Liquid metal layer dynamics in transverse alternating magnetic field

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***Abstract*—We study liquid metal layer edge instability in transverse alternating magnetic field, both experimentally and numerically. An inductor is located along one of the layer edges. We find experimentally that liquid metal surface oxidation leads to almost static edge pattern unlike non-oxidized case where wavy oscillations of the edge are observed. In both cases, numerical modelling is a complicated and time-consuming matter, especially due to three-dimensional nature of the phenomena. Nevertheless, preliminary 3D simulations are in a qualitative agreement to experiments.**

***Index Terms*—magnetohydrodynamics, liquid metal, instability**

I. Introduction

Medium- to high-frequency magnetic fields are often used in electromagnetic processing of materials - heating and melting. In some technologies, such as cold crucible induction melting, the liquid metal can semi-levitate - it is supported by a solid base from the bottom but is completely repelled from the crucible side walls by electromagnetic forces. [1] In the case of liquid metal electromagnetic semi-levitation, if the melt layer is relatively thin, so that surface tension and contact line dynamics play an important role, different free surface instabilities have been observed in the past, such as gallium drop oscillations and rotation [2]. The phenomena have been studied theoretically [3], explaining the main causes of the edge pinch instability where some small edge perturbations are amplified by the magnetic field line concentration. Numerical modelling of such dynamic free surface effects, due to the complexity of physics involved and simulation time requirements, has not been done.

In this work, we study thin liquid metal layer edge instability near a high-frequency inductor. Experimental work involves studying the edge instability depending on inductor current, frequency, as well as layer thickness. Additionally, the effect of liquid metal free surface oxidation on the dynamics is assessed. Numerical work involves fully coupled 3D simulations, at this stage trying to achieve at least qualitative agreement to experimental observations.

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II. Experimental setup

Experiments were done at the Institute of Electrotechnology, Leibniz University of Hanover in Germany. The setup is shown in Fig.1. The melt is gallium or galinstan (we did experiments with both), the container is acrylic, inductor is a water-cooled copper tube. The inductor is connected to a 100 kW power generator and during the experiments frequencies of 3 to 5 kHz and currents of 1 to 3 kA were used. Melt dimensions are 200 mm along the inductor edge, 100 mm in direction normal to inductor and thickness is from 4 to 11 mm.

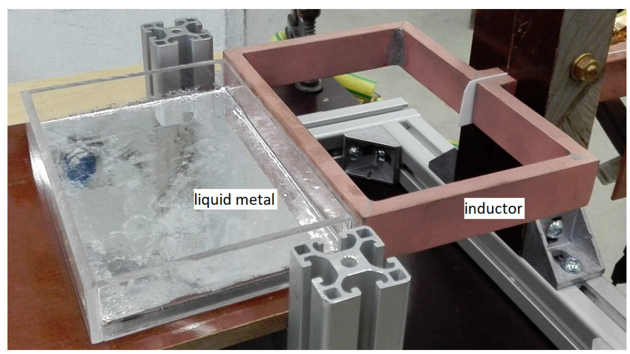

Fig. 1. Experimental setup.

III. Numerical model

The problem is multi-physical and coupled - electromagnetic force induces fluid flow and deforms liquid metal surface and the electromagnetic field depends on the liquid metal volume shape. Numerical approaches to solve such problems have been developed in the past [4] using external coupling between commercial tools for electromagnetics and fluid flow. Recently developed EOF-Library [5] allows efficient coupling of free open-source tools Elmer [6] (electromagnetics, finite element method) and OpenFOAM [7] (fluid flow, finite volume method). These tools have been verified against simulations with commercial software [8]. In this work, we use the open-source tools.

The numerical model consists of two parts - electromagnetics model (part of the inductor near the melt, melt volume and some air around) and two-phase fluid flow model (only the melt domain with some air above it). Elmer solves steady electromagnetics in frequency domain, OpenFOAM solves two-phase flow using the Volume of Fluid method [9] for free surface capturing and k-ω SST model [10] for turbulence.

IV. Results

The most representative results out of all experiments and simulations are shown in Fig.2 and Fig.4 (experiments) and Fig.3 and Fig.5 (simulations), with only the region near the inductor shown. Note that in the case of non-oxidized surface, the edge pattern was fluctuating, whereas the oxidized melt was almost static apart from some small fluctuations perhaps due to turbulent bulk flow. Clearly, the metal surface oxidation plays an important role in the pattern formation. Similar effect has been observed in [2], where the effect of oxidation was explained as a formation of a ”crust” which not only changes the surface tension coefficient but also reduces the mobility of the liquid-solid contact line. We observed that, in the case of smallest thickness used in experiments (4 mm), the oxide layer could even support the deformed melt shape - it remained so even after switching off the inductor current.

Fig. 2. Oxidized galinstan free surface shape in experiments; melt thickness 4 mm, current 1500 A, frequency 5330 Hz.

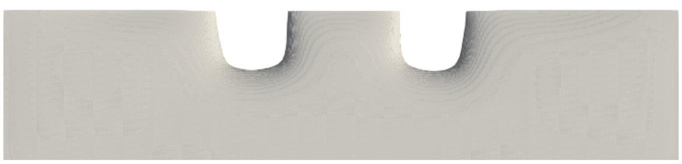

Fig. 3. ”Oxidized” galinstan free surface shape in simulations; melt thickness 4 mm, current 760 A, frequency 5330 Hz.

Fig. 4. Non-oxidized galinstan free surface shape in experiments; melt thickness 11 mm, current 2585 A, frequency 4270 Hz.

The simulations don’t really consider the oxidation but we model the effect as a modified contant angle - in the non-oxidized case it is large (experimental estimation is around 150 degrees) and for oxidized melt it is small (estimation of around 30 degrees). Such approximation, of course, is not ideal and we cannot obtain the melt support only by the oxide crust that we observed experimentally. Nevertheless, the preliminary simulations are in a qualitative agreement to experiments.

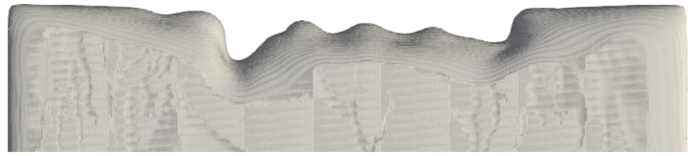

Fig. 5. ”Non-oxidized” galinstan free surface shape in simulations; melt thickness 11 mm, current 2585 A, frequency 4270 Hz.

V. Conclusions

The liquid metal free surface edge near a high-frequency inductor can assume different shapes depending on oxidation, field intensity, layer thickness etc. Since the phenomena are three-dimensional, numerical modelling is very time-consuming. Simplified preliminary simulations using coupled open-source tools are in a qualitative agreement to experimental observations. More precise mathematical models are necessary to account for the oxide layer effects on surface tension and contact line dynamics. More experiments are planned in near future to obtain data in a wider range of the parameter space considered (layer thickness, current and frequency etc).

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