tiny cavitation bubbles were observed at this moment (Fig. 3c). The bubble density under this condition decreased to 8.8%, which was much lower than those during the violent cavitation stage. The cavitation intensity showed a marked decrease at 380 T (Fig. 3d), and then the cavitation process entered the weak cavitation stage. Large cavitation bubbles were seldom observed during the weak cavitation stage. This occurrence can be attributed to the gas loss after the violent cavitation stage. The cavitation bubbles showed random sizes and distributions with low bubble densities during the weak cavitation stage (Fig. 3e and 3f).

Fig. 3 shows that cavitation intensity decreased with time. The descending of cavitation intensity with time was also observed under other experimental conditions. Fig. 4 shows the duration of violent cavitation stages under different experimental parameters. We observed that the duration of the violent stages ranged from 252 T (obtained at Mode II + 3-mm layer) to 408 T (obtained at Mode III + 3-mm layer) but did not have a specific variation law when changing the experimental parameters. This difference in duration can be attributed to the different gas contents trapped at the liquid/glass interfaces. As introduced in the experimental section, the liquid alloy was manually placed on the glass by an injector, which could result into different gas contents that were trapped at the liquid/glass interface. The gas contents in return affected the duration of the violent stage. Besides, the duration of the violent cavitation stages were all longer than 250 T; thus, the trapped gas at the liquid/glass interface cannot be completely eliminated when manually placing the liquid alloy on the glass.

3.3. Cavitation bubble characteristic at violent cavitation stage

Fig. 3 shows that the cavitation characteristics during the violent and weak cavitation stages were different. Therefore, the cavitation bubble characteristics during the two stages were studied.

Fig. 5 shows the cavitation bubble characteristics within 5 T (250 µs) during the violent cavitation stage. The ultrasonication power was Mode II, and the liquid layer was 3 mm thick. The images were obtained at an acquisition rate of 20,000 fps. Numerous cavitation bubbles were observed at 24 T (Fig. 5a). Several bubbles were larger than 200 µm, but most were tiny cavitation bubbles. Notably, these tiny bubbles did not appear in the previous period. Most of these bubbles grew during the following period and evolved into a small cavitation cloud at 25 T (Fig. 5b). Meanwhile, several large bubbles, which already existed before 24 T, collapsed and disappeared (region A). All the large bubbles (marked by yellow arrows) shown in 24 T disappeared and numerous tiny bubbles appeared after the large ones collapsed at 26 T (Fig. 5c). At the same time, some tiny bubbles and the small cavitation cloud at 25 T evolved into a large cavitation cloud at the center of the sight at 26 T. This cavitation cloud collapsed and changed into numerous tiny cavitation bubbles at 27 T (Fig. 5d). Simultaneously, the tiny cavitation bubbles at the sight’s sides grew into a cavitation cloud again. The cavitation cloud at the sight’s sides collapsed and changed into tiny cavitation bubbles and the tiny cavitation bubbles at the sight center evolved into a cavitation cloud at 28 T (Fig. 5e). The large cavitation cloud at the sight’s center collapsed and disappeared at 29 T (Fig. 5f), and a new cavitation cloud formed by the tiny cavitation bubbles at 28 T was observed at the sight’s upper right region.

Fig. 5 shows that cavitation clouds easily appeared during the violent cavitation stage. Much more gas was trapped at the glass/liquid interface when the liquid alloy was just placed on the glass, compared to the other periods of the cavitation process. The cavitation cloud is in fact a lot of tiny gas bubbles that emerged and collapsed simultaneously at the glass/liquid interface. The results in Fig. 5 show that the cavitation cloud always had a size larger than 1 mm and a life period longer than 1 T.

3.4. Cavitation bubble characteristic at weak cavitation stage

Fig. 6 shows the cavitation characteristics within 5 T during the weak cavitation stage. Some tiny cavitation bubbles were observed at 5680 T (Fig. 6a). A small bubble with a diameter of approximately 50 µm appeared in region A. This bubble grew to 100 µm at 5681 T (Fig. 6b), 150 µm at 5682 T (Fig. 6c), and 200 µm at 5683 T (Fig. 6d). The size of the cavitation bubble began to decrease from 5684 T (Fig. 6e), further shrank at 5685 T (Fig. 6f), and finally disappeared at 5686 T.

