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Effects of electromagnetic stirring on microstructures of solidified aluminum alloys①

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Abstract: Al-20% Cu, Al-33% Cu and Al-7% Si alloys were solidified with electromagnetic stirring(EMS). The fluid flow induced by electromagnetic stirring leads to the increases of the lamellar spacing of Al-$CuAl_2$ and Al-Si eutectics and the secondary dendritic arm spacing. Rod-like eutectic structure plus pro-eutectic α(Al) are observed in Al-Cu eutectic alloy when the agitating voltage is increased over 130 V, and in the hypoeutectic alloys, globular grains of proeutectic α(Al) grains may form when the magnetic field is strong enough. The Si flakes in the Al-Si eutectic are also coarsened by applying forced flow during solidification, which is always related to the depression of their branching in the growth by the forced convection.

Key words: electromagnetic stirring; fluid flow; eutectic; solidification
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1 INTRODUCTION

Practically, mechanical stirring and electromagnetic stirring (EMS) are widely used to generate forced flow in solidification and casting of metals and alloys, resulting in great changes of the solidified structures, segregations and properties of the castings. Much attention has been paid to solidification of dendritic alloys superposed with forced flow, and many previous works have been focused on the effects of fluid flow on the structural transitions, such as columnar-equiaxed transitions(CET) or macro-segregation in the alloys[1-3]. Some authors investigated the eutectic structures grown from the melts with strong flow[4, 5]. In the electromagnetically-stirred solidification, the microstructures are strongly dependent upon the applied magnetic field and thermal field due to the two notable effects of electromagnetic field, forced flow and Joule's heat, on solidification. In this paper, Al-Cu and Al-Si alloys are employed in the solidification with electromagnetic stirring so as to investigate the effects of EMS on dendritic and eutectic microstructures.

2 EXPERIMENTAL

One eutectic alloy, Al-33.2 % Cu(mass fraction), and two hypoeutectic alloys, Al-20 % Cu and Al-7% Si, were heated up to 700 ℃(for eutectic alloy) and 840 ℃(for hypoeutectic alloys) respectively, and then solidified by cooling within a rotating magnetic field. The revolution rate of the imposed field was 1 000 r/min, and the magnetic flux density of the AC field could be varied by changing the agitating voltages. The experimental setup is schematically shown in Fig. 1(a), and the alloys were solidified into samples of 40mm in diameter and 50 mm in length.

Fig. 1(b) indicates the electromagnetic force on an elementary melt. An induction current could be produced in the melt as magnetic field starts rotation, and the interaction between the current and magnetic field gives rise to a Lorentz force on the melt that will drives the melt to flow. According to Maxwell equations and Ohm's law, the Lorentz force per volume of melt is expressed as

$$\boldsymbol{F}_E = \boldsymbol{j} \times \boldsymbol{B} = \sigma_E[-\nabla \Phi_E + (\boldsymbol{v}_M - \boldsymbol{v}_F) \times \boldsymbol{B}] \times \boldsymbol{B}$$

and

$$\nabla \cdot \boldsymbol{j} = 0$$

where $\boldsymbol{j}$ is the current vector through melt, σ_E designates electric conductivity of melt, Φ_E is static electric potential, $\boldsymbol{v}_M$ and $\boldsymbol{v}_F$ are velocities of the melt and the magnetic field, respectively, and $\boldsymbol{B}$ is magnetic flux density of the field.

Microstructures were observed on the cross sections of these samples, while the samples of Al-Si alloy were performed a deep etch by 10% (volume fraction) hydrochloric acid to reveal stereo morphology of Si.

3 RESULTS

The macrostructures of the aluminum alloys solidified without electromagnetic field are typically coarse equiaxial grains that can be drastically refined by EMS. This phenomenon have been discussed by many researchers and will not be concerned in this

