The formation mechanism of non-dendritic primary $\alpha$-Al phase in semi-solid AlSi$_7$Mg Alloy

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Abstract

In this paper, a process to make non-dendritic semi-solid AlSi$_7$Mg alloy by electromagnetic stirring and the temperature field of the stirred melt cooled is continuously investigated. It is proposed that a new kinetic factor for primary $\alpha$-Al nucleation is that a low thermal gradient exists in the electromagnetically stirred melt, for which the primary dendrite arms and secondary dendrite arms are refined. The results also show that the root remelting of the secondary dendrite arms is an important mechanism of the primary $\alpha$-Al refinement. Strong electromagnetic stirring greatly reduces the composition supercooling in the melt and eliminates the preferred growth of primary dendrite arms, therefore, many rosettes or spherical primary $\alpha$-Al phase particles form finally. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: AlSi$_7$Mg alloy; Semi-solid; Electromagnetic stirring

1. Introduction

The primary $\alpha$-Al phase deposited from liquid is dendritic when AlSi$_7$Mg alloy solidifies under traditional conditions, however, the primary $\alpha$-Al phase stirred violently by electromagnetic field during solidification is of spherical or rosette-type, and the grains of the $\alpha$-Al phase are obviously refined. With respect to the stirred structures of alloys, Flemings has pointed out that the fragments fractured from the primary dendrite gradually become dendritic, then rosette, and finally spherical, as a result of ripening, shearing and abrasion with other grains or with liquid when continuously stirred during solidification [1]. However, Vogel et al. have proposed that the secondary arms of primary $\alpha$-Al phase are bent at a large angle, which gives rise to dislocation grain boundaries with a misorientation of large angle on the root of the secondary arms so that the liquid will wet the boundaries and the bent secondary arms will finally separate from the main stem [2,3]. Hellawell has also considered that it is impossible for the secondary arms of primary $\alpha$-Al dendrites to fracture during stirring, and that the secondary arm root can be remelted off the main stems [4]. The results in this paper have further demonstrated the mechanism for the formation of microstructure in AlSi$_7$Mg alloy stirred by electromagnetic field during solidification.

2. Experimental method

The aluminum–silicon alloy used in this study consists of 7Si, 0.45Mg and 0.2Fe in wt%. In order to study the evolution of primary $\alpha$-Al, two methods of isothermal electromagnetic stirring were used, one of which was that the stirring did not begin until the melt temperature decreased to 10°C below the liquidus temperature (about 615°C), and the other was that the stirring started when the melt temperature was 5°C higher than the liquidus temperature. Small samples, of 12 mm diameter and 12 mm height, were sucked from the stirring chamber regularly and quenched in water. The microstructures of the samples were examined with an optical microscope. The temperature gradient of the melt is important when continuously cooled and stirred, so the temperatures of the central and peripheral regions of the melt as a function of time were detected. The distance of the two thermocouples, which were placed on a horizontal plane, was 18 mm, and the chamber size was 54 mm diameter and 130 mm height.

3. Results and discussion

3.1. Electromagnetic stirring isothermally

The liquid of AlSi$_7$Mg alloy was poured into the stirring chamber, but it was not stirred until the melt temperature reached 605°C. After the liquid had been stirred for 47 s, the
melt temperature was lowered to 600°C and kept isothermally: the developed dendrites can be seen in the microstructures as shown in Fig. 1(a). While the liquid was continuously stirred, the secondary arms were detached from the main stem, and became increasingly larger and more spherical. However, Fig. 1(b) shows that long α-Al phase can also be seen after stirring for 1274 s, which could be the main stems after having lost the secondary arms. When the electromagnetic stirring was started as soon as the superheated liquid of AlSi3Mg alloy was poured, many fine rosettes without any large main stem of primary α-Al were formed, when the melt temperature was below the liquidus temperature, as shown in Fig. 1(c). Fig. 1(d) shows that as the stirring continued, the secondary arms were separated in succession from the rosette to produce a large amount of granular or spherical α-Al phase in shape, and the granular α-Al phase grew larger at the end and some spherical α-Al phase particles welded together.

3.2. Radial temperature gradient of the melt

The melt temperatures of the central and peripheral regions with cooling time, unstirred and stirred by electromagnetic field, are shown in Table 1.

