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Investigation of Liquid Phase Motion Generated by the Thermoelectric Current and Magnetic Field Interaction

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Abstract

On the crystallization front of metallic alloy temperature variations can take place in very small length scales, which means that significant temperature gradients can exist locally. This can lead to thermoelectric current circulation in the vicinity of the front. When external magnetic field is applied, volume force appears, and flow of the liquid phase is introduced (thermoelectromagnetic convection). This flow can have significant influence on the mass and heat transfer conditions on the front, which can lead to changes in the structure of metal.

Our experiment was designed to experimentally observe and investigate the thermoelectromagnetic convection in macroscopic scale. Experimental setup consists of cobalt needle, which represent the dendrite arm, surrounded by the liquid phase represented by the GaInSn eutectics. Measurements of the magnetic field influence on the temperature distribution were performed. Mathematical modelling of the current distribution and liquid phase motion due to current and magnetic field interaction were done as well.

1. Theoretical Background

The purpose of the model experiment is to experimentally investigate the flow of the liquid metal, generated by the thermoelectric current and magnetic field interaction. This flow has physical similarity with the processes which may take place during dendritic solidification of liquid metallic alloy. Thermal inhomogenities may appear due to latent heat release and composition inhomogenities which lead to different melting temperatures in different places on the crystallization front. On crystallization front such temperature variations can take place in very small length scale, which means that local temperature gradient value can be high, and thermoelectric current circulation can take place. When external magnetic field is applied, mass flow appears. Under certain conditions thermoelectric current and magnetic field interaction can generate motion, which can have significant impact on the heat and mass transfer conditions in the vicinity of crystallization front, which can lead to the formation of different dendrite and grain structure of the metal. Better understanding of this phenomenon could make it possible to gain desired structure of the alloy by choosing right crystallization front speed, and applying magnetic field with corresponding configuration and strength.

Current flow in continuous media is described by generalized Ohms law, where S is absolute thermoelectric power of the material. For most of the metals S is within the range from -30 μV/K to 30 μV/K.: [1]

$$\vec{j}/\sigma = \vec{E} + \vec{u} \times \vec{B} - S \cdot gradT, \tag{1}$$

Liquid phase motion is governed by Navier-Stokes equation:

$$\rho\left(\frac{\partial \vec{u}}{\partial t}+\vec{u}\cdot\nabla\vec{u}\right)=-\nabla p+\mu\nabla^2\vec{u}+\vec{f}. \tag{2}$$

In our case term f is Lorentz force density generated by the current and magnetic field interaction

$$\vec{f}=\vec{j}\times\vec{B}. \tag{3}$$

Substituting current density from Ohm’s law into Navier-Stokes equation we get

$$\rho\left(\frac{\partial \vec{u}}{\partial t}+\vec{u}\cdot\nabla\vec{u}\right)=-\nabla p+\mu\nabla^2\vec{u}+\sigma\vec{E}\times\vec{B}-\sigma S\vec{\nabla}T\times\vec{B}+\sigma\left(\vec{u}\times\vec{B}\right)\times\vec{B}. \tag{4}$$

There are two terms in the Navier-Stokes equation due to thermoelectric current and magnetic field interaction. Term $\sigma S\vec{\nabla}T\times\vec{B}$ is force which is generating flow, but term $\sigma(\vec{u}\times\vec{B})\times\vec{B}$ is force caused by the liquid metal motion induced current and magnetic field interaction, and acts as a motion damping force. In weak magnetic fields first term is dominant, and damping due to induced current can be neglected. As damping force is proportional to the square of the magnetic field induction, when magnetic field is increased it increases faster than thermoelectric flow generating force. At certain magnetic field value the maximum motion intensity is reached. This value is depends on many factors and is unique for each material and geometry.

