SEGREGATION CONTROL DURING DIRECTIONAL SOLIDIFICATION USING MAGNETIC FIELD AND ELECTRIC CURRENT

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Abstract: Component segregation during solidification of a multicomponent alloy is an important practical problem. Segregation can be caused by gravity field or melt flow in the crucible. Applied magnetic field during solidification creates thermoelectromagnetic convection (TEMC). Magnetic field creates Lorentz force if electric current is applied. Secondly, magnetic field damps large scale melt convection thus limiting heat and solute exchange. These two mechanisms allow us to modify net melt convection and segregation in the crucible by applying electric current and magnetic field during solidification of a metallic alloys.

1. Introduction

Electric current may appear near solidification front due to thermoelectric effect between solid and liquid phases, caused by temperature gradient and differential thermoelectric power between solid and liquid phases [1, 2]. However direction and magnitude of this current is mainly defined by the material properties and interface morphology, and temperature gradient at the interface, which are difficult to control and maximum intensity of this current is limited. If transverse magnetic field is applied to directionally solidifying alloy, then macrosegregation in the crucible scale perpendicular to magnetic field direction is observed as a consequence of thermoelectromagnetic convection (TEMC) [3]. Electric current may also be applied externally, thus creating Lorentz force and convection flow of the liquid melt. Directional solidification under applied electric current and magnetic field has been studied by several authors [4, 5]. If direct electric current is applied through the solidification front, then current component which is perpendicular to the magnetic field interacts with it and melt convection is caused by this force.

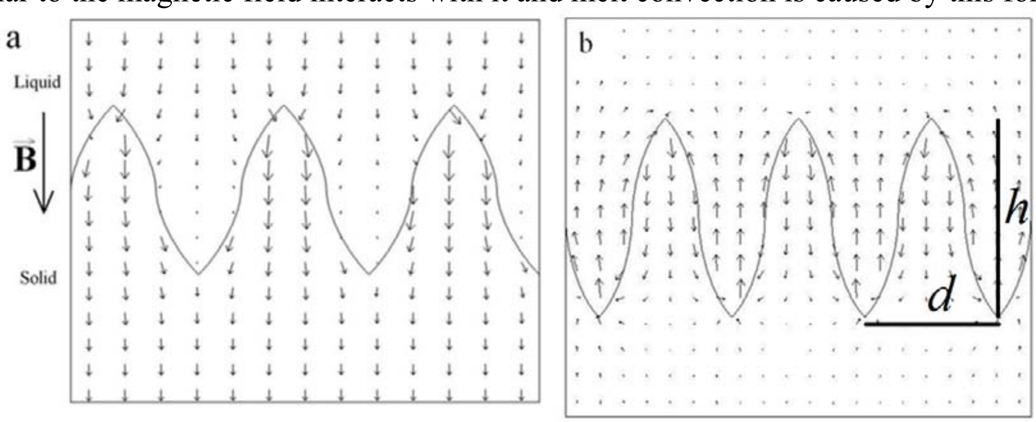

Figure 1: Conduction current redistribution at the dendritic interface due to different conductivities of solid and liquid phases: a) current distribution at the interface between two media with different conductivities; b) current component when axial current in the bulk of the liquid is subtracted.

Electrical conductivities of solid and liquid phases can differ several times for metals and metallic alloys, thus at the dendritic solidification interface electric current redistribution takes place. In the bulk of the solid and liquid domains current density is uniform and Lorentz force caused by homogeneous magnetic field is irrotational. If this current component is neglected then we obtain current pattern at the interface similar to TE current as shown in Fig. 1.

In this work Sn-Pb alloy is directionally solidified under 0.5 T static transverse magnetic field and applied electric current through the solidification interface. Macrosegregation caused by current and magnetic field interaction caused electromagnetic convection is experimentally investigated in this work. Study has been focused on investigation of simultaneous action of electromagnetic convection and thermoelectromagnetic convection. Possibilities to control macrosegregation by applied electric current and magnetic field during directional solidification has been experimentally and theoretically analyzed and possibilities to eliminate or enhance effect on the solidified structure caused by TEMC has been verified.

