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SEGREGATION CONTROL AT DIRECTIONAL SOLIDIFICATION USING MAGNETIC FIELD AND ELECTRIC CURRENT

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Component segregation at solidification of multicomponent alloys is an important practical problem. One of the main causes of segregation is the melt flow in the crucible. In this article, experimental results of directionally solidified Sn-Pb alloy under a static transverse magnetic field and conductive electric current through the solidification front are presented. The applied magnetic field causes thermoelectromagnetic liquid phase convection, while the electric current and magnetic field interaction causes electromagnetic (EM) convection. These two mechanisms allow us to modify net melt convection and segregation in the crucible by modifying the electric current and magnetic field value and direction at solidification of metallic alloys. In this article, similarity between these two convection mechanisms is investigated.

Introduction. The electric current may appear near the solidification front due to the thermoelectric effect between solid and liquid phases caused by a temperature gradient and differential thermoelectric power between solid and liquid phases [1–4]. However, the direction and magnitude of this current is mainly determined by the material properties and interface morphology and by the temperature gradient at the interface, which are difficult to control. This limits the maximum intensity of thermoelectric current. Thermoelectric current interacts with an external magnetic field creating a Lorentz force and inducing a liquid phase motion and also can cause deformation of solid phase dendrites [5–7]. If a transverse magnetic field is applied to a directionally solidifying alloy, macrosegregation perpendicular to magnetic field direction is observed as a consequence of thermoelectromagnetic convection (TEMC) [3]. The electric current through the solidification front can also be applied externally, thus creating a Lorentz force and electromagnetic convection of liquid melt. Directional solidification under the applied electric current and magnetic field has been studied by several authors demonstrating the influence of convection on the metal structure [8–10].

If a direct electric current is applied through the solidification front, the current component which is perpendicular to the magnetic field interacts with it and melt convection is caused by this force. Electrical conductivities of solid and liquid phases can differ several times for metals and metallic alloys, thus, at the dendritic solidification interface the electric current redistribution takes place. In the bulk of the solid and liquid domains, the current density is uniform and the Lorentz force caused by a uniform external magnetic field is irrotational. If this current component is subtracted from the total electric current density, then we obtain a current component which is responsible for electromagnetic convection. This has been done in Fig. 1 showing that the current circulates through the primary dendrite arm and returns through the liquid. This current pattern is similar to thermoelectric current circulation at the dendritic solidification front [7].

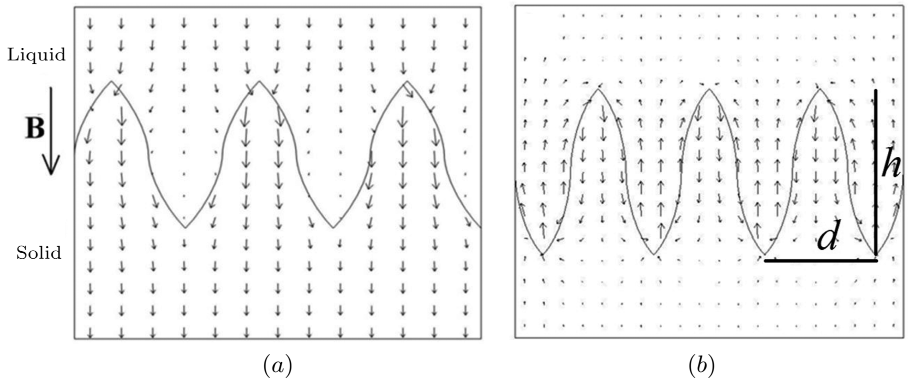

Fig. 1. Conductive current redistribution at the dendritic interface due to different conductivities of solid and liquid phases: (a) current distribution at the interface between two media with different conductivities; (b) current component when the axial current in the liquid bulk is subtracted.

In this work, a Sn-Pb alloy is directionally solidified under the 0.5 T static transverse magnetic field and simultaneously applied DC electric current through the solidification interface. This study is focused on the investigation of the simultaneous action of electromagnetic convection and thermoelectromagnetic convection. It has been experimentally found that electromagnetic convection can cause a similar effect on macrosegregation as thermoelectromagnetic convection.