2. Experiment

Experimental setup consists of one or multiple cobalt needles, which represent solid dendrite arms, and liquid phase around the needles is being represented by GaInSn eutectic alloy (Fig.1). Heat flow is applied from the bottom of the needles, thus significant temperature gradient can be reached along the solid-liquid boundary. Heat is removed from the system through side walls, which are 0.5 mm thick copper cooled with water circulation. Permanent magnet system allows varying transverse magnetic field from 0.2 to 0.6 T by changing the distance between magnet poles. Axial magnetic field up to 0.2 T created by ring magnets can be applied as well. The diameter of the liquid metal pool is 16 mm, and depth is 2 mm deep. In experimental setup with one cobalt needle, diameter of needle is 3 mm. Cobalt was chosen as a needle material because it has one of the highest absolute value of absolute thermoelectric power among metals (approx. -26 μV/K at room temperature range), and it has good electrical conductivity as well. Bottom of the liquid metal pool is covered by 0.1 mm thin copper foil to ensure good wetting conditions between eutectic and pool bottom. Absolute thermoelectric power of GaInSn eutectics is about -0.4 μV/K and of copper 1.8 μV/K in room temperature range. Cobalt needle is 30 mm long and is placed into the copper rod with hole to ensure larger amount of heat which is inserted into the cobalt needle.

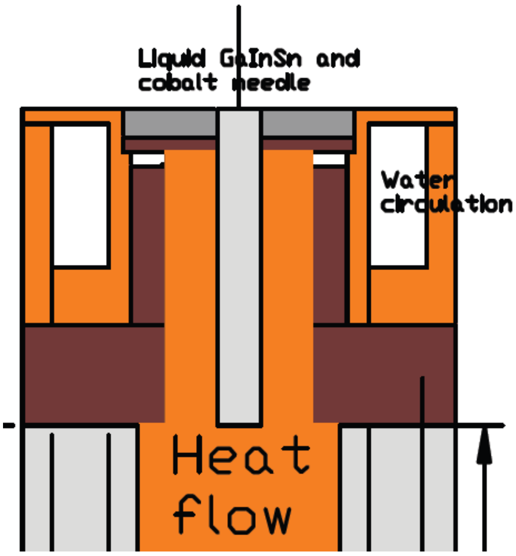

Fig. 1. Cross section of the experimental setup

Power applied to the heating element which is placed around the copper rod is 100 W, but estimated heat flow inside the needle is only about 10 W. It was assumed in the model that heat flow is evenly distributed along the cross section of the needle and that heat is only lost trough outer wall, which is 0.5 mm thick copper surrounded by water circulation and is assumed to be isothermal at a temperature of 17 ^{0}C.

Potential drop on the boundary is calculated as $\Delta\varphi = \Delta S \cdot T$ where $\Delta S=(S_w-S)$ is absolute thermoelectric power difference between the wall material and liquid metal.
Both boundaries (Co-GaInSn and Cu-GaInSn) act like potential sources, and thermoelectric current distribution can be calculated.

The electrical conductivities used in the calculations are

$$\sigma_{copper} = 5.97*10^7 sim/m, \quad \sigma_{cobalt} = 1.61*10^7 sim/m, \quad \sigma_{GaInSn} = 3.60*10^6 sim/m.$$

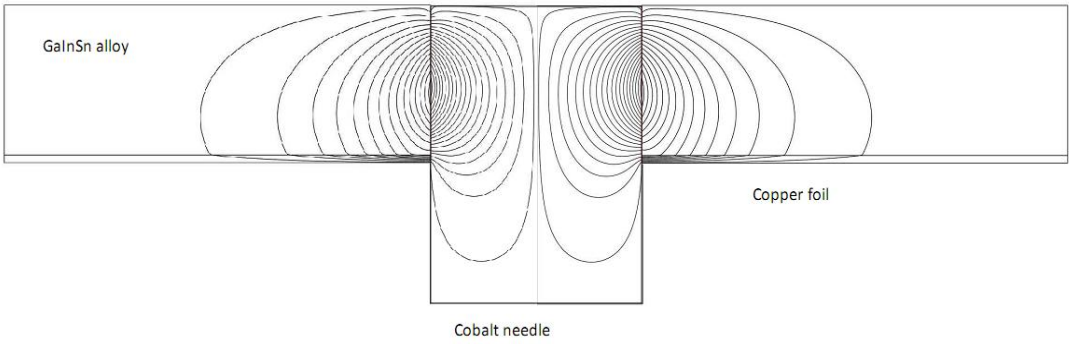

Fig. 2. Current distribution (cross section of 3D model). Total current in this case is about 75µA

Modelling results show that copper bottom has significant influence on the current distribution, and most of the current in radial direction is flowing through it. Velocity scale in the pool can be estimated by comparing thermoelectric and inertial forces [2]

$$\rho\frac{u^2}{l} \approx \sigma SB(grad(T)); \tag{5}$$

$$u = \left(\frac{\sigma SBl \cdot grad(T)}{\rho} \right)^{1/2}; \tag{6}$$

When inserting the parameters (*B=0.2 T, grad(T)=5 K/mm,* $\rho=6400$ *kg/m*^{3}) of our experimental device we get $u \approx 20$ *cm/s,* which is quite large value for such a small size. In reality speed is lower due to induction current and magnetic field interaction which acts as a damping force and viscosity.

