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Abstract

Three alloys were directionally solidified at low growth speeds under a transverse magnetic field. The results show that the application of the transverse magnetic field significantly modified the solidification structure. Indeed, we found that along with the refinement of cells/dendrites, the magnetic field caused the deformation of liquid-solid interfaces, extensive segregations (i.e., freckles and channels) in the mushy zone. Moreover, we observed that dendrite fragments and equiaxed grains were moved approximately along the direction perpendicular to the magnetic field. Modification of the solidification structure under a weak magnetic field is attributed to a TEMC-driven heat transfer and interdendritic solute transport and a TEMF-driven motion of dendrite fragments.

Keywords: Transverse magnetic field; Directional solidification; Solidification structure.

Introduction

Solidification in a magnetic field is an interesting topic and has attracted much attention from researchers. However, the effect of a static magnetic field on solidification has not been well understood, mainly because the experimental observations were made in different configuration, such as ingot solidification or directional solidification. In ingot solidification, the magnetic field brakes the convection in the liquid and reduces the heat-transfer rate [1-2]. In directional solidification, the magnetic field also brakes the convection, but in directional solidification in the dendritic regime, some unexpected behaviors are observed [3-7]. These behaviors depend on the composition of the alloy and the experimental conditions. Youdelis and Dorward [3, 4] applied a 3.4 T transverse field on the directionally solidified Al-Cu alloy. The result showed that the value of the effective partition coefficient decreased with the presence of the field, as if the magnetic field enhanced mass transport in the liquid. Tewari *et al*. [5] found that the cellular array was severely distorted, and stripes of freckles on the plane perpendicular to the magnetic field formed when a Pb-Sn alloy was solidified vertically at very low growth speeds under a 0.45 T transverse magnetic field. The experiment were performed by Alboussière *et al*. [6] and Laskar [7] on Bi-60wt.%Sn and Cu-45wt.%Ag alloys, solidified vertically under solutally and thermally stabilizing condition with a 0.6 T transverse or 1.5 T axial magnetic field. Large freckles appear in this case, showing that a new movement has been created. Alboussière *et al*. [6] suggested that this new flow was induced by the interaction between the magnetic field and thermoelectric effects. Subsequently, Lehmann *et al*. [8] offered some experimental evidence for thermoelectromagnetic convection (TEMC).

In this work, the effect of a transverse magnetic field on the solidification structure in three different alloys was investigated experimentally. The results show that along with refinement of the cell/dendrite, the magnetic field caused the deflection of the liquid-solid interfaces, extensive segregations (i.e., freckles and channels) in the mushy zone and the change of the mushy zone length. Furthermore, the processing of solidification experiment under the magnetic field was recorded by *in-situ* synchrotron X-ray imaging. Dendrite fragments and equiaxed grains were observed to be moved approximately along the direction perpendicular to the magnetic field.

Experiment description

Three alloys (i.e., Al-2.5wt.%Cu, Sn-20wt.%Pb, and Sn-20wt.%Bi alloys) were solidified directionally under a weak transverse magnetic field. Cast samples were enveloped in tubes of high-purity corundum with an inner diameter of 3 mm and a depth of 200 mm for directional solidification. The experimental device is comprised of an electromagnet, a Bridgman-Stockbarge type furnace, and a growth velocity and temperature controller. The electromagnet with a pole diameter of 20 cm and a pole separation of 18 cm can produce a transverse static magnetic field with adjustable intensity up to 1 T. The furnace, consisting of non-magnetic material, has a negligible effect on the field uniformity. The temperature in the furnace can reach 1600 ℃, A water-cooled cylinder containing liquid Ga-In-Sn metal (LMC) was used to cool the sample. During the experiment, the samples in the corundum crucibles were melted and directionally solidified in the Bridgman apparatus by pulling the crucible assembly into the LMC cylinder at various velocities. The etched samples obtained from these experiments were examined by optical microscope. In situ and real-time observation of the solidification process was realized using synchrotron X-ray radiography at the European Synchrotron Radiation Facility (ESRF). The main surface of a thin sheet-like sample ($40\times6\times0.2$ mm^3) was set perpendicular to the incident monochromatic X-ray beam. Directional solidification was realized by the power-down method, with displacement of neither the sample nor the furnace. In this method, the temperatures of the hot and cold zones of the furnace were first adjusted to achieve the desired temperature gradient, in the range 20-40 K/cm. The energy of the monochromatic X-ray beam was adjusted to 14 keV, which is an appropriate value for hypoeutectic Al-Cu alloys. Real-time images were recorded by a fast readout-low noise CCD camera.