1. Experimental. High purity tin and lead (99.99%) was used to prepare the Sn-10%wt.Pb alloy, which was then casted into an alumina799 crucible (the length is 110 mm, the inner diameter is 6 mm, the outer diameter is 10 mm). Samples were then remelted and solidified under intense electromagnetic stirring to ensure good homogeneity of initial samples, which were later directionally solidified in a Bridgman setup at a controlled growth velocity and temperature gradient. In those experiments, growth velocities of 3 and 10 μm/s were used. The temperature gradient at the interface was maintained $\theta = 8$ K/mm in all experimental sessions of the work. The upper part of the sample was melted in a resistive furnace around the crucible, whereas the bottom part was kept solid by a water-cooled copper ring. The furnace and the water cooled ring were stationary, while the crucible was lowered by a programmable pulling system. The solidification front was always located between the heater and the cooler at the same location. Thus, the actual solidification velocity was assumed to be equal to the pulling velocity of the crucible. A transverse magnetic field of 0.5 T was created by a permanent magnet system. For optical microscopy analysis, the samples were polished to 1 μm surface roughness and then chemically etched with a 4% nitric acid ethanol solution, which darkened the lead-rich fraction. An electric current was introduced in the liquid part through a 4 mm-diameter stainless steel electrode, as shown in Fig. 2.

Estimations of the TEMC magnitude are given in [7, 11] by solving a simplified Navier-Stokes equation. According to these estimations for a given material with properties given in Table 1 and solidification conditions, the characteristic velocity estimated from Eq. (1) is about 0.25 mm/s.

$$u = \frac{1}{2\rho}\left[\sqrt{\left(c\sigma LB^2 + \frac{\mu}{L}\right)^2 + 4\rho cP\theta B\sigma L} - \left(c\sigma LB^2 + \frac{\mu}{L}\right)\right], \qquad (1)$$

where c is a form constant characterizing the current loop shape at the interface.

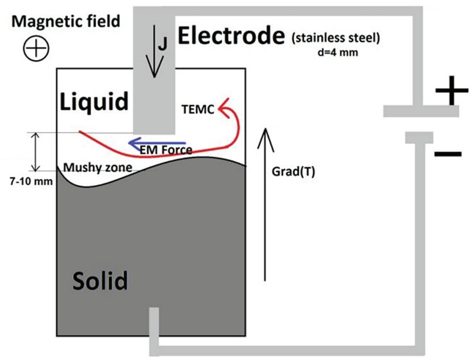

Fig. 2. Experimental scheme for directional solidification with the applied electric current and magnetic field.

Table 1. Physical properties of the Sn-10%wt.Pb alloy used in estimations given for the melting temperature $T_{\mathrm{m}} = 220^{\circ}$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_{L}	$-1{\cdot}10^{-6}$	V/K
Differential thermoelectric power	P	$1{\cdot}10^{-6}$	V/K
Temperature gradient at the front	θ	8	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	

It can be estimated as the ratio $h\sigma_{\mathrm{S}}/(l\sigma_{\mathrm{L}})$. In this case, it is assumed to be 0.5 based on microscopy images of the metal structure. h and l are the vertical and horizontal structure lengths, as shown in Fig. 1. L is the characteristic length which, in this case, is a primary dendrite scale of the given alloy which is assumed to be 0.1 mm.

Now let us estimate the necessary electric current density$j$, which has to be applied through the solidifying sample in order to achieve electromagnetic convection with the same magnitude as TEMC. The electric current density component, which is perpendicular to magnetic field, depends on the ratio of electric conductivities of the alloy in solid and liquid states and on the ratio between vertical and horizontal structure lengths, as illustrated in Fig. 1. The expression relating these quantities is given by Eq. (2), which is only valid if conductivities and sizes are of the same orders of magnitude:

$$j_{\perp} = j\left(1 - \frac{\sigma}{\sigma_{\mathrm{S}}}\right)\frac{h}{d}. \tag{2}$$

The order of magnitude of the thermoelectric current near the solidification interface can be estimated as given in [3]:

$$j_{\mathrm{TE}} = c\sigma\theta\left(S_{\mathrm{L}} - S_{\mathrm{S}}\right) = 1.1 \cdot 10^4\ \mathrm{A/m}^2. \tag{3}$$

