3P4-3

Mechanism of liquid Ga/In dispersion by ultrasonic cavitation

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1. Introduction

The miniaturization of electronic devices has been rapidly advancing, and as part of this trend, microscale metal particles with diameters of around 20 µm are widely used in the assembly of electronic circuits. It is predicted that with the development of electronic devices, the demand for microscale metal particles smaller than 20 µm and nanoscale metal particles will increase[1)].

Presently, various methods, such as chemical reactions and mechanical metal grinding, are used to generate metal particles. However, these methods have disadvantages including environmental impact and non-uniform particle size. Therefore, ultrasonic cavitation has attracted increasing attention as a new method for generating metal particles[2)]. However, the detailed mechanism of particle generation by this method remains unclear.

In this study, we recorded the dispersion of liquid Ga/In under ultrasonic irradiation using a high-speed video camera. We then investigated the mechanism of metal particle formation.

2. Materials and methods

Ga/In, an alloy of Ga (99.99%) and In (99.999%), was used to synthesize the sample. Ga and In were mixed in a weight ratio of 75.5:24.5 and heated to 200°C using a hot stirrer. The melting point of Ga/In is 15.7°C, which is lower than room temperature, making it liquid under the experimental conditions.

Fig. 1 shows a schematic of the experimental setup. A direct irradiation transducer was connected to the ultrasonic driving device (QUAVA-mini, Kaijo Corporation), and a glass cell (optical path length, 10 mm) was placed on top of the transducer. The frequencies used were 26 and 200 kHz, with an applied power of 50 W. A cooling fan was continuously operated to prevent the temperature of the transducer from rising. For visualization, a high-speed video camera (Hyper Vision HPV-X2, SHIMADZU) was used with LED light (WITSTRO AD360, GODOX) illumination. The frame rate was 10 to 100 kfps and the resolution was 250 × 400 pixels. Exposure time was 2 to 10 µs and the F value was 5.

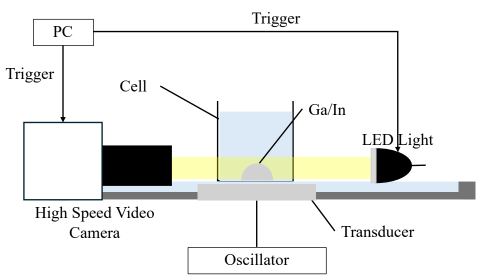

Fig. 1 Experimental apparatus for sonication.

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3. Results and discussion

The three liquid metal dispersion processes induced by ultrasound that were observed in this experiment are described in this section.

3.1 Microjets from cavitation in water

Fig. 2 shows snapshots of the dispersion caused by bubbles in the water surrounding the liquid Ga/In during ultrasonic irradiation (frequency: 26 kHz; frame rate: 10 kfps; exposure time: 7 µs; field of view: 0.17 × 0.27 mm). The gray areas correspond to water, and the black areas correspond to liquid Ga/In. Fig. 2(a) shows an ultrasonic cavitation bubble expanding (red circle), and Fig. 2(b) shows the generation of a microjet (arrow). Fig. 2(c) and (d) show fine particles generated from the surface of liquid Ga/In (blue circles). These observations confirm that the dispersion is caused by bubbles in the solution around liquid Ga/In.

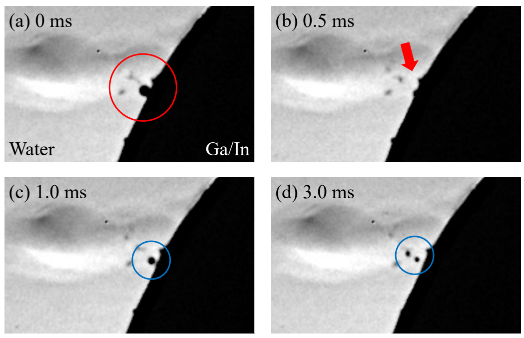

Fig. 2 High-speed camera pictures of dispersion by microjet generation at (a) 0, (b) 0.5, (c) 1.0, and (d) 3 ms during ultrasonic irradiation. Red circle: ultrasonic cavitation bubble; red arrow: microjet generation; blue circles: fine particles.

3.2 Capillary waves

Fig. 3 shows snapshots of the dispersion caused by the generation of capillary waves on the surface of liquid Ga/In during ultrasonic irradiation (frequency: 200 kHz; frame rate: 50 kfps; exposure time: 5 µs; field of view: 0.33 × 0.53 mm). The gray areas correspond to air, and the black areas correspond to liquid Ga/In. In Fig. 3(a), capillary waves are generated at the gas–liquid interface of the liquid Ga/In (red circle). In Fig. 3(b), the amplitude of the capillary waves exceeds the critical value of surface tension, breaking the wave crest (arrow). Fig. 3(c) and (d) show the droplet generation (blue circles).

