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EFFECT OF SUPERIMPOSED DC MAGNETIC FIELD ON AN AC INDUCTION SEMI-LEVITATED MOLTEN COPPER DROPLET

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While a piece of copper on a ceramic substrate was inductively melted by a 9 to 18 kHz AC magnetic field with an axial magnetic DC field superimposed, the liquid metal stably semi-levitated in the expected "conical" free surface shape. The diameter of the liquid metal at the base was 30 mm, the volume more than 20 cm^3. Replacing the ceramic substrate with a non-wetted glassy carbon crucible causes instability of the semi-levitated copper droplet. In the absence of the DC field severe chaotic instabilities of the liquid metal shape occurred, causing splashes and uncontrolled contact with the crucible walls. When an axial DC magnetic field with induction 0.35 T was superimposed, the liquid metal droplet exhibited a harmonic azimuthal wave deformation of the free surface. Higher frequencies lead to smaller characteristic wavelength. The transverse DC magnetic field direction suppressed the travelling wave deformations of the droplet shape. The stabilizing effect of the DC magnetic field during induction melting has been shown for axial and transverse directions of the DC magnetic field. These results experimentally demonstrate the possibilities to improve the stability of levitated metal volumes by a superimposed DC magnetic field.

Introduction. High frequency magnetic field induction melting of metals is a well-known technique in crystal growth and advanced metallurgy. The alternating magnetic field can be used not only to heat or melt the metal, but also to shape the liquid metal surface. One of its most known applications is electromagnetic levitation and semi-levitation [1–3]. In this field, there are many researches on the stability problems of the levitating liquid [3, 4]. An overview of the technologies was given by Mühlbauer [5]. One of the techniques is the cold crucible semi-levitation induction melting, while liquid metal is supported by a water-cooled base from below [6]. Semi-levitation is easily to maintain because in this case the pinch effect can be avoided, which is the main problem in full levitation due to zero electromagnetic force on the axis of the inductor [7]. Instabilities usually lead to waves on the levitating or semi-levitated liquid metal surface, which in some cases may lead to destruction of the droplet [8].

Static magnetic fields are used to damp unwanted liquid metal flows [9]. Static magnetic fields also produce a significant influence on instabilities in liquid metals [10]. The behaviour of a liquid metal droplet in a static magnetic field has been analyzed by Gailitis [11] and Priede [12]. It is concluded that the magnetic field stabilizes the droplet and the effective viscosity of the liquid metal is increased. There are quite scarce experimental studies of this phenomenon because of technical problems to apply a DC magnetic field around the liquid metal containing a high frequency (HF) inductor [13].

We have overcome this problem by creating a water cooled permanent magnet system around the inductor to achieve combined AC and DC magnetic fields. In this paper, we report some curious observations of high melting point liquid metal

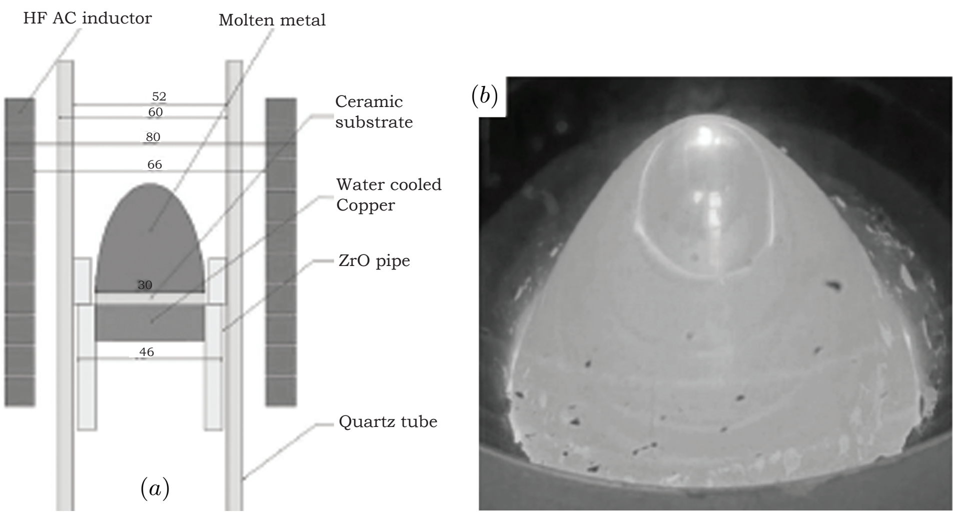

Fig. 1. (a) Schematic of the setup; (b) semi-levitated copper in the axial 10 kHz AC field and DC field.

electromagnetic processing using HF AC semi-levitation with a superimposed DC magnetic field.