No cavitation bubble was observed inside region B at 5680 T (Fig. 6a). Two connected cavitation bubbles appeared at 5681 T (Fig. 6b), and the two bubbles collapsed at 5682 T (Fig. 6c). Another two new bubbles appeared after 1 T (Fig. 6d) and collided again after 1 T (Fig. 5e). Only several tiny bubbles were observed in region C at 5681 T. These bubbles grew into larger sizes and some new small bubbles appeared at 5682 T. Some of these bubbles collapsed and only the large ones remained at 5683 T. The large ones collapsed and disappeared after another 1 T (Fig. 6e).

Fig. 6 shows that no cavitation cloud was observed during the weak cavitation stage, because most of the gases trapped at the glass/liquid interface were pulled out. Most of the tiny bubbles had short life periods, and the large ones had slightly longer life periods because of their higher gas content.

Fig. 7 shows the effect of ultrasonication power on cavitation characteristic. The thickness of the liquid layer was 2 mm. Fig. 7a shows the cavitation characteristic at the ultrasonication power of Mode I. Only some tiny cavitation bubbles appeared in the center of the sight. No cavitation cloud was observed during the entire cavitation process. The cavitation intensity obviously increased when the ultrasonication power was changed to Mode II (Fig. 7b). Numerous cavitation bubbles were distributed randomly in the sight, and several large cavitation bubbles were observed. The cavitation intensity further increased when the ultrasonication power was increased to Mode III (Fig. 7c). Cavitation bubbles were observed almost everywhere of the sight, and several small cavitation clouds with sizes of approximately 1 mm were observed.

3.5. Effect of substrate variant on cavitation characteristic

Fig. 8 shows the cavitation characteristic using the Q235B substrate. The thickness of the liquid layer was 2 mm, and the ultrasonication power was Mode II. This figure was obtained 0.43 s after the ultrasonic vibration started. Numerous cavitation bubbles with different sizes were distributed almost everywhere of the sight. The bubble density was
Fig. 5. Cavitation bubble characteristic within 5 T during the violent cavitation stage: (a) 24 T, (b) 25 T, (c) 26 T, (d) 27 T, (f) 28 T, and (g) 29 T.

Fig. 6. Cavitation bubble characteristic within 5 T during the weak cavitation stage: (a) 5680 T, (b) 5681 T, (c) 5682 T, (d) 5683 T, (f) 5684 T, and (g) 5685 T. Effect of ultrasonication power on cavitation characteristic.
the parameters of substrates that were considered in calculation. Acoustic reflection at the substrate borders is considered during the vibration calculation. During experiment, the glass pool was rigidly embedded in the aluminum substrate, and we assumed the vibration on the glass to be the same as those on the Al substrate. Fig. 9b shows the vibration condition of the substrate, in which different colors represent different vibration intensities. The result of Fig. 9b was a frequency domain solution. We can see that the vibration at the pool bottom is symmetric on the X-axis. The vibration extraction region is shown in Fig. 9b. Under ultrasonication, the vibration was mainly transmitted into the liquid through the lower boundary of the pool. Therefore, we only extracted the vibration at the centerline of the pool for simplicity. Second, the extracted vibration data was applied to the liquid pool and calculated. Vibrations were applied to the bottom surface through user-defined function, as shown in Fig. 9c. The parameters used during calculation are as follows: the surface tension of the GaIn alloy is 0.624 N/m; the density of the GaIn alloy is 6.35 g/cm$^3$; the viscosity of the GaIn alloy is 1.99 × 10$^{-3}$ Pa·s; the contact angle between the GaIn alloy and substrates is 130°; the surface roughness of the substrate is 0.0015 μm. Lastly, the acoustic pressure field of the thin liquid and the acoustic pressures at typical regions were extracted and analyzed by Tecplot 360 2012R1.

