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Motion of equiaxed grains during directional solidification under static magnetic field

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ABSTRACT

The in situ and real time observations of the equiaxed grain motion during directional solidification of Al–10 wt% Cu under static magnetic field has been carried out by means of synchrotron X-ray radiography. It was observed that equiaxed grains moved approximately along the direction perpendicular to both the imposed magnetic field and the temperature gradient. Based on the radiographs, the motion of the solid grains was analyzed for various temperature gradients, and it was shown that the trajectories were imposed by the combination of the Thermo-Electric Magnetic forces, induced by the coupling of thermo-electric currents with the permanent magnetic field and the gravity force. The variations of the velocities and sizes of grains during the equiaxed growth under static magnetic field were measured and compared to a simple analytical model for the Thermo-Electric Magnetic forces and the Stokes law. A good agreement was achieved for the deviation angle as a function of the grain diameter, while a large discrepancy was observed for the velocity intensity when the dimensions of the equiaxed grains increased. In the latter case, it was shown that the corrections for both sample confinement and grain morphology were mandatory to explain the very low values of grain velocities.

1. Introduction

The use of external magnetic fields is a widespread technique to control the flows in the melt during metal solidification and then to modify the final properties of the grown material, leading to improvement of the process performance and better quality products [1–3]. The main advantage of this technique is to be contactless, which prevent alloy contamination, and also to avoid any risk when using brittle crucible. A non-permanent magnetic field may be utilized to increase melt stirring, which may be useful for producing either a more uniform melt by a strong mixing in the liquid phase, or a shear flow to induce grain refinement effects during metal casting. Alternatively, a permanent magnetic field can be used in order to damp or eliminate convection during solidification due to the Lorentz force, generated by the interaction between the induced electric current and the applied magnetic field [4,5]. It is well recognized that electromagnetic braking reduces inclusions and improved uniformity of compositions and mechanical properties. In addition, Shercliff [6] pointed out that a static magnetic field can produce flows in melt during the metallurgy process caused by the interaction of the magnetic field with variations of the Seebeck coefficients at the solid–liquid interface. Such flows have been well studied in the case of solidification of metallic alloys [7–9] and in the context of pumping or stirring liquid metal coolants in nuclear reactor [10].

Another important but neglected aspect up to now is the existence of the Thermo-Electro-Magnetic Forces (TEMF), created by the interaction between the electric current generated by the thermoelectric effect in the vicinity of the liquid–solid interface submitted to a temperature gradient (Thomson–Seebeck effect) and the static magnetic field [6,8]:

$$F_{TEM} = j \times B_0 \qquad (1)$$

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where F_{TEM} stands for the Thermo-Electro-Magnetic force (TEMF), j the electric current and B_0 the applied static magnetic field. Thermo-electric currents in each phase are generated by a temperature difference along the solid–liquid interface and are function of the solid and liquid phase Seebeck coefficients (S_l and S_s) and the temperature gradient $G = \nabla T$. Then the electric current density in each phase may be written as follows:

$$j_i = -\sigma_i(\nabla V + S_i \nabla T),\ i = l, s \text{ respectively in the liquid and in the solid.} \quad (2)$$

In Eq. (2) V denotes the electric scalar potential and σ_ι the electrical conductivity of solid or liquid phase. The second term of the right hand side in Eq. (2) accounts for the contribution of the thermoelectric current via the thermoelectric power S_i of the materials. The electric current created by the interaction between the fluid motion and the applied magnetic field, which is given by $\sigma_l(u \times B)$, is neglected in Eq. (2). In fact, the influence of that contribution to the total electric current density is quantified by the Hartmann number, $Ha = B_0 L \sqrt{\sigma_l/\mu}$, the ratio of the electromagnetic force to the viscous force [11], with μ the dynamic viscosity. Taking $L \approx 50\ \mu\text{m}$, the typical dimension of the liquid flow around the solid grain, the value of Ha is around 0.2, which is lower than 10, the value over which braking is felt, and justifies the above approximation. Note that for large size grains there is a confinement of the electric current density in the liquid bath due to the presence of the lateral walls. The latter effect tends to decrease the electromagnetic force on the particle [12].

