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

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Abstract: While a piece of pure Copper on a ceramic substrate was inductively melted by 9 to 18 kHz AC magnetic field with 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 basis was 30 mm, the volume – more than 20 cm^3. Replacing the ceramic substrate with a Glassy Carbon, which was not wetted by the molten Copper, caused 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 crucible walls. When axial DC magnetic field with induction 0.35 T was superimposed the liquid metal droplet exhibited harmonic azimuthal wave deformation of the free surface. Higher frequencies lead to smaller characteristic wavelength. Transverse DC magnetic field direction suppressed the travelling wave deformations of the droplet shape. Stabilizing effect of the DC magnetic field during induction melting has been shown for axial, transverse and 45 degree direction magnetic field. These results experimentally demonstrate the possibilities to improve the stability of levitated metal volumes by superimposed DC magnetic field.

High frequency magnetic field induction melting of metals is a well-known technique in crystal growth and advanced metallurgy. An overview of the technologies was given by A. Mühlbauer [1]. One of the techniques is the cold crucible semi-levitation induction melting, while liquid metal is supported by a water cooled substrate from below [2]. Here we report some curious observations while developing a small scale experimental setup for high melting point liquid metal electromagnetic processing during HF AC semi-levitation with superimposed DC magnetic field. A schematic of the initial experimental setup and the stably semi-levitated pure liquid Copper region are shown on the Figure 1. The AC field frequency range was from 9 to 18 kHz, maximum induction up to 0.09 Tesla. The DC magnetic field with maximum induction 0.35 Tesla was delivered by a permanent magnet assembly, permitting to apply 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 ^{o}C. The magnitude of the DC field was not sufficient to considerably damp the flow in the liquid metal, but was sufficient to suppress turbulence in the semi-levitated liquid metal. In the absence of the DC field and sufficiently high dimensionless frequency Ω 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 the balance of magnetic and hydrostatic pressure on the surface of the melt:

$$\rho \frac{U_0^2}{\delta} = \sigma\omega\delta B^2 \qquad \frac{B^2}{\mu_0} = \rho g H$$

$$\delta = \sqrt{\frac{1}{\sigma\omega\mu_0}} \qquad \Omega = \sigma\omega\mu_0 R^2 \gg 1$$

$$U_0 = \sqrt{gH} = \frac{B}{\sqrt{\rho\mu_0}}$$

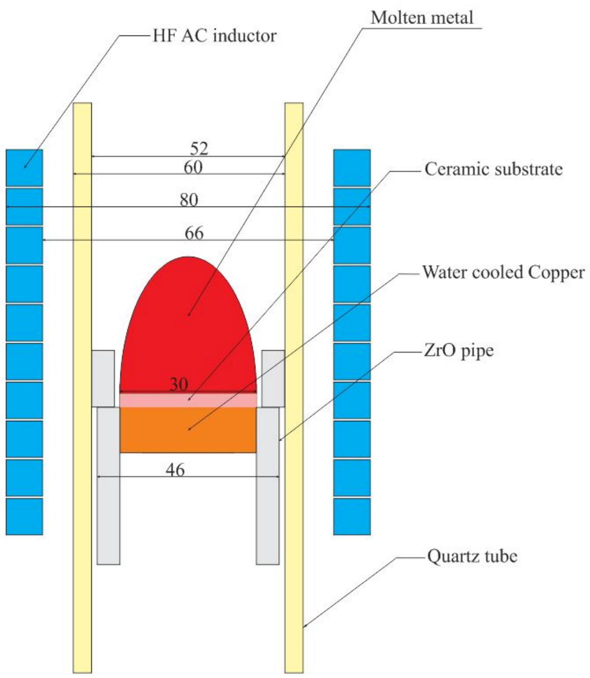

Figure 1. A schematic of the setup on the left and the semi-levitated Copper in axial 10 kHz AC field and DC field on the right.

where is the density of the liquid metal, – conductivity, – angular frequency of the AC field, B – the induction of the AC field at the bottom rim of the semi-levitated region, δ – the skin-depth, R – the radius of the substrate, H – the height of the semi-levitated region. The dimensionless frequency magnitude was Ω = 160 in liquid Copper at 18 kHz AC field. When DC field is superimposed, the flow in the core region inside the skin-depth would be damped to U, if MHD interaction parameter N >> 1:

$$U = \frac{U_0}{N} \qquad N = \frac{\sigma}{\rho}\frac{B_D{}^2 R}{U_0} = \frac{\sigma}{\rho}\frac{B_D{}^2 R}{\sqrt{gH}}$$

where B_D is the induction of the DC magnetic field. During the reported experimental tests, assuming liquid Copper physical properties, N ≈ 2 at maximum AC and DC field inductions.