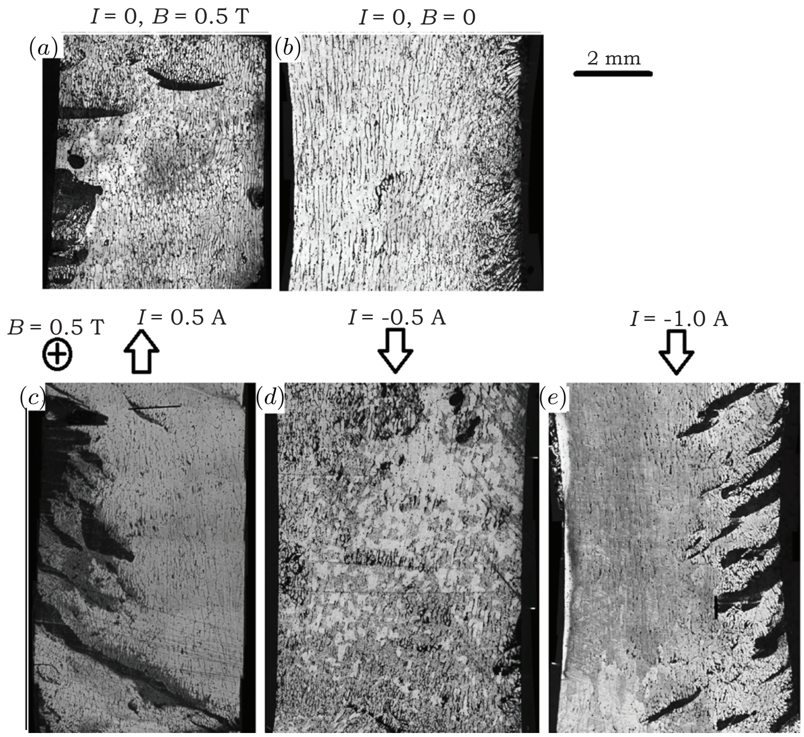

Fig. 3. Directionally solidified Sn-10%wt.Pb alloy at v = 3 μm/s under the 0.5 T static transverse magnetic field and electric current: (*a*) $I = 0$, $B = 0.5\,\mathrm{T}$; (*b*) $I = 0$, $B = 0$; (*c*) $I = 0.5\,\mathrm{A}$, $B = 0.5\,\mathrm{T}$; (*d*) $I = -0.5\,\mathrm{A}$, $B = 0.5\,\mathrm{T}$; (*e*) $I = -1.0\,\mathrm{A}$, $B = 0.5\,\mathrm{T}$.

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

2. Results and discussion. Experiments were performed to test the hypothesis that electromagnetic convection can eliminate the crucible scale macrosegregation caused by the transverse magnetic field and thermoelectric effect, or enhance, or reverse the macrosegregatin direction if an appropriate electric current value is chosen. In our case, the temperature gradient was directed along the axis of the crucible from bottom to top and the differential thermoelectric power was positive [12]. This means that the applied current from the sample bottom enhances TEMC, while the current from the top creates a convection opposite to TEMC. Several solidification experiments were performed to verify this hypothesis.

The experimental results are summarized in Figs. 3, 4. The results agree well with a previous study on directional solidification of Sn-Pb alloys [13]. Fig. 3 shows a directionally solidified 6 mm-diameter Sn-10%wt.Pb sample at a velocity of 3 μm/s, with different electric current values through the sample. Fig. 3*b* shows a directionally solidified sample without magnetic field and electric current. Fig. 3*a* shows the solidification structure with an applied transverse magnetic field of 0.5 T, the segregation, in this case, was 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*, thus we can observe the segregation of the heaviest phase perpendicular to the magnetic field. This result has been observed and considered by several authors [2, 3]. Fig. 3*c* shows how the