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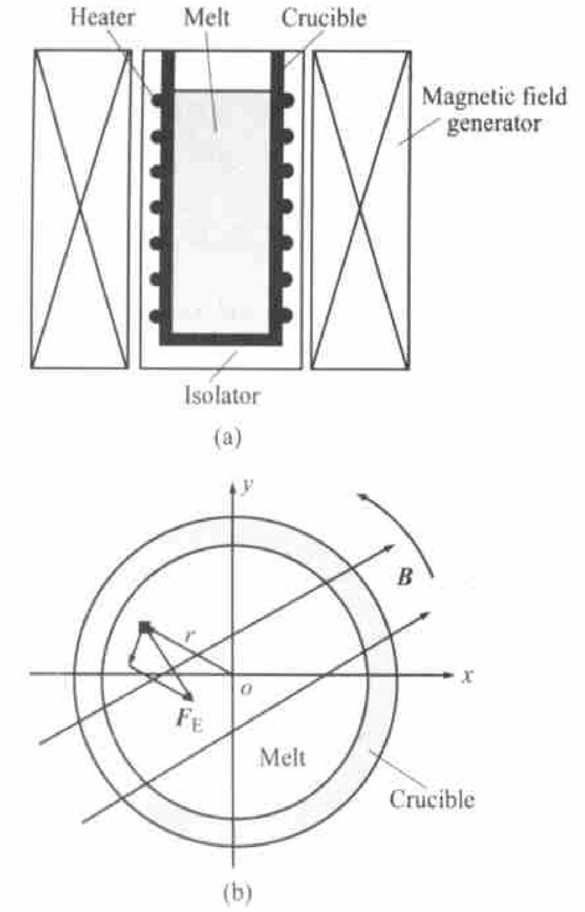

Fig. 1 Schematic experimental setup(a) and Lorentz force induced upon melt(b)

paper.

3.1 Al-CuAl$_2$ eutectic

Figs. 2 and 3 show the effects of electromagnetic stirring on the microstructures of Al-33.2% Cu eutectic alloy. The microstructure of Al-CuAl$_2$ eutectic frozen without EMS is a typical lamellar structure with the inter-lamellar spacing being around 3.5 μm.

Electromagnetic stirring brings about notable changes of the Al-CuAl$_2$ eutectic morphology. When

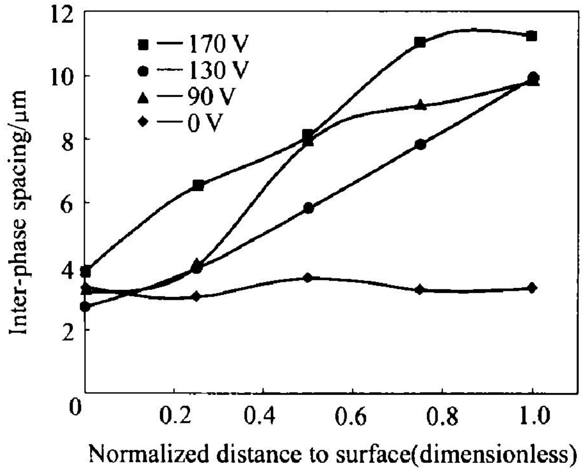

Fig. 2 Relationship of inter-phase spacing of Al-CuAl$_2$ eutectic with agitating voltage

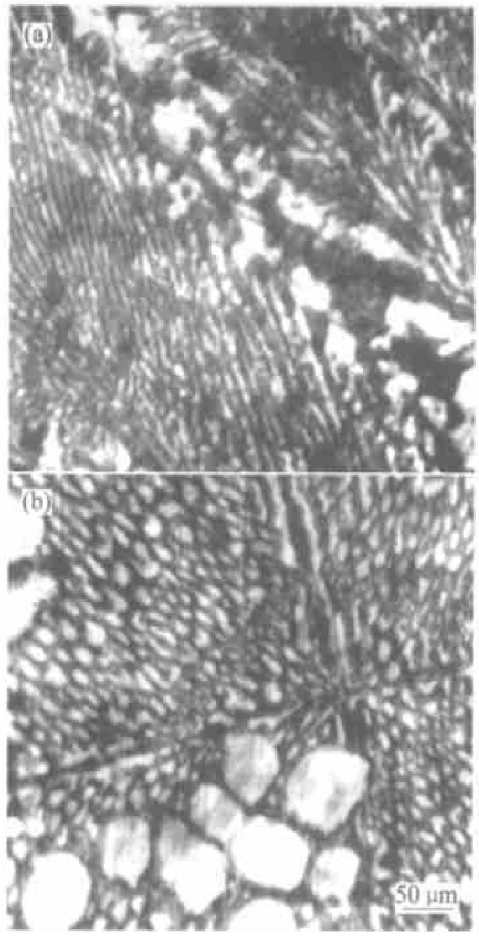

Fig. 3 Effect of EMS on microstructures of Al-CuAl$_2$ eutectic
(a) —Solidified structure without EMS;
(b) —Solidified structure with EMS at 170 V

the alloy is solidified with EMS, the inter-phase spacing increases with the increase of agitating voltage, and a rod-like eutectic plus proeutectic α(Al) begins to form when the agitating voltage is increased over 130 V. As the agitating voltage is increased up to 170 V, most eutectic forms rod-like structure. Analysis via electronic microprobe indicates that the rod-like phase is always α(Al) in this case.