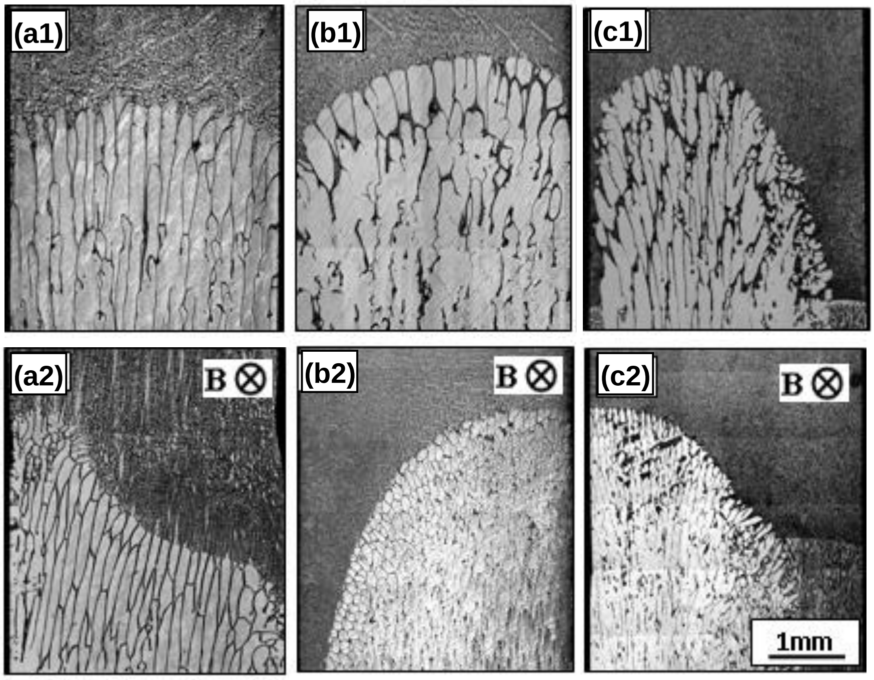

Fig. 1. Microstructures near the liquid-solid interface in three directionally solidified alloys both without and with a 0.5 T transverse magnetic field: (a) Al dendrite in Al-2.5wt.%Cu alloy, 5 μm/s; (b) Sn dendrite in Sn-20wt.%Bi alloy, 1 μm/s; (c) Sn dendrite in Sn-20wt.%Pb alloy, 1 μm/s.

Results and discussion

Fig. 1 shows the longitudinal structures near the quenched liquid-solid interface obtained in directionally solidified above mentioned alloys at low growth speeds (1-5μm/s). The growth length at quenching was 60 mm. The dendrite morphology without the magnetic field is typically columnar, and the liquid-solid interface is nearly protruding. However, when a transverse magnetic field is applied, the liquid-solid interface shape becomes sloping. Moreover, the cellular/dendritic spacing reduces and segregation (i.e., freckles and channels) occurs under the magnetic field. The Al-2.5wt.%Cu were used to study the effect of the magnetic field on the cellular/dendritic spacing in detail. Fig. 2 shows the cellular spacing as a function of the magnetic field intensity during directional solidification of the Al-2.5wt.%Cu alloy. One can notice that the cellular spacing decreases as the magnetic field increases. Fig. 3 shows four typical X-ray images at successive times during the directional solidification of the Al-4wt.%Cu alloy at a temperature gradient of 20 K/cm and a cooling rate of 2 K/min under a 0.08 T transverse magnetic field. The X-ray images indicate that the sloping liquid-solid interface and channel segregation formed during directional solidification under a transverse magnetic field. This is good agreement with the results as shown in Fig. 1. Moreover, one can notice that dendrite fragments were detached from dendrites and moved approximately along the direction perpendicular to the magnetic field.

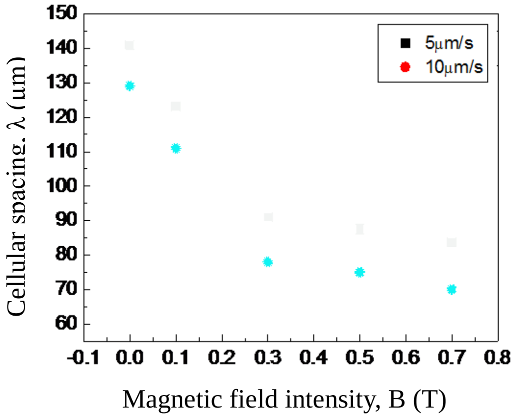

Fig. 2. Cellular spacing as a function of the magnetic field intensity during directional solidification of the Al-2.5wt.%Cu alloy.