Fig. 10 shows the variation process of the acoustic pressure field inside the thin liquid alloy within the 11th T after ultrasonication started. The acoustic pressure inside the thin liquid was positive at the end of the 10th T. The maximum pressure value of 1.49 × 10$^6$ Pa was obtained at the pool’s bottom region (Fig. 10a). The pressure gradually decreased toward the pool’s surface. The acoustic pressure inside the thin liquid evolved into negative values after 0.1 T, and the maximum negative pressure value reached –4.59 × 10$^5$ Pa (Fig. 10b). Cavitation bubbles easily nucleated during this period as shown in Fig. 2b. The acoustic pressure further decreased and the maximum negative pressure value reached –2.58 × 10$^6$ Pa after 0.2 T (Fig. 10c). Thus, the existing cavitation bubbles grew and some new ones nucleated (Fig. 2c). The acoustic pressure began to decrease but remained negative at the end of the positive half wave (Fig. 10d). Therefore, the cavitation bubbles grew larger (Fig. 2d). The acoustic pressure changed into positive values at 530 μs, and the sound wave entered into the negative half wave (Fig. 10e). Some bubbles with extremely small sizes collapsed and the large ones contracted under the positive acoustic pressure (Fig. 2e). The acoustic pressure further increased at 540 μs (Fig. 10f), and some large cavitation bubbles continued to contract or collapse (Fig. 2f). The acoustic pressure remained positive but had smaller values at the end of this acoustic period (Fig. 10g). Most of the cavitation bubbles collapsed and disappeared at this moment. The acoustic pressure evolved into another cycle and resulted into a new bubble emergence—growth—shrink—collapse progress.

The results showed that the morphology changes of cavitation bubbles are fundamentally determined by the acoustic pressure inside the
liquid. Acoustic pressure can be obtained by simulation or experimental measurement [46-50] and has been extensively studied by researchers. Kang et al. [46] simulated ultrasonic streaming in water, aluminum, and steel melts. A negative pressure of $4 \times 10^5$ Pa has been obtained in their work, and they found that the cavitation area is largest in water and smallest in steel melt because of different cavitation thresholds. The relative low acoustic pressure in their work was obtained because the sonotrode was directly submerged into bulk liquid. Tzanakis et al. [47] measured the acoustic pressures of water and liquid aluminum by a calibrated high-temperature cavitometer and reported the maximum pressures of 70 and 60 kPa when the cavitometer was located below the sonotrode and operated at 17 kHz. The acoustic pressure reached a high value of approximately 800 kPa in liquid aluminum when the driving frequency was 1 MHz. Another work of Tzanakis et al. [48] reported that a higher temperature of 720°C resulted into a 10%–15% lower acoustic pressure in the liquid than that obtained at 690°C because of the stronger acoustic shielding by the cavitation zone containing more bubbles and the greater volume occupied by the cavitation zone due to the lower viscosity and density of the melt at 720°C. Niazi et al. [49] simulated the acoustic pressure in water and crude oil and reported that the maximum negative pressure inside crude oil and water reached $2.049 \times 10^7$ and $5.238 \times 10^6$ Pa, respectively, at 20 kHz, 2 kW, and 25°C.

The result in Fig. 10 shows that the acoustic pressure presents alternating positive and negative characteristics. This result combined with that in Fig. 2 showed that cavitation bubbles appear and grow during the negative-pressure stage and shrink and collapse during the positive-pressure stage. Most of the small cavitation bubbles appeared and collapsed within 1 T, and the large ones could have life cycles of several periods. The collapse of cavitation bubbles gives rise to some particular phenomena [3-9]. But all these phenomena are extremely local. The extensive application of cavitation is due to the heavily repeating appearance and collapse of these cavitation bubbles.

The results in Fig. 10 show that the acoustic pressure was uneven from the pool’s bottom to its upper surface. Fig. 2 shows that the

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Table 1

| Material | Modulus of elasticity (GPa) | Density (kg/cm$^3$) | Poisson’s ratio |
|----------|-----------------------------|---------------------|----------------|
| Pure Al  | 68.9                        | 2.7                 | 0.31           |
| Q235B    | 210.0                       | 7.8                 | 0.31           |

---

Fig. 9. Vibration extraction position at the pool’s bottom and pressure extraction point position.
cavitation bubble evolution is closely related to the variation of the acoustic pressure inside the liquid. Thus, acoustic pressure is an effective indicator that predicts the cavitation intensity inside the thin liquid layer. Fig. 11 shows the pressure variation trend from the pool’s bottom to the upper surface at different positions. The acoustic pressure curves were extracted from 2, 4, 6, and 8 mm from the left side of the filler pool (marked in Fig. 9c) and were extracted at the negative pressure stage. The results showed that the absolute maximum pressures were obtained at the pool’s bottom, and these values gradually decreased toward the liquid’s upper surface. Therefore, we predicted that the strongest cavitation was obtained at the bottom of the liquid pool and bubble density gradually decreased toward the liquid surface. Besides, the acoustic pressure showed similar curve morphologies with very slightly different values at different positions of the pool. This result showed that the descending trend of cavitation toward the pool’s surface could be obtained inside the entire liquid pool.