2. Presentation of the problem

High purity tin and lead (99.99%) was used to prepare Sn-10%wt.Pb alloy, which was then casted into the alumina799 crucible (*L*=110mm, *ID*=6mm, *OD*=10mm). Samples were then remelted and solidified under intense electromagnetic stirring to ensure good homogeneity of initial samples, which are later directionally solidified in a Bridgman setup at controlled growth velocity and temperature gradient. In these experiments growth velocities from 2 μm/s to 10 μm/s was used. Temperature gradient at the interface was θ=8 K/mm in all experimental sessions of this work. Upper part of the sample is melted by the resistive furnace around the crucible while bottom part is kept solid by water cooled copper ring. Furnace and water cooled ring are stationary while crucible is lowered by a programmable pulling system. Solidification front is always located between heater and cooler at the same location. Thus, the actual solidification velocity was assumed to be equal to the pulling velocity of the crucible. Transverse magnetic field of 0.5 T was created by a permanent magnet system. For optical microscopy analysis samples were polished to 1 μm surface roughness and then chemically etched with 4% nitric acid ethanol solution, which darkened the lead-rich fraction. Electric current is introduced in liquid part through 4 mm diameter stainless steel electrode as shown in Fig.2.

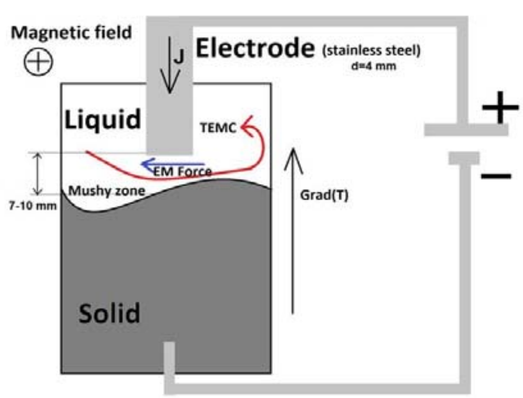

Figure 2. Experimental scheme for directional solidification with an applied electric current and magnetic field.

Estimation of TEMC magnitude is given in Ref.[3, 6] by solving simplified Navier-Stokes equation. According to these estimations for given materials and solidification conditions characteristic velocity is about 0.25 mm/s. Electric current density which would allow to achieve same convection velocity can be estimated. Electric current density component, which is perpendicular to magnetic field, depends on ratio of electric conductivities of alloy at solid and liquid states, and ratio between vertical and horizontal structure lengths as illustrated in Fig.1. Expression relating these quantities is given by Equation 1, which is only valid if conductivities and sizes are of the same order of magnitudes.

$$j_{\perp} = j\left(1 - \frac{\sigma}{\sigma_s}\right)\frac{h}{d} \tag{1}$$

The order of magnitude of TE current can be estimated as given in Ref [3].

$$j_{TE} = c\sigma\theta(S_l\text{-}S_s) = 1.1\cdot 10^4 \text{ A/m}^2 \tag{2}$$

If $h \approx d$, then $j \approx 2j_{TE}$ and necessary electric current to achieve similar convection as TEMC is approximately $2\cdot 10^4$ A/m^2 or 0.5 A current through 6 mm diameter sample.

Table 1: Physical properties of Sn-10%wt.Pb alloy used in estimations. Physical properties are given for melting temperature (Tm = 220 ^{o}C)

Quantity	**Symbol**	**Value**	**Unit**
Density	ρ	6974	kg/m^3
Electric conductivity	σ	$2\cdot 10^6$	sim/m
Dynamic viscosity	μ	0.0021	Pa·s
Absolute thermoelectric power (s)	S_s	$-2\cdot 10^{-6}$	V/K
Absolute thermoelectric power (l)	S	$-1\cdot 10^{-6}$	V/K
Differential thermoelectric power	P	$1\cdot 10^{-6}$	V/K
Temperature gradient at the front	θ	3	K/mm
Crucible radius	R	3	mm
Volumetric thermal expansion	β	$6.8\cdot 10^{-5}$	1/K
Free fall acceleration	g	9.81	m/s^2
Form constant	c	0.5	