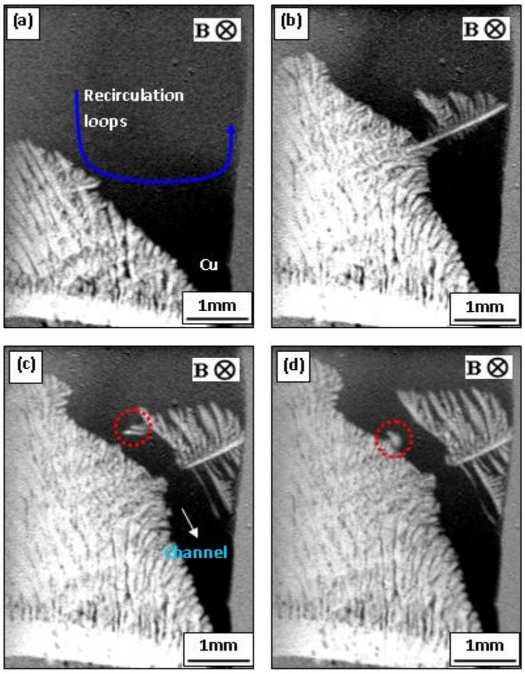

Fig. 3. The successive *in-situ* Synchrotron X-ray images with a 0.08 T transverse magnetic field during directionally solidified Al-4wt.% Cu alloy at a temperature gradient of 20 K/cm and a cooling rate of 2 K/min.

The above result should be attributed to the effect of convection on the distribution of the solute in the bulk melt ahead of and in the mushy zone. When the magnetic field is applied during directional solidification, a thermoelectric magnetic force (TEMF) and thermoelectric magnetic convection (TEMC) will form. In the case of the magnetic field perpendicular to the solidification direction, a uniform TEMC forms within the mush just like “interdendritic forced convection”. Fig. 4(a) shows the TEMC during directional solidification under a transverse magnetic field in two cases, $S_S > S_L$ and $S_S < S_L$. The TEMC will further induce recirculation loops in the bulk melt ahead of and in the mushy zone. The TEMC and the corresponding recirculation loops will cause heavier solute to move along the direction perpendicular to the magnetic field (i.e., the direction of the TEMF) as shown in Fig. 4(b). As a consequence, the concentration of the solute increases from one side of the sample to the other side and the sloping solid-liquid interface forms. Because the direction of the TEMC in the above-mentioned two cases is different, the liquid-solid interface shape is different (see Fig. 1). Moreover, the TEMF also acts on the solid grain and cause the movement of the solid grain as shown in Fig. 4(b). The effect of the convection on the dendrite/cell spacing has ever been studied. Lehmann et al. [9] proposed the dendrite/cell spacing to flow velocity U which is parallel to the columnar as follows:

$$\lambda = \lambda_0 / \sqrt{1 + (U/R)} \qquad (1)$$

where λ_0 is the primary spacing without convection, U the velocity and R the growth speed. According to Eq. (1), it can be deduced that the TE magnetic convection will reduce the dendrite/cell spacing.

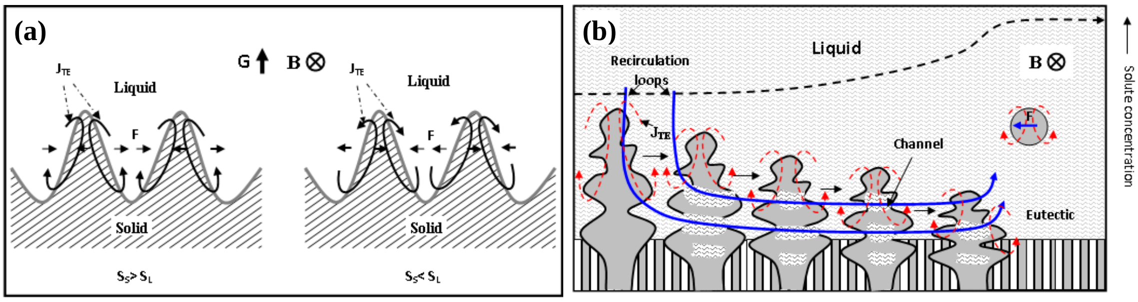

Fig. 4. Schematic sketch of the TEMF and interdendritic TEMC and their effects on solidification structure during directional solidification under a transverse magnetic field: (a) TEMF acting on the solid and liquid under a magnetic field perpendicular to the solidification direction in two cases; (b) TEMC near the sloping liquid-solid interface and TEMF acting on a grain in the liquid.

Conclusion

The application of a weak transverse magnetic field during directional solidification modified the shape of the liquid-solid interface and the cellular/dendritic array significantly. Along with the refinement of the cell/dendrite, the magnetic field caused the deflection of liquid-solid interfaces, extensive segregation in the mushy zone and the change of the mushy zone length in these alloys. Further, we observed that dendrite fragments and equiaxed grains were moved approximately along the direction perpendicular to the magnetic field. The modification of the solidification structure during directional solidification under the magnetic field can be attributed to the TEMC-driven heat transfer and interdendritic solute transport and the TEMF-driven motion of dendrite fragments.

Acknowledgements

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