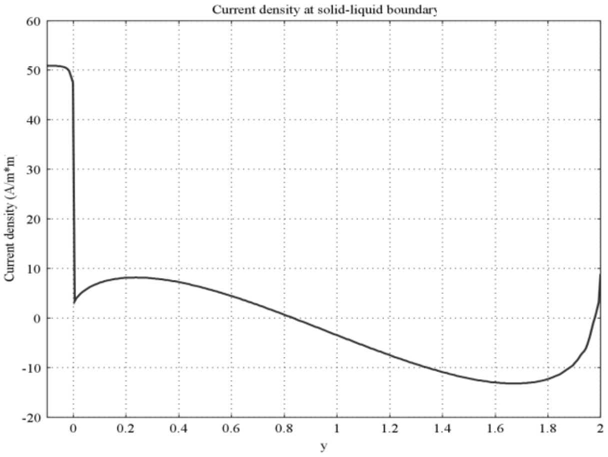

Fig. 3. Current density at cobalt-GaInSn boundary

Ratio between free convection and conduction heat transfers are characterized by Rayleigh number, which is defined as

$$Ra = \frac{g\beta L^3}{\nu\alpha}\Delta T \tag{7}$$

Inserting parameters of our experiment defined in table 1 we obtain Ra≈350

Tab. 1. Values of the physical quantities used in calculations

Quantity	Symbol	Value	Unit
Free fall acceleration	g	9,8	N/kg
Volumetric thermal expansion of GaInSn	β	7*10^{-5}	1/K
Characteristic length	L	8	mm
Characteristic temperature difference between bottom and top of the pool	ΔT	5	K
Thermal diffusivity	α	1,46*10^{-5}	m^2/s
Kinematic viscosity	ν	2,9*10^{-7}	m^2/s

Such value of Rayleigh number means that conduction dominates over free convection in experimental setup when magnetic field is not applied.

3. **Results**

Radial temperature distribution measurements were carried out with T (Copper-Constantan) type thermocouples. Measurements were made at the middle depth of the liquid metal pool. When axial magnetic field is applied temperature distribution remain radially symmetric, but with the presence of magnetic field the convective heat transfer is more effective then without. When magnetic field is applied forced convection appears, and measurement results show that this forced convection have influence on the heat transfer.

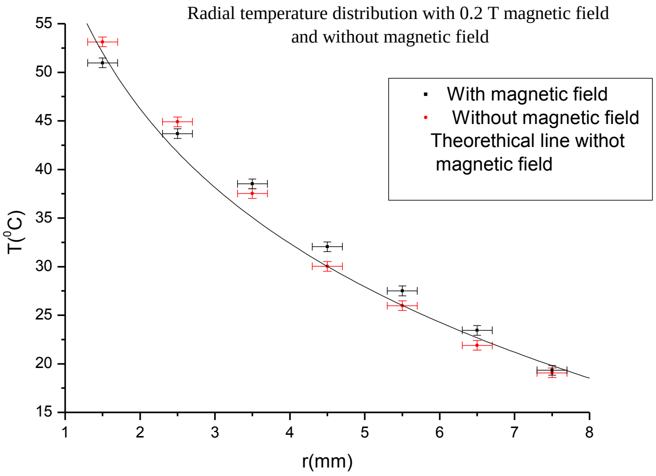

Fig. 4. Radial temperature distribution in the middle depth of the pool with 0.2T axial magnetic field and 0T field

In presence of transverse magnetic field anisotropy of convective heat transfer appears. Measurements were done in magnetic field direction and in perpendicular direction. Though current in GaInSn has radial component, then if axial magnetic field is applied, rotation of the liquid metal appears, what was also observed experimentally as an axially symmetric surface deformation. In right side of the needle, if looking in magnetic field direction, force is directed upwards, but in left side downwards. In this case liquid phase motion is much complicated, but the experimental results show that heat transfer is more effective in all directions in this case compared with situation when no magnetic field is applied.