In our case, the temperature gradient is directed along the axis of the crucible from bottom to the top. This means that applied current from bottom of the sample enhances TEMC, while the current from the top creates convection opposite to TEMC. Several solidification experiments were performed to verify this hypothesis. Experimental results are summarized in Fig.3 and Fig.4. Fig. 3 shows directionally solidified 6 mm-diameter Sn-10%wt.Pb sample at velocity 3 μm/s with different electric current values. Fig. 3(b) shows solidified sample without magnetic field and electric current. Fig.3a shows solidification structure with applied transverse magnetic field of 0.5 T, segregation in this case is caused solely by TEMC. Note that in the latter case the TEM force produces a transverse flow in the direction perpendicular to the magnetic field from right to left in Fig. 3(a). Accordingly, a large segregation normally appears on the left part of the ingot as confirmed by Fig. 3(a). Fig.3(c) shows how segregation can be enhanced by the application of electric current from the bottom of the sample. Fig.3d shows structure of solidified sample if current is applied from the top of the sample. In this case according to the estimations electromagnetic convection acts opposite to TEMC with the same magnitude. As can be seen in this case segregation is significantly weaker. Fig.3(e) shows the case when electromagnetic convection is two times stronger than TEMC and acts opposite to it, it is observed that segregation direction is reversed compared to Fig.3(a) where TEMC only is present.Fig.4 shows solidification structure of Sn-10%wt.Pb alloy solidified at 10 µm/s. It can be seen that in this case macrosegregation is less distinct which agrees to our expectations, because in all works describing TEMC it is concluded that TEMC effects can be better observed if solidification velocity is low. Indeed, segregation formation requires a certain time which is linked to the amplitude of TEMC. Conversely, the latter case indicates that TEM velocities are less or equal at most to 10 µm/s, what is consistent with the theoretical estimates.

