STABILITY OF LIQUID METAL DROPS AFFECTED BY HIGH-FREQUENCY MAGNETIC FIELDS

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Summary The dynamic behavior of sessile liquid metal drops submitted to a high-frequency magnetic field is investigated experimentally. The drops are of Galinstan and placed on a curved glass plate. A ring-like inductor fed by an alternating electrical current generates the magnetic field. The free surface contour of the drop is observed using a high-speed camera system. In the experiment we vary the inductor current and the drop volume while the frequency is fixed. Upon increasing the inductor current static axisymmetric squeezing ($0 \leq I < I_C$) and following azimuthal waves ($I \geq I_C$) were observed.

INTRODUCTION

Alternating electromagnetic fields can induce Lorentz forces within electrically conducting liquids. Due to the so-called skin effect, at high frequency the Lorentz forces are acting only in a thin layer adjacent to the free surface of the liquid metal. They correspond to magnetic pressure that influences directly the shape and the stability of the surface [1], [2]. Within this context we study experimentally the effects of a high-frequency magnetic field acting on liquid metal drops. The motivation of this work comes from electron beam evaporation where it is favorable to form a liquid metal dome supported by electromagnetic forces only. In this case one may avoid intense contact between the aggressive hot melt with the crucible side walls. Hence, contamination of the melt as well as heat losses are reduced.

EXPERIMENTAL SET-UP

Figure 1 shows a principle sketch of the experimental set-up. It consists of a cylindrical container with an inner diameter of D = 60 mm. A curved glass plate forms the bottom. A slight radius of curvature of $r_c = 80$ mm is chosen to provide axisymmetric conditions. In the experiments, we place a certain volume of liquid metal on the glass plate. As a test liquid we use a GaInSn alloy of such a composition that its melting point is as low as -19°C (Galinstan). To provide quasi-isothermal conditions, the bottom of the glass plate is water-cooled. During the experiments we cover the drop with hydrochloric acid to avoid oxidation of the free surface.
The electromagnetic field is generated by an inductor arranged at the same height as the drop. This inductor is made of rectangular copper tubes and consists of 10 windings arranged in two layers with an inner radius of r = 48 mm. The inductor is fed by an alternating electrical current of a constant frequency f = 20 kHz.
In the experiments we observe the drop shape from above via a high-speed camera system at a rate of 307.7 frames per second while increasing the feeding current up to 350 A. The drop volume is varied within the range 0.3 ml < V < 11 ml.

RESULTS

Static deformation Upon increasing the inductor current from I = 0 A, we observe a squeezing of the drop due to the induced magnetic pressure acting on its surface. This squeezing effect is characterized by decrease of the drop radius R combined with a mounting-up of the drop in the center. For drop sizes within the range 0.6 ml < V < 11 ml a static squeezing of typically $R/R_0 \approx 0.85$ is possible where R_0 denote the drop radius when the magnetic field is absent. For smaller drops of the size V = 0.3 the squeezing effect is more pronounced as we get $R/R_0 = 0.75$.

Instabilities Upon a further increase of the inductor current to a critical value I_c, the static drop shape become unstable. Depending on drop size, we observe the excitation of axisymmetric waves with azimuthal mode numbers m = 2, 3 and 4. The dependence of I_c on the drop volume is shown in ***Figure 2***. Typically, upon increasing the drop volume, the corresponding critical current decreases while the mode number increases. The stability diagram, i.e. Fig. 2, shows the three parabolas referring to m = 2, 3 and 4, respectively.
For the unstable condition, the drop is oscillating. The measured oscillation frequencies f_m as a function of the drop volume are shown in ***Figure 3.*** The experimental findings are compared to the natural eigenfrequencies defined by [3]

$$f_m = \frac{1}{2\pi}\left(\frac{\sigma m\left(m^2-1\right)}{\rho R^3}\right)^{1/2},$$

where σ and ρ denote the surface tension and the density of the material, respectively, and R is an average value of the radius of the drop in the magnetic field. As obvious from Fig. 3, for each mode number the oscillation frequency decreases with increasing drop volume. The experimental results are in excellent agreement with the prediction of the above equation.

