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Liquid metal spring: oscillating coalescence and ejection of contacting liquid metal droplets

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Abstract With pretty high surface tension, the room temperature liquid metal may inherit with unexpected behaviors that conventional fluids could not own. Here, we disclosed the coalescence and ejection phenomena of liquid metal droplets via high-speed camera. It was experimentally found that, when gently contacting (rather than colliding) two metal droplets with identical size together in NaOH solution, oscillating coalescence would happen which runs just like a spring after the interface ruptures and forms capillary waves. For two metal droplets with evidently different diameters, the coalescence induces rather unusual ejection phenomena. The large droplet would swallow part of the small one and then eject another much smaller droplet. Such phenomenon provides a direct evidence for the existence of electrical double layer on metal droplets. The dynamics fluid impacting behaviors were quantified through processing images from the recorded movies, and the basic differences between the liquid metal droplets and that of water droplets were clarified. Theoretical mechanisms related to the events were preliminarily interpreted. The present finding refreshes the basic understanding of the liquid metal droplets, which also suggests potential values of applying such fundamental effects to characterize viscosity, surface tension, electrical double layer of the metal fluids and droplet formations.

Keywords Liquid metal spring · Oscillating coalescence · Droplet ejection · Electrical double layer · High-speed image experiment

1 Introduction

As a quickly developing material, liquid metal has aroused tremendous attentions in recent years. With the combination of many benefits from both liquid and metal, such as high conductivity, excellent fluidity and low melting point, liquid metal offers rather superior and unique substitutes for various applications like micro-device [1], micro-fluidics [2], chip cooling [3], printed electronics [4], shape transformable material [5] and more. Despite the increasingly disclosed properties of this material, there still remained a lot of scientific issues waiting for clarification. From the fluidic aspect, it is the high surface tension of the liquid metal that distinguishes it from many conventional liquids like water. Among various important behaviors, droplet coalescence of liquid metal droplet was just one of such cases especially worthy of investigation. Early works regarding droplet coalescence were mainly focused on the formation of cloud [6], spray of fuel [7, 8] and emulsion process [9], etc. Several specific outcomes of water or polymer droplets coalescence have also been revealed both experimentally and numerically. However, few efforts had ever been made on liquid metal droplet coalescence which turns out rather different from the existing fluids. Here, we disclosed a series of dynamic oscillation and ejection phenomena of liquid metal droplets through high-speed

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camera. Two identical liquid metal droplets were placed in NaOH solution next to each other. It was observed that coalescence happens between the two droplets along with the oscillation which runs just like a liquid spring. Besides, we also found another unusual ejection phenomenon during coalescence of two droplets with very different sizes. That is, when gently contacting (rather than colliding) the comparatively large droplet with the smaller one, the coalescence would produce and eject a much smaller droplet. Such fundamental effect may be useful to quantify a variety of important physical properties of the liquid metal such as surface tension, viscosity, and particle fabrication.

2 Materials and methods

In the present experiment, we adopted the liquid metal GaIn10 (weight percentage, Ga 90 %, In 10 %) as the droplet material. Identical liquid metal droplets were formed using the syringe pump (LSP01-2A). The droplets were squeezed into the NaOH solution (5 g/L) in case of oxidization. The high-speed camera (IDT NR4-S3) was applied to record the dynamic coalescence images of two droplets with the frequency of 6,000 frames/s. Two background spotlights (Fiber Optic Illuminator System) were administrated from the left- and right-hand side to guarantee the perspective was bright enough.

3 Results and discussion

3.1 Coalescence of two contacting droplets with identical sizes

Through processing the movie data (more details can be found in Movie 1 of the Electronic Supplementary Material), we obtained a series of representative images as shown in Fig. 1, where the diameters of the two droplets were measured about 1.63 mm. As can be seen, there is a thin film of liquid on the surface of the droplets. This might be the continuous interface between the liquid metal and the solution. Actually, when placing the two droplets next to each other, coalescence happened after several seconds rather than immediately. This can be explained by the drainage of the continuous film between the two droplets [10]. When the distance between the two droplets approximated the atom size, the film ruptured and coalescence commenced rapidly with the growth of the liquid bridge between the two droplets. The two droplets became a unity with the connection of the liquid bridge. Despite the growing of the liquid metal bridge, the rest part of the metal droplets stayed still, which looked like a dumbbell ($T = 0.83$ ms). This oscillation keeps running for many periods ($T = 5.00$ ms and subsequent images).

In order to quantify the oscillation development, we quantitatively processed the images and obtained the dynamic length of the combined components in both X and Y direction (Fig. 1). The calculated data are shown in Fig. 2. For comparative purpose, we have performed a series of coalescence experiments with varied droplet sizes. Figure 2 is typical oscillating curves for three kinds of identical contacting droplets with different diameters in each case, respectively.

As it was revealed, the oscillation curve resembled the damping vibration. The amplitude in both directions appears gradually decayed. The reason lies in that the energy dissipates into the surrounding solution that the oscillation becomes weakened. But there are also several exceptions on the curve. The first is that some fluctuations occur. This is because the total volume of the droplet is constant. When the capillary waves propagate to X direction, the length in Y direction changes in order to maintain the volume constant. When the capillary waves travel along the Y direction, the wave superimposition becomes the main factor. The second is that the amplitude in X direction fluctuates, which first drops and then rises. It seems that the amplitude in the X direction also resembles the damping vibration. But the amplitude in the Y direction decays steadily. The third is that the period of the vibration changes with time. This might be caused by the reason that the droplets are placed on the floor. When the capillary waves propagate, the floor friction may restrict the oscillation.

Further, we can see that the oscillation period decreases with the decreasing droplet diameter. Generally, the free oscillation period is associated with the droplet diameter d, density ρ, and surface tension σ, which can be written as [11]: $T = \frac{\pi}{4}\sqrt{\frac{\rho d^3}{\sigma}}$. The density and surface tension of GaIn10 are about 6,280 kg/m^3 and 0.624 N/m [12], respectively. In the present experiment, the droplet was oscillating in the outer fluid on the floor; thus, the period appears a little bit different from the theoretical prediction. The droplets with the diameter of 1.63 mm as an example were taken. The period calculated from the above equation is 5.19 ms, which is smaller than the experimental data (about 9 ms in average). This difference may be induced by the surrounding fluid viscous dissipation, which slows down the oscillation of liquid metal droplets. It is noteworthy that obtaining a relationship between the period and the surrounding fluid viscosity is rather important for viscosity estimation [13]. In principle, the curve fitting method can possibly be applied for such measurement purpose.

The whole oscillation process demonstrated the propagation of capillary waves, as illustrated in Fig. 3. The