3.2 Dendrites

The dendritic arm spacings of the both hypo-eutectic alloys, Al-20% Cu and Al-7% Si, solidified with and without EMS are shown in Fig. 4. Without EMS, the α(Al) grains are grown into equiaxed dendrites with the dendrite arm spacing being around 42 and 65 μm, respectively. However, as the magnetic field strength increases, the EMS causes a remarkable increase in the spacing; another change that are brought to the dendrites by EMS is that the equiaxed dendrites are turned into granular grains as the EMS is strong enough.

3.3 Al-Si eutectic

The observations of morphological changes of Si phase in the electromagnetically-stirred Al-Si alloy are

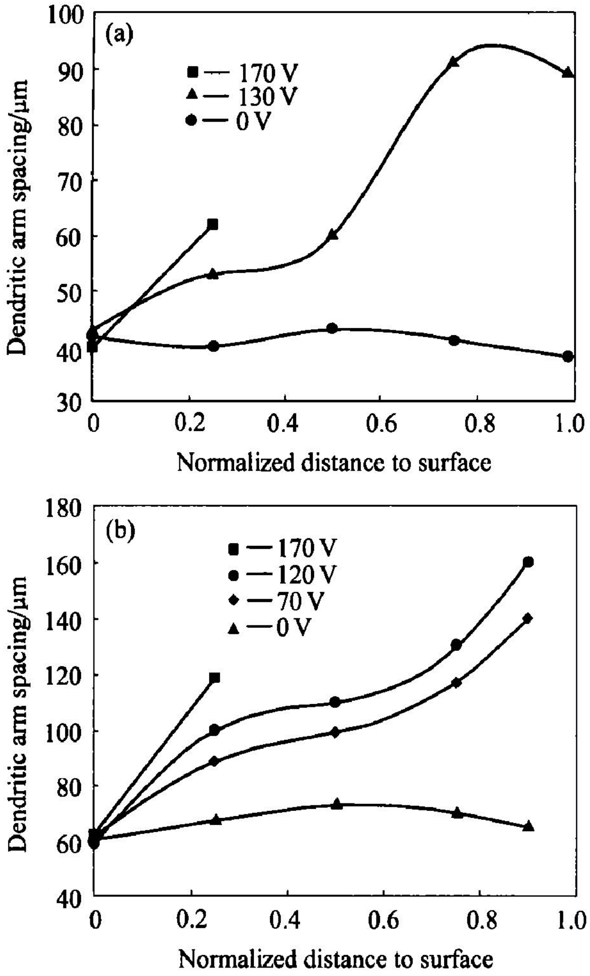

Fig. 4 Relationship of secondary arm spacing in hypo-eutectic alloys with agitating voltages
(a) —Al-20% Cu; (b) —Al-7% Si