The relationship between the wavelength of the capillary waves and the size of the generated particles was investigated. The following equation was used to examine the relationship between wavelength and particle size.[3)]

$$D = 2d = x\lambda = x\left(\frac{8\pi\sigma}{\rho f^2}\right)^{1/3} \qquad (1)$$

Here, D [m] is the particle diameter, d [m] is the particle radius, λ [m] is the wavelength, σ [mN/m] is the surface tension, ρ [kg/m³] is the density, f [Hz] is the frequency, and x [m] is the proportionality coefficient. The proportionality coefficient was set to 0.34 based on empirical rules from previous experiments.[5)] The particle sizes were measured by analyzing the snapshots obtained in Fig. 3, using ImageJ. The theoretical value was D = 27.5 µm, and the measured values ranged from D = 20 to 40 µm. This confirmed that the theoretical values and the measurement results were generally consistent.

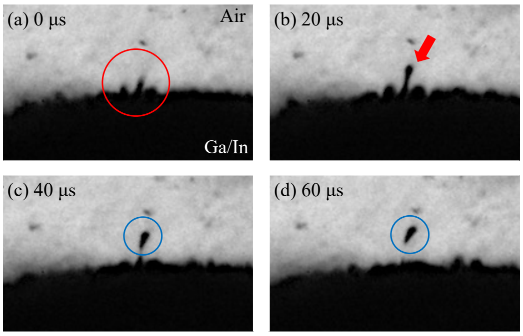

Fig. 3 High-speed camera pictures of dispersion by capillary wave generation at (a) 0, (b) 20, (c) 40, and (d) 60 µs. Red circle: capillary wave generation; red arrow: wave crest breaking; blue circles: droplet generation.

3.3 Ejection of microparticles from cavitation inside the liquid metal

Fig. 4 shows snapshots of the ejection of microparticles from within liquid Ga/In (red circle) during ultrasonic irradiation (frequency: 200 kHz; frame rate: 10 kfps; exposure time: 10 µs; field of view: 1.44 × 2.32 mm). The gray areas correspond to water, and the black areas correspond to liquid Ga/In.

Previous studies have shown that ultrasonic cavitation bubbles can exist inside liquid metals.[4)] In this experiment, a thin cell with an optical path length of 1 mm was used to capture images inside the liquid Ga/In. Fig. 5 (frequency: 200 kHz; frame rate: 166 kfps; exposure time: 5 µs; field of view: 2.54 × 4.07 mm) shows the cavitation observed inside the liquid Ga/In (red circle), which is consistent with the findings of Li et al.[5)]

Based on these results, we discuss the phenomenon observed in Fig. 4. Cavitation is induced inside the liquid Ga/In, and when these bubbles collapse, localized pressure is applied to the surface of the liquid Ga/In. As a result, the surface of the liquid Ga/In is breached, leading to the ejection of microparticles. This observation suggests that cavitation inside liquid metals is a factor that contributes to microparticle generation.

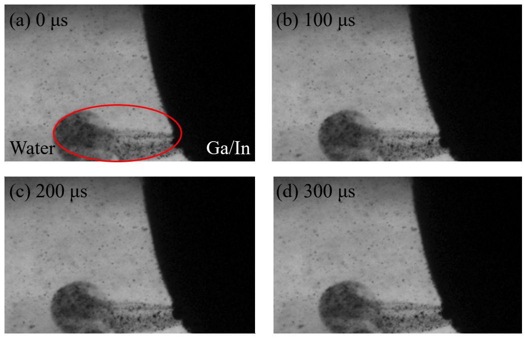

Fig. 4 High-speed camera of particulate jet from liquid Ga/In at (a) 0, (b) 100, (c) 200, and (d) 300 µs. Red circle: particulate jet.

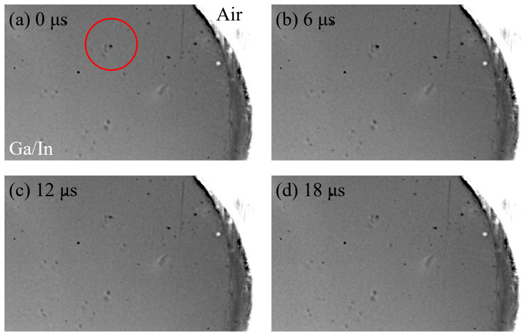

Fig. 5 High-speed camera pictures of the inside of the liquid Ga/In at (a) 0, (b) 6, (c) 12, and (d) 18 µs. Red circle: cavitation.

4. Conclusion

In this study, the dispersion mechanism of liquid Ga/In was investigated. The findings suggest that dispersion of the liquid Ga/In is influenced by microjets from cavitation in the water surrounding the liquid Ga/In, capillary waves on the metal surface, and ejection caused by cavitation within the liquid metal.

References

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