Journal of Crystal Growth 402 (2014) 230–233

Contents lists available at ScienceDirect

Journal of Crystal Growth

journal homepage: www.elsevier.com/locate/jcrysgro

Influence on the macrosegregation of binary metallic alloys by thermoelectromagnetic convection and electromagnetic stirring combination

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ARTICLE INFO

Article history:
Received 8 August 2013
Received in revised form
9 April 2014
Accepted 9 June 2014
Communicated by A.G. Ostrogorsky
Available online 16 June 2014

Keywords:
A1. Directional solidification
A1. Thermoelectromagnetic convection
B1. Alloys

ABSTRACT

Influence of a slowly rotating 0.5 T transverse magnetic field on the directionally solidified metallic alloy has been experimentally studied in this work. Main idea is to study an influence on the melt flow and material structure caused by the simultaneous electromagnetic stirring and thermoelectromagnetic convection with comparable magnitudes. Electromagnetic stirring and thermoelectromagnetic convection intensities have been estimated analytically to find optimal experimental parameters. It is experimentally demonstrated that with such an interaction it is possible to modify component macrosegregation of Sn–10 wt% Pb alloy. Helical macrosegregation within cylindrical sample is obtained as a result of simultaneous influence of thermoelectromagnetic convection (TEMC) and electromagnetic stirring of the liquid melt. Obtained experimental results allow to determine TEMC velocity by comparing the intensities of TEMC and electromagnetic stirring.

1. Introduction

It is well known that a static magnetic field during directional solidification of metallic alloy can affect its structure. For different alloys this influence might have different effects. Applied magnetic field can modify characteristic dendrite arm spacing of the alloy [1–4], component macrosegregation along the cross section of the sample [5], grain orientation, or even change the solidification interface shape [6]. Main mechanism which is responsible for the magnetic field influence on melt flow is thermoelectric effect at the solid liquid interface [7]. Most of the metallic alloys has a jump of the absolute thermoelectric power between solid and liquid phases at melting temperature, temperature gradient is always present across the solidification interface. If these conditions are fulfilled then thermoelectric current circulates near the solidification interface in solid and liquid phases. Applied magnetic field interacts with this current and creates Lorentz force which may drive the thermoelectromagnetic convection (TEMC) [8–9]. Transverse magnetic field creates Lorentz force and TEMC in the plane perpendicular to the magnetic field as shown in Fig. 1(a). Usually effects of TEMC are studied by directional solidification in Bridgman setup, where alloy is solidified at controlled solidification velocity and temperature gradient at the solidification front [10].

Influence of a pulsating or rotating magnetic field on the structure of an alloy has been widely studied experimentally and theoretically. It is demonstrated that electromagnetically induced melt convection decreases characteristic grain size [11], modifies columnar to equiaxed (CET) transition [12], and homogenizes the material structure [13]. Usually of a practical interest is relatively high magnetic stirring intensities, thus TEMC and natural convection are secondary effects and are normally disregarded in these studies.

In this work we investigate the regime when TEMC and electromagnetic stirring caused by a rotating magnetic field is of comparable magnitudes. In this case influence on the microstructure and macrosegregation in the sample caused by magnetic field is defined by net melt flow formed by the TEMC and electromagnetic stirring combination as shown in Fig. 1(b)

2. Experimental procedure

High purity tin and lead (99.99%) is used to prepare Sn–10 wt% Pb alloy, which is then casted into the alumina799 crucible ($L=110$ mm, $ID=6$ mm, $OD=10$ mm). Samples are later remelted

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http://dx.doi.org/10.1016/j.jcrysgro.2014.06.029
0022-0248/

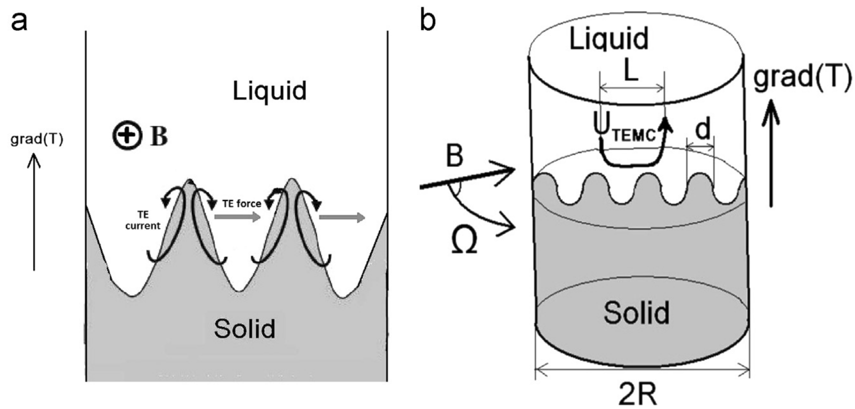

Fig. 1. (a) Thermoelectric current and force at the solidification interface caused by transverse magnetic field and (b) TEMC flow above solidification interface in a cylindrical crucible under a rotating transverse magnetic field.