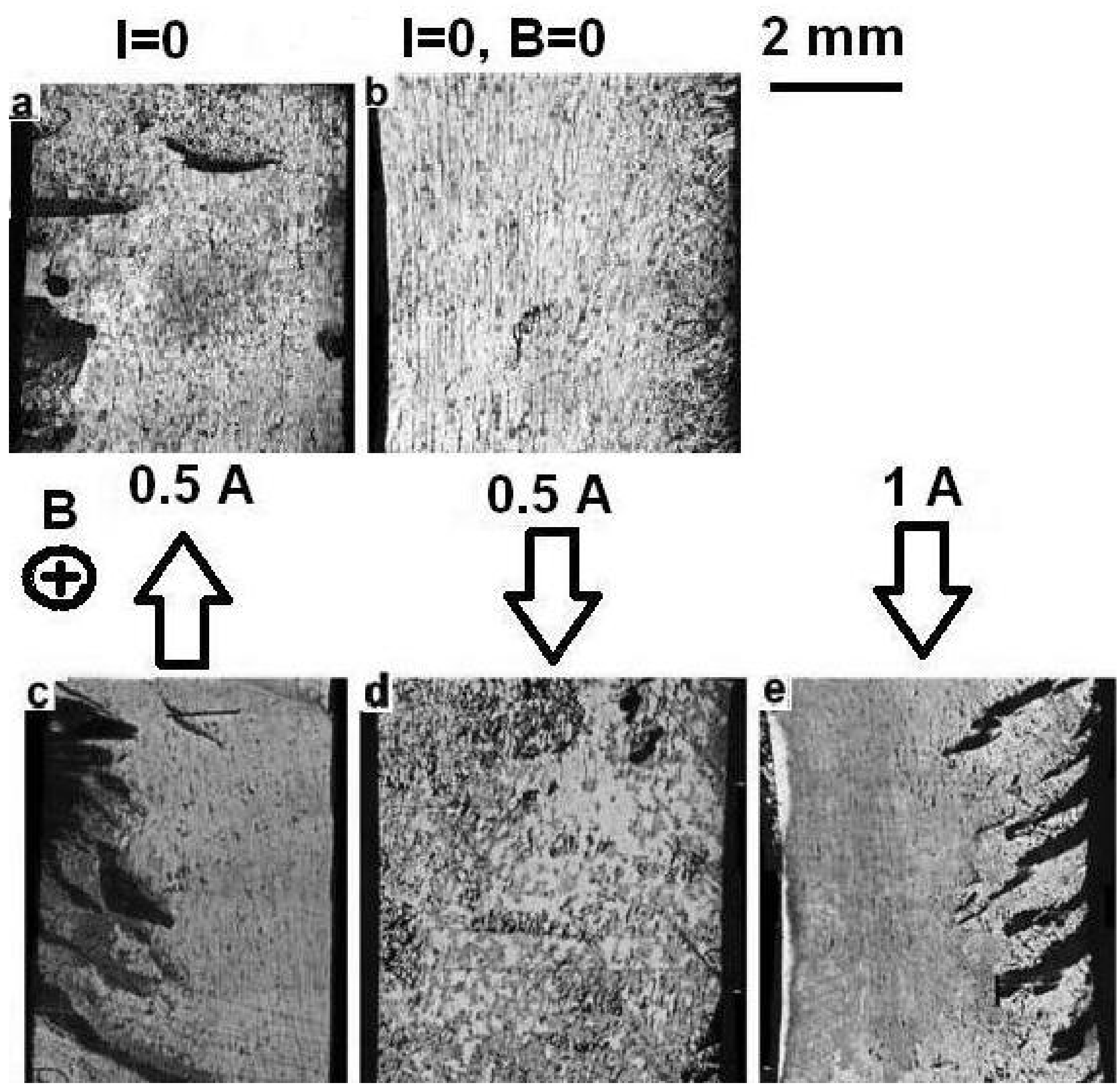

Figure 3: Directionally solidified Sn-10%wt.Pb alloy at v =3 µm/s under static transverse magnetic field 0.5 T and electric current: a) I = 0, B = 0.5 T; b) I = 0, B = 0; c) I = 0.5 A, B = 0.5T; d) I = -0.5 A, B = 0.5 T; e) I = -1 A, B = 0.5 T.

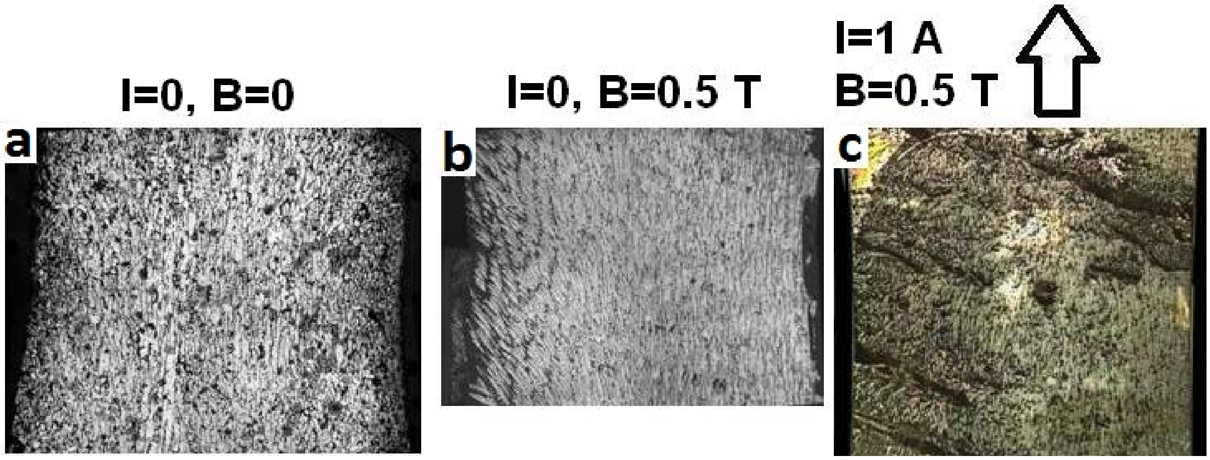

Figure 4: Directionally solidified Sn-10%wt.Pb alloy at v =10 μm/s under static transverse magnetic field 0.5 T and electric current: a) I = 0, B = 0; b) I = 0, B = 0.5 T; c) I = 1 A, B = 0.5 T.

3. Conclusion

It is experimentally demonstrated that direct current through the sample can be used to control macrosegregation during directional solidification of the metallic alloy. Theoretical analysis and numerical simulation show that transverse magnetic field and applied electric current produce force distribution similar to thermoelectric force density. Thus this method allows enhancing or suppressing the macrosegregation caused by thermoelectromagnetic convection. Experimental work presented in this paper confirms this hypothesis that by choosing appropriate electric current value, segregation caused by thermoelectromagnetic convection can be fully compensated, enhanced or reversed by electromagnetic convection.

4. References

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