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Macro segregation formation mechanism of the primary silicon phase in directionally solidified Al–Si hypereutectic alloys under the impact of electric currents

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ABSTRACT

Understanding the macro segregation formed by applying electric currents is of high commercial importance. This paper investigates how electric currents control the solute distribution in the directionally solidified Al–20.5 wt%Si hypereutectic alloy. Experimental results show that a severe macro segregation of the primary silicon phase occurs at the initial solidification stage of the samples. This is accompanied by two interface transitions in the mushy zone: quasi planar → upwards V-shaped → quasi planar. The corresponding numerical simulations present a vortex ring flow pattern as a consequence of the electric current distortion in the mushy zone. The peculiar macro segregation phenomenon can be fully explained by considering the effect of the forced flow on the solute distribution. At the initial growth of the samples, the forced flow generates a rigorous solute exchange between the mushy zone and the bulk melt and encourages the primary silicon to continuously precipitate and segregate. As the solute content in the bulk melt gradually approaches the eutectic point, the precipitation of primary silicon is profoundly reduced. Eventually, a significant segregation of the primary silicon phase is observed in the initial directional growth. The present study not only presents a new approach to control the solute distribution by applying an electric current through a generated forced flow, it also facilitates the understanding of the underlying grain refinement mechanism and the growth of crystals in the solute that are controlled by the electric currents.

1. Introduction

Applied electric currents have shown the ability to significantly modify the solidification process of alloys in regards to their grain size [1–10], crystal growth [11–15] and the solute, or inclusion distribution [16–19]. The influence of electric currents on the grain size has been scrutinized due to the reduction of size guaranteeing enhanced mechanical properties in the alloy. Numerous experiments have demonstrated that the remarkable grain refinement was achieved in the solidifying process of Sn, Zn, Al and Fe based alloys under the impact of electric currents [1–10]. On the other hand, the crystal growth under the influence of electric currents was carried out in directionally solidified alloys [11–15]. The results showed that the utilization of electric currents could promote the stability of the solid–liquid interface [11,12], decrease the primary cellular spacing [12], and modify the crystal morphology [13–15]. Additionally, the electric current treatments are being used in industry to control the grain size and dendrite morphology of alloy ingots at a large-scale production pace.

Controlling the macro segregation of alloy ingots is of high commercial importance due to the inhomogeneous mechanical properties of product it can cause along with remarkably deteriorating the quantity of the alloy ingots. However, it is unfortunate that there is not wider spread knowledge about the impact of electric currents on the macro segregation formation in solidified alloys. The idea remains fragmented and inconsistent, which greatly limits the implementation of electric currents to the large commercial ingot production. For example, Li et al. [16] and Ma et al. [17] reported that the carbon macro segregation in a steel ingot can be improved by electric currents. Researchers have also shown that

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electric currents have the potential to induce the segregation in metal alloys due to various effects caused by the application of the currents, such as the free energy minimizing [18,19], the electro migration [20], and the Lorenz force [21,22].

To control the macro segregation of alloys, many studies have been performed and concluded that the forced flow in the mushy zone played a key role in the macro segregation formation [23–32]. The forced flow can be driven by produced magnetic fields such as the rotating magnetic field (RMF) and traveling magnetic field (TMF) [33–37]. Applying RMF in a directionally solidified AlSi7Mg0.6 alloy, Zimmermann et al. found that the forced flow resulted in axial macro segregation (rich silicon) in the centre part of sample [33]. Meanwhile, Zaïdat et al. reported that a freckled segregation in the directionally solidifying Al–3.5 wt%Ni alloy was induced under the influence of TMF [34]. Noeppel et al. gave a further explanation regarding the macro segregation formation process in directionally solidified alloys under the influence of RMF or TMF [35]. Furthermore, a novel approach was invented by Willers et al. to control the macro segregation of solidified Al–Si alloy by modulating the application time of RMF [36]. Recently, based on a series of Al–Si alloy solidification experiments with RMF, Jie et al. proposed a macro segregation formation mechanism [37].

Similarly, is it possible to control the macro segregation by the application of a forced flow caused solely by electric currents? The present study is devoted to confirming the macro segregation formation under the impact of forced flow induced by electric currents. The configuration was designed by applying axially aligned electric currents through a cylindrical Al–20.5 wt%Si hypereutectic alloy sample during the directional solidification process. A series of experiments were carried out to take full consideration of the occurrence and formation of macro segregation with influence of the electric currents. Corresponding numerical simulations were conducted in the same configuration with regards to the forced flow. Finally, the macro segregation formation mechanism of primary silicon phase was discussed along with various effects of electric currents on the segregation.