and solidified under intense magnetic stirring to ensure good homogeneity of the initial samples. Samples are directionally solidified in a Bridgman setup at controlled growth velocity and temperature gradient. Upper part of the sample is melted by the furnace around the crucible while bottom part is kept solid by a water cooled copper ring. Furnace and water cooled ring are stationary while crucible is lowered by a programmable pulling system. Experiments are started at stationary situation when temperature field is constant and convection is well established. Solidification front is always located between heater and cooler at the same location, thus actual solidification velocity is assumed to be equal to the pulling velocity of the crucible. Magnetic field of 0.5 T is created by the permanent magnet system, which is rotated around the furnace by electric step motor allowing to vary field rotation velocity between 0.1 rev/min and 2 rev/min. Solidified samples are latter cut and longitudinal and transverse cross sections are examined. For optical microscopy analysis samples are polished to 1 μm surface roughness and then chemically etched. To visualize the cellular structure of Sn–Pb alloy, pretreatment with the 10% aqueous HCl solution is done to remove oxidation products from the surface. Dendritic structure and qualitative component distribution is revealed by etching the polished samples with 4% nitric acid ethanol solution, which darkens the lead rich phase.

3. Theoretical description

Electric current flow in the continuous media is described by the Ohm's law

$$\frac{\vec{j}}{\sigma} = \vec{E} + \vec{u}\vec{B} - S\nabla T \tag{1}$$

TEMC velocity near the solidification interface is determined by the properties of an alloy at the solid and liquid states and temperature gradient, and also solidification interface shape. Several works exist where TEMC velocity is estimated by solving simplified force balance equation in the liquid melt [6,8]. Liquid phase motion is governed by the Navier–Stokes equation:

$$\rho\left(\frac{\partial \vec{u}}{\partial t} + \vec{u}\nabla\vec{u}\right) = -\nabla p + \mu\nabla^2\vec{u} + \rho\vec{g}\beta\theta L + \vec{j}\vec{B} \tag{2}$$

TEMC velocity order of magnitude at a dendrite scale $L=d$ can be estimated by solving simplified Navier–Stokes equation where derivatives is replaced by the ratios of characteristic quantities. For the order of magnitude estimation in stationary case, Eq. (2) is simplified by replacing derivatives by simple ratios of characteristic values, thus $\nabla\vec{u}$ becomes u/L and $\nabla^2\vec{u}$ becomes u/L^2. Current density is substituted from Ohms law Eq. (1)

$$\rho\frac{u^2}{L} + \mu\frac{u}{L^2} + c\sigma(uB^2 - P\theta B) = 0 \tag{3}$$

where c is a constant introduced because Lorentz force on the liquid is generated by the current in the liquid phase only, thus this constant characterizes current path length in liquid state. Solution of square Eq. (3) gives the following expression for TEMC velocity order of magnitude:

$$u = \left(\sqrt{\left(c\sigma LB^2 + \frac{\mu}{L}\right)^2 + 4\rho cP\theta B\sigma L} - \left(c\sigma LB^2 + \frac{\mu}{L}\right)\right)/2\rho \tag{4}$$

For directionally solidified Sn–Pb alloy with front velocities of 2–10 μm/s used in these experiments, it is reasonable to choose characteristic primary dendrite arm spacing size d=0.1 mm, which is typical spacing reported in other works with directional solidification of this alloy [5,14]. For given alloy this estimation gives characteristic velocity of 0.2 mm/s. This order of magnitude estimation gives characteristic velocity value in infinite continuous media, but oriented convection velocity is smaller due to the limitations of the crucible and uneven Lorentz force distribution along dendritic solidification front, thus u_{TEMC}=0.1 mm/s would be an approximate assumption.

To estimate magnetic stirring velocity caused by the rotating magnetic field we may look at the problem where long liquid metal cylinder under rotating magnetic field is analyzed [15–17]. In order to estimate the balance between forces acting on the fluid it is useful to introduce some dimensionless parameters characterizing the flow regime. Hartman number $Ha = BR\sqrt{\sigma/\mu}$ shows the ratio between electromagnetic and viscous forces, Lorentz force versus inertia is characterized by the magnetic interaction parameter $N = \sigma B^2/\rho\Omega$, and magnetic Reynolds number $R_m = \mu\sigma\Omega R^2$ defines significance of the skin effect. Taylor number $Ta = \sigma\Omega B^2R^4\rho/2\mu^2$ characterizes electromagnetic force created by rotating magnetic field versus viscous force.

Inserting the parameters from Table 1 we get Ha=42 and N=2500 and R_m=7×10^{-7}, and Ta=1000. This parameter combination means that Lorentz force is dominant over viscous force and inertia. Low R_m indicates that skin effect in this case can be neglected. Thus rigid body approximation for liquid metal column rotation can be used in this case

$$u_\theta = Ar \tag{5}$$

Indeed, numerical simulation of this problem given in Ref. [16] shows that with the similar R_m and Ha combination nearly synchronous rotation can be achieved in the bulk of the liquid.