It is recognized from Table 1 that the central temperature was higher than the peripheral temperature when the melt was not stirred and that the temperature difference was usually 4–5°C. The temperature difference, however, became less when primary α-Al solidified, but not less than 3°C. Table 1 also shows that the central temperature

| Time | t (s) | 48 | 60 | 72 | 84 | 96 | 108 | 120 | 132 | 144 | 156 | 168 | 180 | 192 | 204 | 216 |
|------|------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| No stirring | $T_1$ (°C) | 633 | 629 | 623 | 619 | 614 | 609 | 606 | 606 | 607 | 607 | 607 | 607 | 607 | 607 | 605 |
| | $T_2$ (°C) | 629 | 624 | 619 | 614 | 609 | 605 | 603 | 603 | 604 | 604 | 603 | 603 | 602 | 601 | 600 |
| Stirring | $T_1$ (°C) | 621 | 616 | 611 | 609 | 608 | 607 | 606 | 605 | 603 | 602 | 601 | 600 | 600 | 599 | 598 |
| | $T_2$ (°C) | 621 | 616 | 611 | 609 | 608 | 607 | 606 | 605 | 603 | 602 | 601 | 600 | 600 | 599 | 597 |

* $T_1$ and $T_2$, respectively, represent the temperature of the central and peripheral region.
was slightly higher than or equal to the peripheral temperature when the melt was continuously stirred by electromagnetic field until the temperatures reached approximately 598–600°C, but afterwards the temperature difference became larger once again. If the stirring power was higher, the temperature difference of the two thermocouples was smaller [5]. It can be concluded that the electromagnetic stirring made the radial temperature gradient of the melt very small in the liquid–solid phase region.

3.3. Nucleation and growth of the primary α-Al

It is deduced from the radial melt temperature field that violent electromagnetic stirring created a new dynamic factor for nucleation, namely mechanism of low temperature gradient. The nucleation sites for the primary α-Al quickly spread throughout the whole melt region so that the number of nuclei increased, which was an important factor for primary α-Al to be refined.

Flemings, Vogel et al. and Hellawell did not consider the effect of stirring on the primary arms, but the above experiments have shown that the low temperature gradient strongly affected the growth of the primary arms and refined them. Under the conditions of violent stirring, the temperature field and the solute field were more homogeneous, and the constitutional supercooling was reduced greatly, so that growth supercooling was decreased and the growth rate of primary arms dropped or equaled that of secondary arms, which led to the emergence of many rosettes of primary α-Al phase, as shown in Fig. 1(c).

Vogel et al. have presumed that if a secondary arm was bent with more than 20° angle, a grain boundary with a misorientation greater than 20° on the root of the secondary arm was formed and the grain boundary energy was normally as great as the solid–liquid interfacial energy. The boundary was attacked by the liquid, and finally the secondary arm was detached from the dendrite along with grain-boundary induced remelting [2,3]. However, the distance between the secondary arms in Fig. 1(a) was very small, and if one of them was bent by shearing with only a few degrees and not larger than 20° at all, the conditions of Vogel’s model were untenable. The authors of this paper propose that when the melt is stirred by electromagnetic field, the secondary arms that are not bent can also be separated from the dendrites by root remelting. Hellawell has approved the authors’ view, and believes that vigorous stirring can cause local temperature fluctuation and lead to root remelting of the secondary arms, but he did not give the reasons for the fluctuation [4]. The experiments show that the melt stirred by the electromagnetic field turned horizontally, and at the same time an additional flow existed, by which the melt frequently moved up along the internal wall of the chamber and then down to the center [5]. Consequently, the rosette primary α-Al frequently reached the peripheral region, and then came to the center of the melt, and that gave rise to violent fluctuation for the small rosette primary α-Al and many secondary arm roots remelted, therefore, the primary α-Al phase was refined greatly. If the melt was cooled quickly, there was not sufficient time for the secondary arm root to remelt, so that many rosettes were retained in the final microstructures. Fig. 1(a) and (b) shows that when the stirring started at 10°C below the liquidus temperature, the well-developed dendrites required longer time of fluctuation for secondary arm root remelting and it is very difficult for long primary arms that have lost secondary arms to be refined or spheroidized. Fig. 1(c) and (d) also show that when the stirring started at 5°C above the liquidus temperature, the primary α-Al phase particles were not well developed and the secondary arm root was small, so that the remelting time was short and it was easy for the primary α-Al phase to become granular.

4. Conclusions

1. It is difficult for the secondary arm root to remelt and for the primary arms to be refined when the stirring starts at 10°C below the liquidus temperature, however, it is easy for the secondary arm root to remelt when the stirring starts 5°C above the liquidus temperature.
2. The radial temperature gradient of the melt is very small during the electromagnetic stirring.
3. A low temperature gradient is a new kinetic factor for the nucleation and growth of the primary α-Al phase.
4. The root remelting of the secondary arms and the refinement of the primary arms are enhanced by electromagnetic stirring.

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