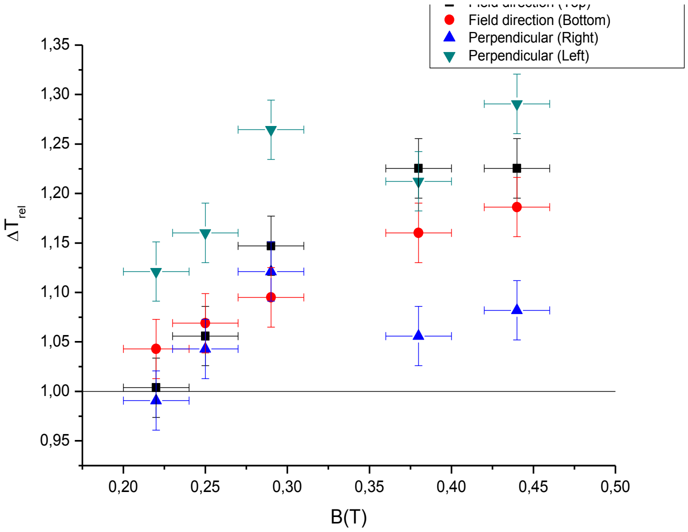

Fig. 5. Relative temperature difference as a function of magnetic field strength. Black line is temperature difference when magnetic field is not applied

Total temperature difference 1mm from the walls were measured in directions parallel and perpendicular to the magnetic field direction, and then compared with temperature difference in case with no magnetic field.

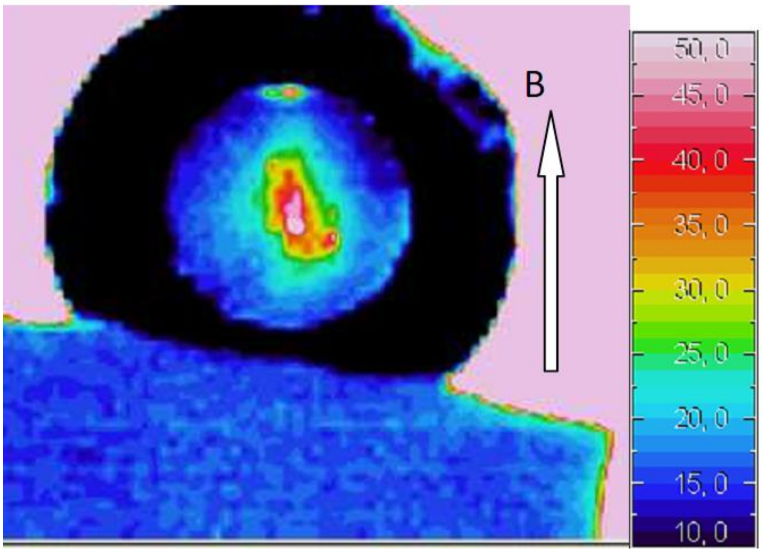

Fig. 6. Surface temperature distribution (B=0.5T). Photographed with infrared camera NEC TH9100ML

Conclusions

Under magnetic field heat transfer is higher due to convective heat transfer component created by magnetic field and thermoelectric current interaction. There are some difficulties to measure these phenomena experimentally, because large temperature gradients cannot be maintained in large distances. Rough approximation of characteristics of liquid phase flow around solid needle can be obtained by mathematical modelling, but precise boundary conditions on solid-liquid boundary are not clear yet. This effect potentially could be used to alter the dendrite structure of the metallic alloys during crystallization, and some experiments has been already done [2]

References

[1] Shercliff, J. A,: *Thermoelectric magnetohydrodynamics.* Journal of fluid mechanics, Vol. 91, 1979, pp 231-251.

[2] Li, X., Fautrelle, Y., Ren, Z.: *Influence of thermoelectric effects on the the solid-liquid interface shape and cellular morphology in the mushy zone during the directional solidification of Al-Cu alloys under a magnetic field.* Acta Materialia, Vol. 55, 2007, No. 11. pp. 3803-3813.

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