4.2. Effect of ultrasonication power on acoustic pressure

Fig. 7 shows that strong cavitation is obtained when using high ultrasonication power. Cavitation intensity is affected by the vibration intensity on the substrate [33]. A stronger cavitation is obtained when the vibration on the substrate’s surface is stronger. Fig. 12 shows the amplitude curves at the right side of the substrate when different ultrasonication powers were used. The amplitude curves showed sine-like morphologies, and the amplitude of the curve gradually increased toward the right side of the substrate. Larger amplitude values were obtained when higher ultrasonication power was used. We extracted the amplitudes at the pool’s bottom under different conditions. The results showed that the vibration intensity increased and then decreased from the left side to the right side of the pool. The maximum amplitude of 11.8 µm was obtained at the right edge of the pool when using Mode I. The maximum value of the amplitude increased to approximately 15.1 µm at the ultrasonication power of Mode II and further increased to 18.3 µm at Mode III.

Cavitation intensity is determined by the acoustic pressure inside the liquid. The acoustic pressure fields inside the thin liquid were simulated.
using different ultrasonication powers. We extracted the acoustic pressure field at 510 µs (at the negative-pressure stage) after ultrasonication started (Fig. 13a). Fig. 13b shows the acoustic pressure field at 510 µs when the ultrasonication power of Mode I was used. The acoustic pressure inside the entire thin liquid layer was negative at this moment. The maximum pressure value of $1.43 \times 10^6$ Pa was obtained. The negative pressure became larger at higher ultrasonication power. The maximum pressure increases to $1.83 \times 10^6$ and $2.19 \times 10^6$ Pa when the ultrasonication power of Mode II and III were used, respectively. Larger negative acoustic pressures at higher ultrasonication powers correspond to faster bubble emergence and growth rates. Therefore, more cavitation bubbles were observed at the ultrasonication power of Mode III. Fig. 13d shows the acoustic pressures of the point (marked in Fig. 10) when different ultrasonication powers were used. The acoustic pressure curves presented sine-like morphologies with the same period as the input ultrasonic vibration. The maximum acoustic pressure when using Mode I was approximately $2.2 \times 10^6$ Pa. Fig. 7a shows that weak cavitation still occurred under this condition; thus, this low acoustic pressure was still higher than the cavitation threshold. The maximum acoustic pressure increased to approximately $2.8 \times 10^6$ Pa when Mode II was used. Higher acoustic pressure results in stronger cavitation as shown in Fig. 7b. The maximum acoustic pressure of approximately $3.2 \times 10^6$ Pa was obtained at Mode III; thus, the strongest cavitation was obtained under this condition (Fig. 7c).

A region with extremely low vibration intensity was found 3.15 mm from the left side of the liquid pool (Fig. 12). Its amplitude value was only 0.066 µm. Thus, we speculated whether such low vibration intensity could result in low acoustic pressure and low cavitation intensity. We extracted the acoustic pressure variation at this point and compared the result with those at other points inside the pool to verify this speculation. The coordinates of the three points are (0.001, 0.00005), (0.00315, 0.00005) and (0.008, 0.00005), respectively. Fig. 14 shows the acoustic pressure curves at different points inside the liquid. The result showed that the acoustic pressure at different points had similar values and trends. These results indicated that high acoustic pressures can still be obtained at weakly vibrated regions. This finding was confirmed by the uniform bubble distribution shown in Figs. 3 and 5–8. This phenomenon can be explained by the acoustic streaming inside the liquid layer, which is extensively applied in fabricating particle-reinforced composites [30,36,43].