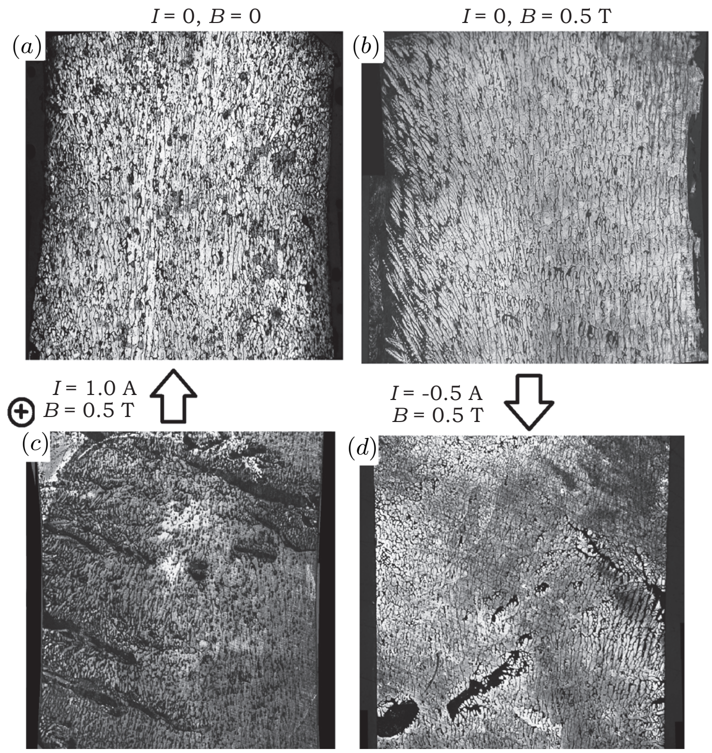

Fig. 4. Directionally solidified Sn-10%wt.Pb alloy at $v = 10\,\mu\text{m/s}$ under the 0.5 T static transverse magnetic field and electric current: (*a*) $I = 0$, $B = 0$; (*b*) $I = 0$, $B = 0.5\,\text{T}$; (*c*) $I = 1.0\,\text{A}$, $B = 0.5\,\text{T}$; (*d*) $I = -0.5\,\text{A}$, $B = 0.5\,\text{T}$.

segregation can be enhanced by the application of the electric current from the bottom of the sample. In this case, electromagnetic convection acts in the same direction as TEMC, thus, as we can see in Fig. 3*c* that the segregation is more distinct than in Fig. 3*a*, where it is caused only by TEMC. Fig. 3*d* displays the structure of a solidified sample if the current is applied from the top of the sample. In this case, according to the estimations given in section 2, electromagnetic convection acts opposite to TEMC with the same magnitude. As can be seen in this case, segregation is significantly weaker. In Fig. 3*d*, it can be seen that there are larger lead rich zones and the vertical structure size is shorter than in the reference experiment with no magnetic field (Fig. 3*b*). This can be explained by the fact that the magnetic field damps natural convection in the crucible, which also produces a significant influence on the solidification structure [14, 15]. Fig. 3*e* presents a case when electromagnetic convection is twice stronger than TEMC and acts opposite to it; it is observed that the segregation direction is reversed compared to Fig. 3*a*, where only TEMC is present, but the segregation magnitude in these two pictures is similar. Fig. 4 shows the solidification structure of the Sn-10%wt.Pb alloy directionally solidified at $10\,\mu\text{m/s}$. It can be seen that in this case macrosegregation is less distinct than in Fig. 3, which agrees with our expectations, because in all works describing TEMC it is concluded that the TEMC effects can be better observed if the solidification velocity is low [2, 3]. Fig. 4*a* shows the reference sample of the directionally solidified Sn-10%wt.Pb alloy with no electric current and magnetic field. Fig. 4*b* illustrates the directionally solidified alloy at $10\,\mu\text{m/s}$ under the 0.5 T static transverse magnetic field. It can be clearly observed in Fig. 4*b* that the segregation is much less distinct than in Fig. 3*a*, where the solidification rate is 3 μm/s. In Fig. 4*c*, we can see the solidification structure in the case when TEMC and EM convections act in the same direction causing a stronger net flow and, hence, a stronger segregation than only by TEMC in Fig. 4*b*. Fig. 4*d* demonstrates the case when TEMC and EM convections of similar magnitudes act opposite to each other, and no macrosegregation to one side is observed. This can indeed be observed if we compare Fig. 4*d* to Fig. 4*b* and Fig. 4*c*.

3. Conclusion. It has been experimentally demonstrated that the direct current through the directionally solidified sample can be used to control macrosegregation at directional solidification of the metallic alloy. Theoretical analysis and numerical simulation of the current distribution along the interface show that the transverse magnetic field and the applied electric current produce a force distribution similar to the thermoelectric force density. This means that by choosing the appropriate electric current value, the segregation caused by thermoelectromagnetic convection can be fully compensated, enhanced or reversed by electromagnetic convection. This hypothesis is proven by a series of experiments which are summarized in Figs. 3, 4. Macrosegregation of the heavier fraction is more distinct with the 3 μm/s solidification rate. This case gives evidence of good agreement between experimental results and estimation of necessary current value. Figs. 3*a*,*c* show that macrosegregation can be enhanced if TEMC and EM convections act in the same direction. Fig. 3*d* shows that macrosegregation is less distinct if TEMC and EM convections of similar magnitudes act in opposite directions. Fig. 3*e* shows the case when TEMC and EM convection directions are opposite, but the macrosegregation direction is defined by electromagnetic convection which is twice stronger. This approach allows to enhance or suppress the melt flow and the macrosegregation caused by TEMC. Thus, it also makes possible to control segregation of metallic alloys with low absolute thermoelectric power or with poor electric conductivity.

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