CONCLUSIONS

We have investigated experimentally the effects of a high-frequency magnetic field on (i) the static shape of a liquid metal drop and (ii) the stability of the drop shape. The experiments show that below a certain threshold value of the feeding inductor current, I_c, a static squeezing of the drop is possible. This corresponds to the forming of a stable liquid metal dome in application. However, when $I > I_c$, the drops starts to oscillate with an azimuthal mode number depending on drop volume. The critical inductor current as well as the oscillation frequency decrease with increasing drop volume. The measured oscillation frequencies correspond well with the natural eigenfrequencies of drops based on surface tension.

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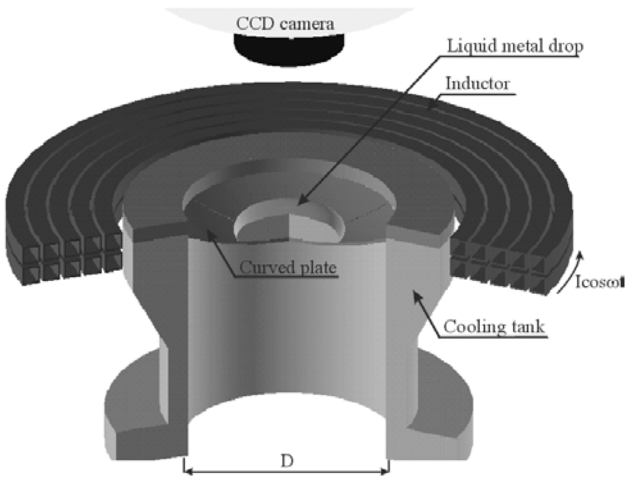

FIG. 1. Sketch of the experimental set-up.

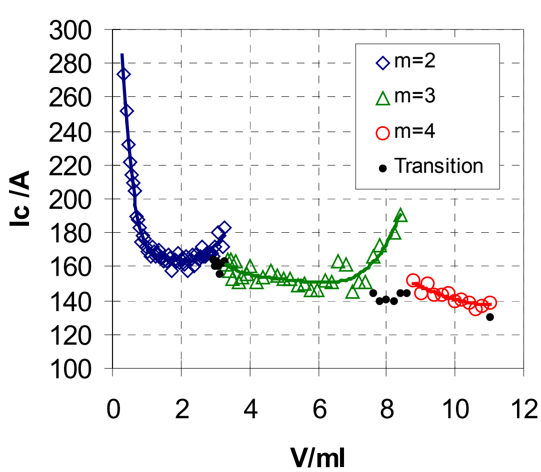

FIG. 2. Stability diagram of a puddle of GaInSn by 20kHz. Critical current for instability.

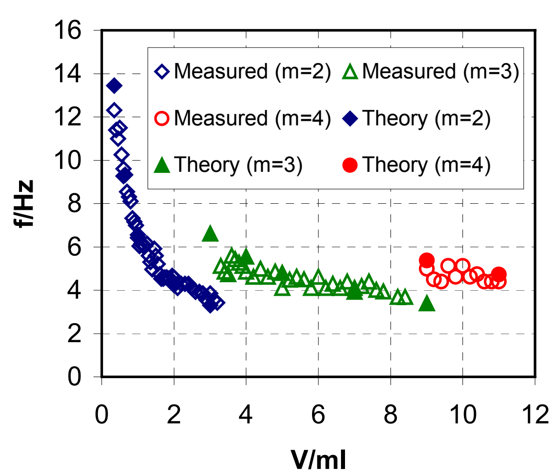

FIG. 3. Comparison between theory and measurement of the drop oscillation frequency.