1. Experiment and theory. A schematic cross-section of the initial experimental setup and the stably semi-levitated pure liquid copper region are shown in Fig. 1a. The AC field frequency range was from 9 to 18 kHz, the maximum induction amplitude up to 0.09 T. An induction melted copper droplet is shown in Fig. 1b. The DC magnetic field with a maximum induction of 0.35 T was delivered by a permanent magnet assembly, permitting to apply a quite uniform field over the sample region in the direction range from axial to horizontal. Under the impact of the axial DC field the semi-levitated liquid copper free surface was very stable up to the overheat level when the boiling of the copper in vacuum happened at approximately 1650°C. The magnitude of the DC field was not sufficient to considerably damp the flow in the liquid metal, but was sufficient to alter turbulence in the semi-levitated liquid metal.

$$\Omega = \sigma\omega\mu_0 R^2 \gg 1, \tag{1}$$

where σ is the conductivity of the liquid metal, ω is the angular frequency of the AC field, R is the radius of the droplet, μ_0 is the magnetic constant. In the absence of the DC field and sufficiently high dimensionless frequency Ω given by Eq. (1), the magnitude of the flow velocity U_0 may be estimated from the balance of the electromagnetic forcing in the skin-layer and the inertia force, and from the balance of magnetic and hydrostatic pressure on the surface of the melt, as given by

$$\begin{gathered}\delta = \sqrt{\frac{1}{\sigma\omega\mu_0}}, \quad \frac{B^2}{\mu_0} = \varrho g H, \\ \rho = \frac{U_0^2}{\delta} = \sigma\omega\delta B^2, \quad U_0 = B\sqrt{\frac{1}{\rho\mu_0}},\end{gathered} \tag{2}$$

where ρ is the density of the liquid metal, B is the induction of the AC field at the bottom rim of the semi-levitated region, δ is the skin-depth, H is the height of the semi-levitated region, g is the free fall acceleration. The skin depth in the liquid copper is 0.9 mm for 9 kHz and 0.6 mm for 18 kHz. This approximation gives a characteristic velocity of 80 cm/s and $H = 7$ cm. From Eq. (1) it follows that the dimensionless frequency magnitude is $\Omega = 160$ in the liquid copper under the 18 kHz AC field. When the DC field is superimposed, the flow in the core region inside the skin-depth would be damped to U, if the MHD interaction parameter $N \gg 1$:

$$U = \frac{U_0}{N}, \quad N = \frac{\sigma}{\rho}\frac{B_{\mathrm{D}}^2 R}{U_0} = \frac{\sigma}{\rho}\frac{B_{\mathrm{D}}^2 R}{\rho\sqrt{gH}}, \tag{3}$$

where B_{D} is the induction of the DC magnetic field. Using the liquid copper properties, we get $N \approx 2$ at maximum AC and DC field inductions. Obviously, the direction of the DC field is important, how the flow and turbulence is damped. What type of conducting fluid flow would be damped? The flow interacting with the DC field should induce the electrical current circulation; otherwise, there would not be any damping impact. Applying a curl operation on the Ohms law delivers a necessary condition for the electrical current circulation, assuming zero divergence of magnetic field and velocity:

$$\nabla \times \frac{\mathbf{j}}{\sigma} = (\mathbf{B}_{\mathrm{D}}\nabla)\,\mathbf{U} - (\mathbf{U}\nabla)\,\mathbf{B}_{\mathrm{D}} \vee \nabla \times \frac{\mathbf{j}}{\sigma} = \mathbf{B}_{\mathrm{D}}\frac{\partial \mathbf{U}}{\partial l_B} - \mathbf{U}\frac{\partial \mathbf{B}_{\mathrm{D}}}{\partial l_U}. \tag{4}$$

Eq. (4) may be interpreted in a way that the motion of a conductor in the magnetic field produces an electric current only if the magnetic field varies along the direction of the velocity and/or if there is a variation of the velocity along the direction of the magnetic field. Or, if the DC field is uniform, there is no induced current if the velocity of the melt does not vary in the direction of the field and there is no interaction with the flow.

2. Results and discussion. An unexpected situation happened when the ceramics support was replaced by a glassy carbon. During the impact by the superimposed axial AC and DC fields, a highly-organized azimuthal wave pattern of the molten copper droplet shape was observed. If the melt has zero velocity at the interface with the substrate, nothing like the observed situation should ever happen! The only obvious experimental observation was that above the temperature 1200°C the glassy carbon was not wetted by the copper melt. It was obvious that the phenomenon resembles the well-known behaviour of fully levitated liquid droplets [11, 12]. In the described experiment, there was no full levitation; the droplet was supported by the glassy carbon crucible. A similar behaviour is known: the historical priority, being an unstable droplet of water on a well heated substrate due to the Leidenfrost effect, when similar azimuthal waves were also observed. Experimental observations of such type of instability has been reported [10], but the former cases demonstrate a substantial difference from the described one – during the cited experiments, there was a layer of an encapsulating, substrate wetting, non-conducting fluid between the oscillating fluid and the substrate. In our case, the vacuum surrounding pressure eliminates any vapour cushion beneath the semi-levitated molten metal. The only questionable suspect regarding the fluid interface may be the copper oxide, which becomes liquid at a temperature above 1200°C. But, on the other hand, the copper oxide decomposes in vacuum at a temperature above 1200°C. It was obvious that no-slip boundary condition on the bottom was not valid.