4.3. Effect of substrate variant on acoustic pressure

Fig. 15 shows the amplitudes at the bottom of the liquid pools using different substrates. The vibration curves show similar morphologies, and slightly higher values were observed when using the Q235B substrate. The maximum values were obtained at the right side of the filler pool. The maximum value using the Q235B substrate reached approximately 20 µm, which was much larger than that using the pure Al substrate. The vibration intensity at the pool’s bottom was determined by the elasticity modulus of the substrates. Pure Al has a low elasticity modulus (68.9 GPa) and thus resulted in small amplitudes. By contrast, the elasticity modulus of Q235B was higher (210 GPa) and therefore produced stronger vibrations.

We calculated the acoustic pressure inside the liquid based on the simulation results of the amplitudes shown in Fig. 15, and the results are

![Fig. 12. Amplitudes on the bottom surface of the filler pool at different ultrasonication powers.](image)

![Fig. 13. (a) Schematic of acoustic pressure field simulation period; (b–d) acoustic pressure fields at 510 µs after ultrasonication started using the ultrasonic powers of (b) Mode I, (c) Mode II, and (d) Mode III; (e) acoustic pressures in the liquid within 2 T.](image)
shown in Fig. 16. Fig. 16a shows the acoustic pressure field of the liquid layer at 510 \( \mu \)s after ultrasonication started using the Q235B substrate. Its acoustic pressures were much larger than those using pure Al substrate. The maximum value was 4.97 \( \times 10^6 \) Pa, which was two times higher than that using the pure Al substrate. This high acoustic pressure means that the cavitation bubbles have larger appearance and growth energy; thus, more cavitation bubbles with larger sizes were observed when using the Q235B substrate than using the pure Al substrate.

Moreover, we extracted the acoustic pressure evolution process of a certain point marked in Fig. 9, and the result is shown in Fig. 16b. The result shows that the acoustic pressure inside the thin liquid using the Q235B substrate reached 7.1 \( \times 10^6 \) Pa when the ultrasonication power of Mode II and the 2 mm-thick liquid layer were used. This value was much higher than that obtained when the pure Al substrate was used (2.8 \( \times 10^6 \) Pa).

4.4. Bubble dynamics inside the thin liquid layer

Figs. 13, 14, and 16 illustrate the sine-like variation characteristics of the acoustic pressure in the thin liquid layer. Here, we fitted the extracted acoustic pressure by Origin software, and the result is shown in Fig. 17. The fitted curve shows excellent sinusoidal morphology. The acoustic pressure equation is listed in Equation (1).

\[
P = -9248.5 + (2.78 \times 10^6) \times \sin \left( \frac{2 \pi \times 20,000}{x - (2.91 \times 10^{-3})} \right)
\]

which follows the format:

\[
P = P_0 + P_A \times \sin(2\pi f(x - x_0))
\]

where \( P \) is the transient acoustic pressure, \( P_A \) is the amplitude of the acoustic pressure, \( P_0 \) is the offset of the sinusoidal curve, \( f \) is the frequency, and \( x_0 \) is the initial phase. The result shows that the variation frequency of acoustic pressure inside the thin liquid is consistent with that of ultrasonic wave under ultrasonication and the sinusoidal acoustic pressure curve is negatively offset.

In this work, we used the modified Rayleigh–Plesset (R–P) equation to investigate the bubble dynamics [53,54]:

\[
R \left( \frac{d^2 R}{dt^2} + \frac{3}{2} \left( \frac{dR}{dt} \right)^2 \right) = \frac{1}{\rho} \left[ \left( P_0 + 2\sigma R_0 \right) \left( \frac{R_0^3}{R} \right)^n - P_A - P_0 - \frac{2\sigma}{\rho R} - \frac{R}{\rho c} \frac{dP_0}{dt} + \frac{R}{\rho c} \frac{dP}{dt} \right]
\]

where \( \sigma \) is the surface tension of a cavitation bubble; \( \mu \) is the viscosity coefficient of the liquid, which is assumed to be 0.0013; and \( n \) is the exponent reflecting the thermodynamic state of the bubble variation. Here, we suppose the bubble pulsation process to be isothermal; thus, \( n = 1 \).