In a recent paper [13], it has been demonstrated using in situ observation by means of synchrotron X-ray radiography that TEMF forced the dendrite fragments to move roughly horizontally, instead of vertically downward as it is the case in solidification experiments without magnetic field. Actually, for Al–Cu alloys having a composition lower Al–10 wt% Cu, the solid grains are weakly denser than the surrounding melt and thus settle down in the liquid phase in the absence of magnetic field [14]. This observation is in qualitative agreement with the prediction of an analytical model assuming a spherical solid particle immersed in a liquid metal under an imposed constant vertical thermal gradient, which shows that the TEMF acting on the particle has only one component along horizontal y-direction and its intensity is proportional to the volume Vol of the sphere [13]:

$$F_y = -2\left[\frac{\sigma_s \sigma_l}{2\sigma_l + \sigma_s}\right](S_s - S_l)\, G B_0 Vol \quad (3)$$

In the present paper, we describe experimental results on the effect of TEMF on the motion of equiaxed grains, formed during the solidification of an Al–10 wt% Cu sample. For this purpose and since these phenomena were in essence dynamic, it is of major interest to be able to investigate in situ and in real time the solidification process. As a consequence, synchrotron X-ray imaging was used, which has been established as a method of choice for such studies [15,16].

2. Experiments

The experiments were carried out on beamline BM05 at the European Synchrotron Radiation Facility (ESRF, Grenoble, France). Directional solidification experiments were performed inside a Bridgman furnace, which has been described in detail previously [17]. The thermal gradient G (along the z-direction) was imposed by two separated heating elements and the solidification was controlled by applying the same cooling rate R on the two heating elements. The temperature adjustment was monitored using two embedded K-type thermocouples, one at the top and other at the bottom on either side of the sample, 2 cm away from each other. A series of solidification experiments were carried out with the same cooling rate $R = 2$ K/min, the same permanent magnetic field, and various temperature gradient G decreasing from 20 K/cm to nearly zero. The thin sample studied was 35 mm in length, 5 mm in width and 230 μm in thickness. To minimize grain sinking phenomena, solidifications were conducted on Al–10 wt% Cu alloy for which the grain density is weakly larger than the surrounding liquid [14].

The static magnetic field was generated by a cubic neodymium magnet (50 mm × 50 mm × 50 mm), which was fixed close to the Bridgman furnace and imposed a permanent magnetic field B_0 of 0.08 T. The direction of the field was set before the experiment parallel (x-direction) to the beam, and its intensity was almost uniform over the sample.

The solid–liquid interface was visualized by X-ray radiography: the main surface of the sample (y–z plane) was set perpendicular to the incident monochromatic X-ray beam. Absorption is the main source of the image contrast and mainly depends on the atomic number of the elements and the solute content. In our experiments, the X-ray energy was adjusted to 17.5 keV, which is an appropriate value for hypoeutectic Al–Cu alloys. In all the radiographic images, the aluminum solid microstructures appear in white and the copper-rich liquid in dark gray. The optics were chosen to obtain a large field of view (10 mm × 6 mm), which is essential in these kinds of studies to visualize and follow the motion of equiaxed grains over a long distance. The resolution was then imposed by the optics (pixel size 7.46 μm × 7.46 μm), which was sufficient for our purpose. The high intensity of synchrotron radiation makes it possible to record images with enough contrast in a reasonable timescale (~0.7 s), which is sufficient to investigate the movement of the equiaxed grains during solidification. The details of this synchrotron X-ray radiography setup can be found in Ref. [17].

To ease the grain motion analysis, a simple image processing was used, which consisted of taking the maximum intensity of successive radiographs to create a single image (Fig. 1). As the α-Al grains appeared in white in radiographs, this image processing revealed the successive positions of the grain and thus its trajectory (black dashed line with arrow in Fig. 1). Then, the time evolution of key parameters such as the grain surface, the velocity and the angle θ between the trajectory and the gravity direction can be easily measured. It is worth noticing that all the grains are not equivalent, because they nucleated at different instants along the experiment and then experienced different environment (number of neighbors, solute segregation in the sample). For this

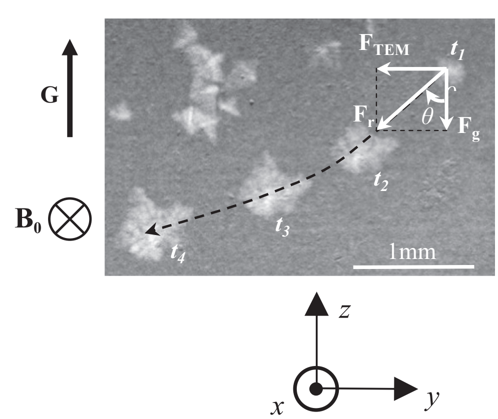

Fig. 1. Image showing the maximum intensity of four successive radiographs, revealing the four successive positions of a growing grain and thus its trajectory. The forces acting on the grain are indicated by the white arrows (F_g: the buoyancy force, F_{TEM}: the Thermo-Electro-Magnetic force and F_r: the resultant force). θ is the angle of the resultant force in respect to gravity.