The axial DC magnetic field did not suppress any waves with fluid motion not varying in the field direction, but the flow became highly ordered, with a 6-mode azimuthal wave travelling anticlockwise, as shown in Fig. 2*a* and Fig. 3*a*. The

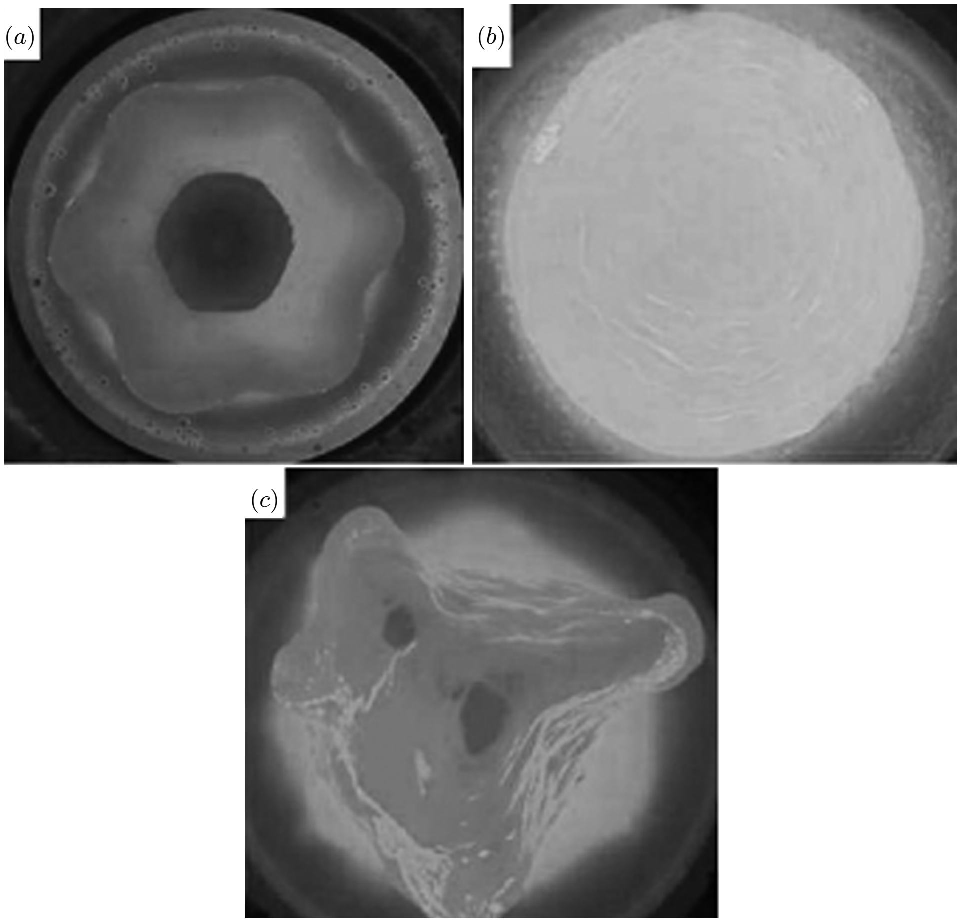

Fig. 2. The semi-levitated liquid copper droplet on the glassy carbon surface under the 18 kHz AC field: (*a*) with the axial 0.5 T DC field; (*b*) with the transverse 0.5 T DC field; (*c*) without the DC field.

axial DC field damped most of the azimuthal flow produced turbulence due to the AC field induced flow in the core of the melt region, which has a pronounced variation along the axial magnetic field, but did not suppress the wavy motion, which has no variation along the DC field.

The transverse DC magnetic field eliminated the azimuthal wave motion, but did not suppress the flow in the core of the droplet as efficiently as in the axial direction. The free surface deformations of the droplet were quite chaotic and fast. The general shape of the droplet became slightly extended along the direction of the DC magnetic field – from top to bottom in Fig. 2*b* and Fig. 3*b*. The free surface was rippled by capillary waves with a wavelength comparable with the skin-depth of approximately 2 mm. It may be suggested that the higher induction of the DC field at $N \gg 1$ would achieve the damping of the flow and surface deformations.