2. Experimental methods

The directional solidification experiments of an Al–20.5 wt%Si hypereutectic alloy were carried out in a modified Bridgman directional solidification furnace, schematically shown in Fig. 1a. A fixed cylindrical electric resistance furnace was used to heat the sample with a temperature control at a precision of ±1 K. A cylindrical alumina tube of 42 cm length and 0.4 cm inner diameter was employed as the crucible. The crucible was vertically located at the axis of the resistance furnace. The bottom of the crucible was connected with the upper part of a stainless steel pulling rod and immersed into a liquid metal (GaInSn) contained in a water-cooled cylinder with a constant temperature of 313 K. A high temperature gradient (about 35 K/mm) was guaranteed when the liquid metal was insulated from the furnace heat by applying a refractory ring (5 mm thick) above the free surface of the liquid metal pool. The pulling rod movement system can reach the downward velocity in the range of 0–24 μm/s. The bottom of the rod was connected with an electric cable as the downward electrode. The specimen in the crucible, acting as the upward electrode, contacted the pulling rod. Customized power supplies generate the electric current pulse (ECP) and the direct current (DC), flowing through electrodes into the solidifying samples. ECP is one type of damping current, which is characterized by three parameter variations of the current amplitude I_p, the frequency f and the pulse length t_p. The waveform is schematically shown in Fig. 1b, given by an equation in one cycle ($1/f$):

$$\begin{cases} I(t) = I_p \exp\left[-1830\left(t - \frac{t_p}{2}\right)\right] \sin\frac{\pi t}{t_p} & 0 < t < 2t_p \\ I(t) = 0 & 2t_p < t < 1/f \end{cases} \tag{1}$$

The parameter of the applied ECP and DC was chosen as $I_p = 400$ A, $f = 200$ Hz, $t_p = 0.5$ ms and $I_{DC} = 43$ A during the solidification experiments. In addition, the electric current can be applied upwards and downwards, respectively.

The Al–20.5 wt%Si hypereutectic alloy (nominal composition) samples were prepared by melting the raw pure Al (99.9 wt%) and Si (99.9 wt%) in a clay graphite crucible. The melt was sucked into a quartz tube of 0.4 cm inner diameter and cooled in the air. In order to homogenize the solute elements, the melt was mechanically stirred before sucking it into the tube. In addition, on account of the fact that the diameter is only 0.4 cm, the melt in the tube can be rapidly solidified. Hence, the homogeneity of solute elements in the sample scale is guaranteed. The prepared specimens were located in the alumina crucible and then remelted in the Bridgman furnace at a constant temperature of 1173 K. A pulling velocity of 14 μm/s achieved the directional solidification of samples, and the treatment of electric currents was initiated simultaneously.

Finally, the solidified sample was sectioned transversely and longitudinally along the mid-plane. Both selected sections were ground on SiC paper and polished from 6 μm to 1 μm. The structure of the samples was examined by using optical microscopy. The area percentage of primary silicon phase was determined using the software package ANALYSIS FIVE (Olympus Europe, Hamburg).

3. Experimental results

3.1. Primary silicon distribution

Fig. 2 displays the evolution of the primary silicon's distribution pattern in the longitudinal section of the sample with a growth length of 0.2–0.4 cm, 0.6–0.8 cm, 1.2–1.4 cm, 1.8–2.0 cm, 3.8–4.0 cm respectively. The corresponding area percentage of primary silicon phase is shown in Table 1. The reference experiment that did not contain the application of the ECP presents a mixed structure of facetted primary silicon and eutectic structures. The similar quantities of primary silicon is observed in all the growth lengths (see Fig. 2a and Table 1). On the other hand, the application of downward ECP generates a significant modification of the primary silicon distribution, as shown in Fig. 2b. A significant enrichment of primary silicon is presented at the growth length of 0.2–0.4 cm (see Table 1). Such primary silicon aggregation is continuously generated in the growth length of 0.6–0.8 cm during the solidification process that applies the ECP (see Table 1). The disappearance of the primary silicon in the axis region occurs when the growth length increases to about 1 cm. The primary silicon that is missing along the radial direction is gradually enlarged with the increasing of growth length, according to the primary distribution in the growth length of 1.2–1.4 cm (see Fig. 2b and Table 1). Eventually, a small quantity of primary silicon remains in the vicinity of the wall when the growth length reaches about 1.6 cm. The same tendency is maintained in the following growth patterns, seeing the structure and the area percentage of primary silicon in the growth length of 1.8–2.0 cm and 3.8–4.0 cm (see Fig. 2b and Table 1).

3.2. Interface transitions in the mushy zone

The evolution of the mushy zone in the longitudinal section along the growth length under the impact of downward ECP is shown in Fig. 3. Two transitions of the mushy zone interface,