We substituted the sound pressure (\( P_A \)) calculated in Equation (1) into Equation (3) to calculate the bubble dynamics inside the thin liquid layer. The growth speed of a cavitation bubble can be obtained by differentiating Equation (3). Fig. 18 shows the bubble growth speed within 1 T. The nucleation radius was assumed to be 25 \( \mu \)m, which is
similar to that observed in Fig. 2. The bubble grew rapidly after nucleation, and the maximum growth speed reached 16.63 m/s. This result corresponded well with the bubble growth speed of 16.8 m/s calculated in Fig. 2 and proved the accuracy of our calculation.

4.5. Cavitation evolution process with time

Based on the cavitation characteristics discussed above, the cavitation evolution process of the thin liquid Ga–In alloy in this work is summarized in Fig. 19. Fig. 19a shows the original state of the system before ultrasonic vibration was turned on. Some gas bubbles were trapped at the glass/liquid interface and inside the liquid after the Ga–In alloy was placed into the pool. A violent cavitation stage began after the ultrasonic vibration started (Fig. 19b). In fact, this violent stage is a degassing stage [51,52] that exhaust the gas trapped at the glass/liquid interface. During this stage, the tiny gas bubbles in Fig. 19a can absorb the gas nearby, rapidly grow, and then collapse [33]. Thus, numerous large cavitation bubbles and even some cavitation clouds were observed during this stage. The violent cavitation stage lasted only several hundreds of acoustic periods because of the finite trapped gas content. Afterward, the cavitation process showed an obvious decrease (Fig. 19c). The cavitation bubbles were smaller compared with those in the violent cavitation stage because of the low gas content trapped into the liquid. After most of the trapped gases were excluded, the cavitation process evolves into a weak cavitation stage. The cavitation intensity was rather low and fewer cavitation bubbles were observed during this stage (Fig. 19d).

From the discussions in this work, we found that the cavitation bubbles inside a thin liquid are more uniform in size and distribution compared with those in bulk liquid [19-21]. This result can be attributed to the high acoustic pressure values and even acoustic pressure distribution inside the thin liquid. Therefore, reducing the volume of the cavitation liquid can increase cavitation intensity. This finding can be helpful in improving the efficiency of ultrasonic extraction, catalysis, and ultrasonic soldering [31]. Besides, we observed from the cavitation observation experiment that the lifetime of the cavitation bubbles inside the thin liquid is short, and most of the cavitation bubbles have life cycles shorter than several acoustic periods. This life cycle is different from those observed in aqueous solutions and results from the physical and chemical properties of the liquid.

5. Conclusions

1. The entire cavitation process is divided into violent and weak cavitation stages. The violent cavitation stage, with bubble densities higher than 30%, occurred within several hundreds of acoustic periods after ultrasonication started. The weak cavitation stage, with bubble densities lower than 10%, occurred after the violent cavitation stage.

2. Tiny cavitation bubble and cavitation clouds were observed during cavitation. A large cavitation bubble can grow to several hundreds of micrometers before collapsing and has a life of several acoustic periods. Tiny cavitation bubbles were observed during the entire cavitation process, and these bubbles always nucleate and collapse within 1 T. The cavitation cloud can only be observed during the violent cavitation stage and has a life cycle of several acoustic periods.

3. Acoustic pressure presents alternating positive and negative characteristics in 1 T. The cavitation bubbles nucleate and grow during the negative-pressure stage and shrink and collapse during the positive-pressure stage.

4. The cavitation bubble has a high growth speed of 16.8 m/s, such result is evidenced by the bubble dynamics calculation based on the R–P equation.

5. Larger amplitude values were obtained when higher ultrasonication power was used. The maximum amplitude of 11.8 µm is obtained when using Mode I, which increases to 18.3 µm at Mode III. Higher amplitude results into higher acoustic pressure inside the liquid layer and leads to stronger cavitation.

6. The Q235B substrate has higher vibration intensities on its surface because of its higher elasticity modulus. Thus, higher acoustic...
pressure and higher cavitation intensity were obtained using this substrate than pure Al.

CRediT authorship contribution statement

Zhengwei Li: Writing - original draft, Software. Zhiwu Xu: Conceptualization, Methodology, Writing - review & editing. Degang Zhao: Software. Shu Chen: Software. Jiuchun Yan: Investigation, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Fig. 19. Schematic of the cavitation process: (a) original state, (b) degassing at the liquid/glass interface, (c) degassing of the gas trapped in the liquid, (d) weak cavitation stage.