Obviously the direction of the DC field would be 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 Ohm's law delivers necessary condition for electrical current circulation, assuming zero divergence of magnetic field and velocity:

$$\nabla \times \frac{j}{\sigma} = (B_D \nabla)U - (U\nabla)B_D \quad \text{or} \quad \nabla \times \frac{j}{\sigma} = B_D \frac{\partial U}{\partial l_B} - U\frac{\partial B_D}{\partial l_U}$$

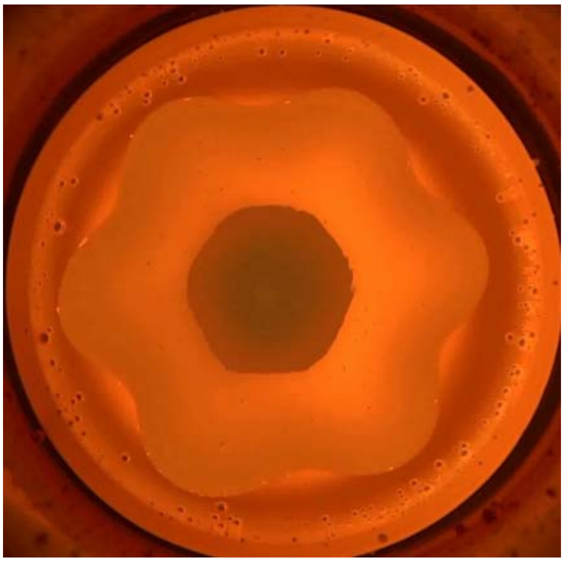
Figure 2. 18 kHz AC field, axial DC field.

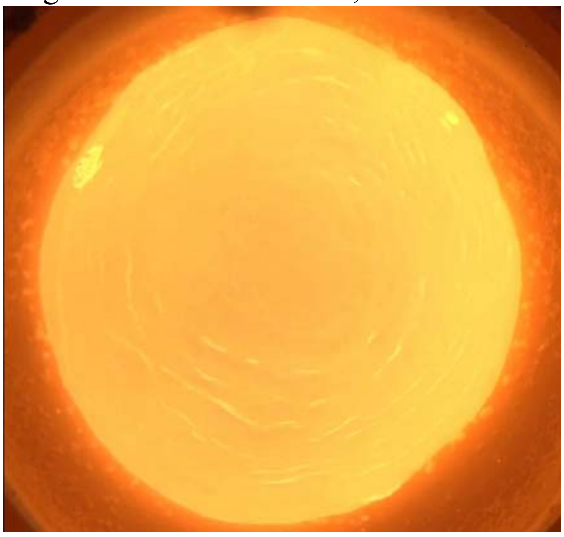
Figure 3. 18 kHz AC field, transverse DC field.

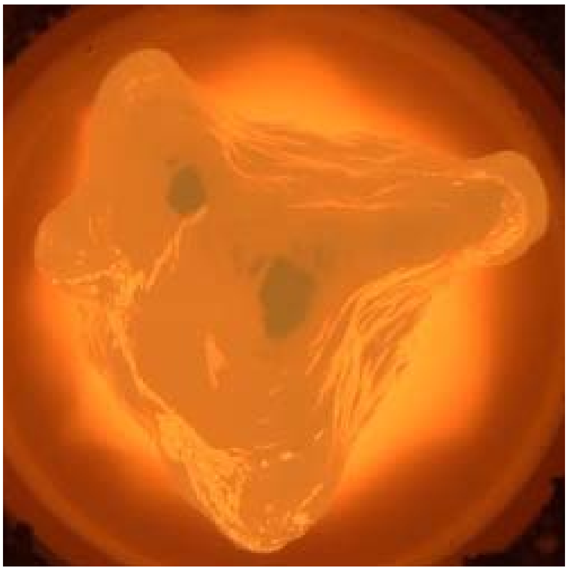
Figure 4. 18 kHz AC field, no DC field.

where j is the current density. The former equation may be interpreted, that the motion of a conductor in magnetic field produces electrical current only, if the magnetic field varies along the direction of the velocity and/or if there is a variation of velocity along the direction of the magnetic field. Or, if DC field is uniform, there is no induced current, if velocity of the melt does not vary in in the direction of the field and no interaction with the flow.

