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Separation mechanism of the primary Si phase from the hypereutectic Al–Si alloy using a rotating magnetic field during solidification

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Abstract

Understanding solidification behavior under an intense flow field is important in controlling the microstructure and macrostructure of alloys in industry. In the present study, we show that using a rotating magnetic field (RMF) during solidification of hypereutectic Al–Si alloy can efficiently congregate the primary Si phase to the inner wall of the crucible and form a Si-rich layer with 65–698 wt.% Si content. The Al–Si melt flow under an RMF and the temperature field of the liquid metal are the two dominant conditions for the segregation of the primary Si phase. The intense melt flow, i.e., secondary flow and Taylor–Görtler vortices, carries the bulk liquid with higher Si content to promote the growth of the primary Si phase formed close to the inner wall of the crucible where the temperature is low, finally resulting in the remarkable segregation of the primary Si phase. This work has demonstrated that a forced intense melt flow combined with proper cooling conditions can greatly change the solidification structure of alloys, which is beneficial to microstructure control.

Keywords: Rotating magnetic field; Al–Si alloy; Separation; Solidification; Microstructure

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1. Introduction

It has been recognized for many years that fluid flow within a melt can have profound effects on the solidification structure. Whenever fluid flow is artificially applied during the casting of alloys, some changes in the microstructure can be observed [1–6]. One observation, for instance, is a transition from equiaxed to globular microstructure, dendrite growth or grain refinement, or macrosegregation [4,5]. Research under microgravity conditions in the last decades has shed light on the importance of fluid flow, and it became clear that even in the best experimental set-ups, residual flows can change the microstructure appreciably [7].

One of the common flows in a solidifying, electrically conducting melt can be generated by applying time-varying magnetic fields. The most prominent realizations of these are induction coils [8] in furnaces and rotating [9] or traveling [10] magnetic fields. Such fields are a powerful tool to provide a wide variety of flow patterns through which the solidifying microstructure can be tailored in situ. Considerable progress has been made in the past 10 years, in particular with rotating magnetic field (RMF)-driven fluid flow, by employing careful model experiments of low-melting-point alloys and adapted numerical simulations [3,4,11,12]. A standard case is the axisymmetric arrangement of a cylindrical liquid metal column exposed to an RMF [13,14].

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As is well known, inhomogeneous solute distribution is accompanied by a gradual change in composition and is an important and well-known phenomenon during solute-rich alloy solidification, which includes macrosegregation and microsegregation. This may occur on various scales in the ingot; microsegregations are linked to composition variations on the scale of the lowest solid structure, whereas macrosegregations concern the scale of the product [15–17]. Macrosegregation often results in the deterioration of the material properties. However, it has a great use in some cases, such as the preparation of materials with high purity.

The hypereutectic and hypoeutectic Al–Si alloys are extensively used in the automotive and aerospace industries due to their low density, good castability, low thermal expansion and higher mechanical properties [8,18]. The effect of fluid flow on typical hypoeutectic Al–Si-based cast alloys is well understood, since in the last decade intensive research on that subject was performed, including experimental investigation and simulation methods [19–27]. For hypereutectic Al–Si alloys, because the primary Si phase is first formed and can move with the liquid metal, it is considered that a forced flow field may have a remarkable influence on the segregation behavior of Si solute.

Hence, in the present study, we introduced an intense melt flow induced by RMF to greatly alter the solidification structure of hypereutectic Al–30Si alloy. The mechanism of segregation behavior of the primary Si phase during solidification under RMF was investigated by a series of experiments.

2. Experimental

A hypereutectic Al–Si alloy with 30 wt.% Si was prepared by conventional casting from commercial Al (99.7 wt.%) and metallurgical Si (99.7 wt.%). First, the Al–Si alloy was melted in an electrical resistance furnace, and then poured into a preheated (840 °C) cylindrical graphite crucible with an inner diameter of 60 mm. The crucible was placed under an RMF with a frequency of 50 Hz, which was induced by a three-phase, three-pole magnetic generator. The magnetic flux densities in the present study were 12, 17 and 25 mT, respectively. After switching on the RMF, the Al–Si melt was stirred vigorously by the electromagnetic field. A large amount of the primary Si phase congregated close to the inner wall of the crucible during solidification. According to the experimental requirement, the thermal insulation material was placed at different positions of the graphite crucible to prevent the Al–Si melt from fast cooling and investigate the segregation behavior under variant cooling conditions. Fig. 1 is a schematic illustration of the experimental setup. As an example, asbestos was placed at the top of the crucible. To measure the liquid temperature, the heads of thermocouples 1, 2 and 3 with a distance interval of 15 mm were fixed $\sim$1 mm into the liquid metal close to the sidewall, and thermocouple 4, which measured the central liquid, was placed $\sim$3 mm above the bottom surface of the crucible. All the thermocouples were connected to the temperature recording system. The prepared samples were cut to expose the vertical and cross-sections, and the microstructures were observed by an MEF-4A optical microscope.

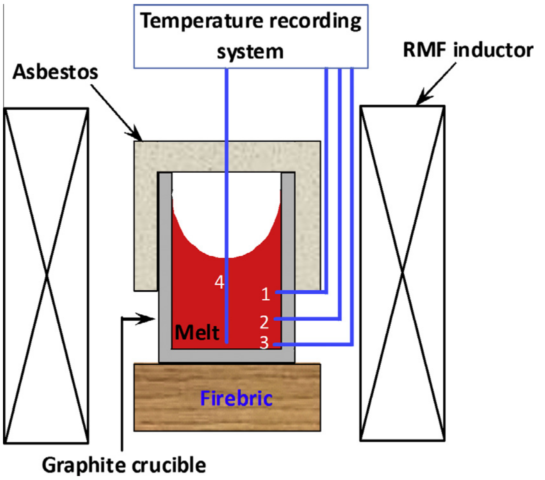

Fig. 1. Schematic illustration of Al–30Si alloy solidified under an RMF, in which the thermal insulation material is placed at the top of the crucible. Thermocouples 1, 2, 3 and 4 were used to measure the temperatures of liquid metal.

3. Results

Fig. 2 shows the vertical sections of Al–30Si alloy solidified under an RMF with different magnetic flux densities. It should be noted that the thermal insulation material was placed on the top position of the crucible during the solidification process, as shown in Fig. 1. Thus, the heat is released from the bottom and sidewall. For the alloy solidified without RMF, similar to the previous work [28], the primary Si phase tends to uniformly distribute in the alloy (Fig. 2a). Because the Si content is high and the size of Si is large, the primary Si phase can drop and form holes in the sample during the grinding process. The length of the primary Si phase is $\sim$2–6 mm due to the slow cooling rate. However, when solidified under RMF with different magnetic flux densities, a large amount of the primary Si phase is separated from the Al–30Si alloy and distributes in the periphery of the sample. In addition, the separation effect of 25 mT (Fig. 2d) is better than those of 12 mT (Fig. 2b) and 17 mT (Fig. 2c). Furthermore, the primary Si phase is still formed in the center of the alloy.

In order to further exhibit the segregation of the primary Si phase, the half cross-sections of Al–30Si alloy solidified under RMF with different magnetic flux densities were examined and the results are shown in Fig. 3. It should be noted that the cross-sections were cut from the position that is 20 mm above the bottom surface of the ingots. For the alloy solidified without RMF, the primary Si phase tends to uniformly distribute in this section of alloy (Fig. 3a). The primary Si-rich layers are formed when the Al–30Si alloy solidified under RMF with different magnetic