The copper droplet became extremely unstable, when the DC magnetic field was removed, as shown in Fig. 2*c* and Fig. 3*c*. The chaotic shape of the droplet was changing very rapidly: video recording with 50 frames per second delivers evidence that during a period of 20 ms the shape was completely transformed. The turbulent flow in the core of the droplet, the azimuthal wave instability and the capillary surface rippling add up to the unstable state of the droplet, saved

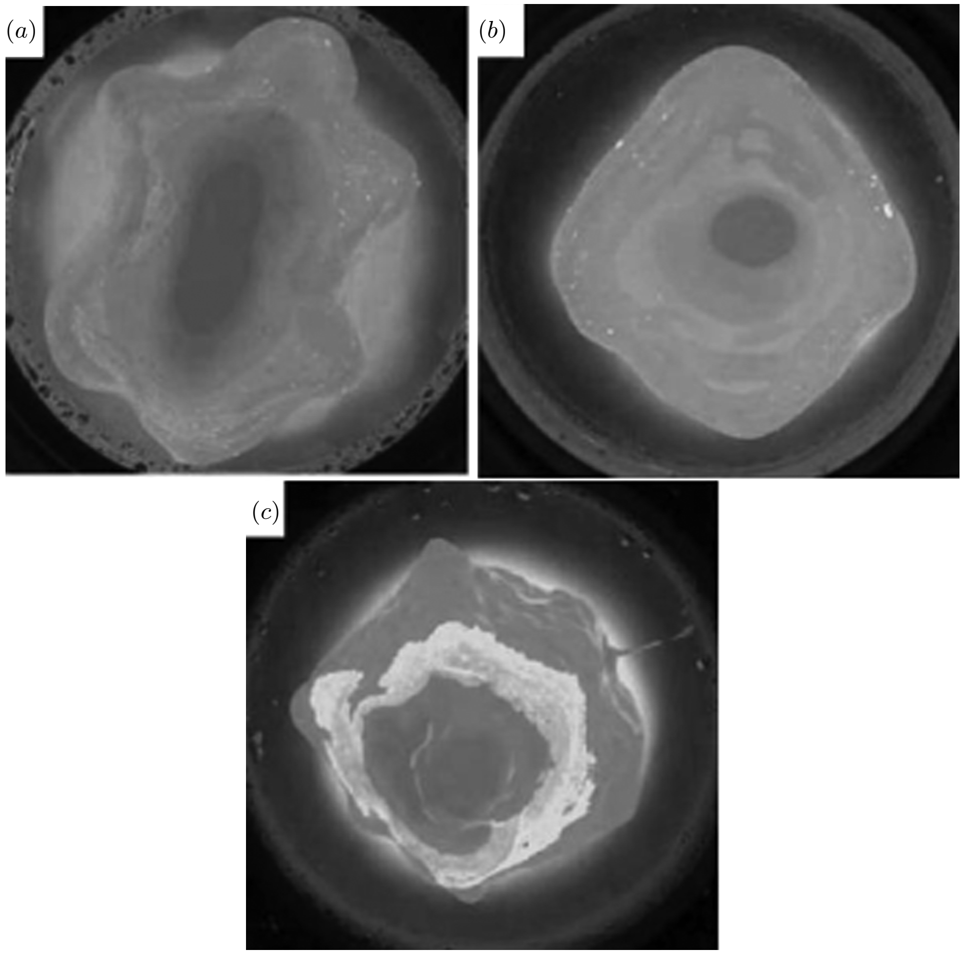

Fig. 3. The semi-levitated liquid copper droplet on the glassy carbon surface under the 9 kHz AC field: (*a*) with the axial 0.5 T DC field; (*b*) with the transverse 0.5 T DC field; (*c*) without the DC field.

from complete destruction only by the walls of the glassy carbon crucible, from which the droplet bounces back.

The twice reduction of the frequency of the AC magnetic field to 9 kHz increased the skin-depth. In general, the droplet behaved similarly as described above, but it became considerably more unstable. In the axial DC field, the azimuthal wave exhibited 5 and 6 mode numbers, the amplitude of the wave was higher. Without the DC field, small diameter jets were splashed out quite often, as may be seen on the right side of Fig. 3*c*. The orientation of the DC magnetic field at the 450 angle to the axis was also applied during the melting, displaying a similar stabilizing effect as the transverse direction field.

3. Conclusion. The reported unstable behaviour of the semi-levitated droplet crucially depends on the wetting of the substrate. Only if there is no wetting and probably the no-slip boundary condition the behaviour becomes acceptable. The azimuthal wave type instability is observed both in the absence of the DC magnetic field and in the axial magnetic field. The DC field delivers a substantial stabilization of the droplet, even if the MHD interaction parameter is not too large. The direction of the DC field with a considerable transverse component seems most promising for stabilization. It may be suggested that in the AC field configuration for full levitation of the molten metal, the correct choice of the magnitude and direction of the DC magnetic field may allow a stable levitation of the large drops of liquid metal even with a very high magnitude of the high frequency AC magnetic field.

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