The unexpected happened when the ceramics support was replaced by a Glassy Carbon. During impact by the superimposed axial AC and DC fields a highly organized azimuthal wave pattern of the molten Copper droplet shape were observed. If the melt has zero velocity at the interface with the substrate, nothing like observed should ever happen! The only obvious experimental observation was that above the temperature 1200 C^{o} the Glassy Carbon was not wetted by the Copper melt. It was obvious that the phenomenon resembles well known behavior of the fully levitated liquid droplets [3, 4]. In the current experiment there was no full levitation, the droplet was supported by the Glassy Carbon substrate. Similar behavior is known, the historical priority being the unstable droplet of the water on a well heated substrate due to Leidenfrost effect, when similar azimuthal waves are also observed. Experimental observations of such type of instability has been reported [5, 6], but the former cases include substantial difference from the current one – during cited experiments there have been a layer of an encapsulating, substrate wetting, nonconducting fluid between the oscillating fluid and the substrate. In our case the vacuum surrounding pressure eliminates any vapor cushion beneath the semi-levitated molten metal. The only questionable suspect regarding the fluid interface may be the Copper oxide, which becomes liquid at temperature above 1200 C^{o}. But, on the other hand, Copper oxide decomposes in vacuum at the temperature above the 1200 C^{o}. 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 6-mode azimuthal wave travelling anticlockwise. The axial DC field has 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 axial magnetic field, but did not suppress the wavy motion, which has no variation along the DC field.

The transverse DC magnetic field eliminated azimuthal wave motion, but did not suppress the flow in the core of the droplet as efficiently as 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 DC magnetic field – from top to bottom on the Figure 3. The free surface is rippled by a capillary waves with a wavelength comparable with skin-depth, approximately 2 mm. It may be suggested that higher induction of the DC field at N >> 1 would achieve damping of the flow and surface deformations.

The Copper droplet became extremely unstable, when DC magnetic field was removed. The chaotic shape of the droplet was changing very fastly, video recording with 50 frames per second deliver evidence, that during the period of 20 ms the shape was completely transformed. Turbulent flow in the core of the droplet, azimuthal wave instability and capillary surface rippling add up to unstable state of the droplet, saved from complete destruction only by the walls of the Glassy Carbon crucible, from which the droplet bounces back.

Reduction of the frequency of the AC magnetic field two times to 9 kHz, increased the skin-depth. In general the droplet behaved similarly as described above, but became considerably more unstable. In axial DC field the azimuthal wave exhibited 5 and 6 mode numbers, the amplitude of the wave was higher. Without DC field small diameter jets were splashed out quite often, as may be seen on the right side of Figure 7.

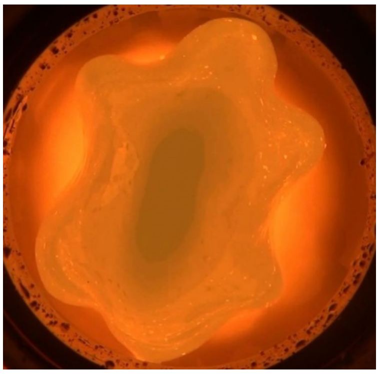

Figure 5. 9 kHz AC field, axial DC field.

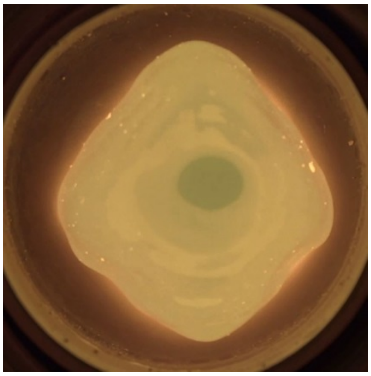

Figure 6. 9 kHz AC field, transverse DC field.

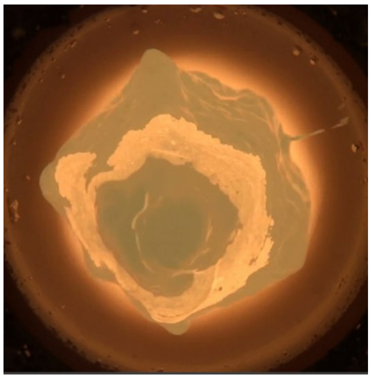

Figure 2. 9 kHz AC field, no DC field.

The orientation of the DC magnetic field at 45 degree angle to the axis was also aplied during melting, displaying similar stabilizing effect as the transverse direction field.

Conclusion

The reported unstable behavior 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 behavior becomes acceptable. The azimuthal wave type instability is observed both in absence of the DC magnetic field and in axial magnetic field. The DC field delivers substantial stabilization of the droplet, even if the MHD-interaction parameter is not too large. The direction of a DC field with a considerable transverse component seems most promising for stabilization. It may be suggested that in 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 stable levitation of the large drops of liquid metal even during very high magnitude of the high frequency AC magnetic field.

References

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