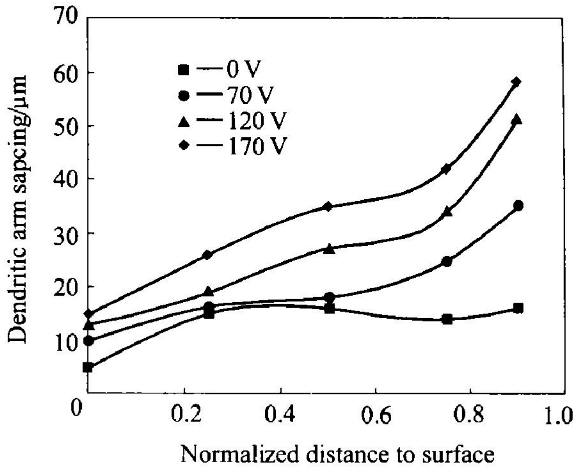

Fig. 5 Distribution of inter-phase spacing of Al-Si eutectic affected by EMS

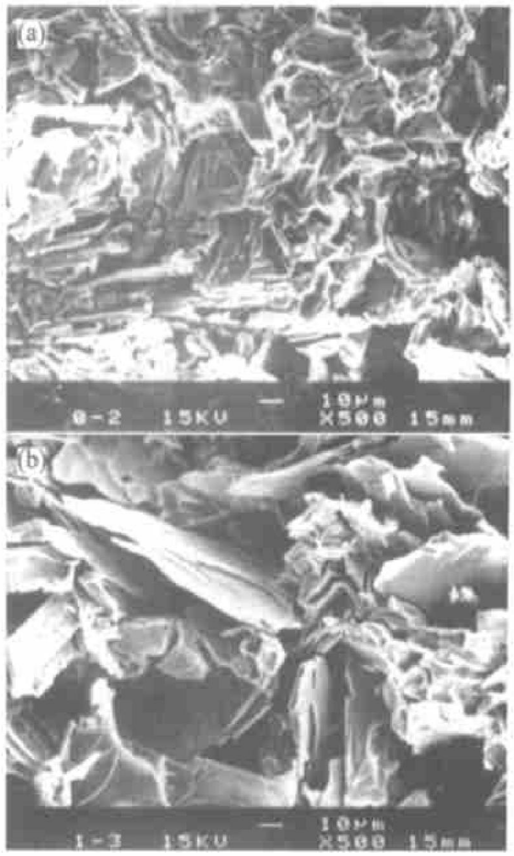

Fig. 6 SEM microstructures of Al-7% Si alloy
(a) —Without EMS; (b) —Solidified with EMS at 170 V

shown in Figs. 5 and 6. Eutectic structures in the Al-Si alloy are located among the primary α dendrites, and the eutectic Si is grown into a flake-like form. The forced flow results in not only an increase of inter-phase spacing but also an increase of dimensions of Si phase. Fig. 5 indicates the distribution of the inter-phase spacing of Si with respect to the agitating voltage. Similarly to the case in Al-$CuAl_2$ system, the inter-phase spacing increases with increasing the agitating voltage. The Si flakes also grow thicker and longer in the stirred solidification as indicated in Fig. 6. Moreover, the morphology of Si flakes grown from the unstirred melt is more irregular than that from the stirred solidification, reflecting that electromagnetic stirring enhances Si to grow extensively and reduces the frequency of branching.

4 DISCUSSION

There are two main factors of EMS that may result in the coarsening of solidified structures.

1) Fluid flow enhances the mass transportation in solidification. In the crystal growth of dendrites or eutectics, both the dendritic arm spacing and inter-phase spacing basically depend upon the diffusion of atoms ahead of the interface and the interfacial energy. It is evident that a stronger external magnetic field leads to more severe forced flow that enables the diffusion distance of atoms to increase. This enhanced mass transport in front of the solidifying interface produces larger dendritic arm spacing or eutectic spacing so as to decrease area of the interface or the interfacial energies in solidification.

2) The Joule's effect of the induction current

will reduce the solidification rate, which causes an additional enhancement of the structural coarsening, and the higher the agitating voltage is applied, the more the Joule's heat is generated on the solidified alloys, and the coarser the microstructures form.

The mechanism of lamellar eutectic transformation to the rod-like structure in the Al-$CuAl_2$ system is not clear. The coexistence of proeutectic and rod-like α phase, of which the latter is the minor constituent in the binary eutectic system, implies that the interface of α phase/liquid possibly has a weaker structural stability than that of $CuAl_2$/liquid in the eutectic growth with fluid flow. In general, both the phases, α(Al) and $CuAl_2$, experience a coupled growth to form a regularly lamellar morphology, but the forced flow results in wide lamellae of the eutectic structure, whose size may exceed the limit for the stable lamellar structure at the certain growth rate[6]. Fluid flow also decreases the solute concentration in front of the solid/liquid interface to make the α phase more preferably grow than $CuAl_2$. This tendency may allow α phase to develop into proeutectic grains with the prohibition of the coupled growth of the lamellar eutectic. This proeutectic growth of α phase consequently results in an increase of solute(Cu) concentration in the liquid where the α phase in the eutectic grows into rod-like or fibrous morphology due to its low volume fraction formed.

Si is a faceted phase in the growing Al-Si eutectic, which will develop in the preferential orientation. Branching of Si may occur in its growth as the concentration of Al atoms enriched ahead of the interface is high enough to retard the further progress of the interface. The forced flow decreases the enriched solute concentration in front of the interface, which allows Si flakes to grow larger without branching than those flakes grown without convection.

5 CONCLUSIONS

1) Electromagnetic stirring applied into solidification of proeutectic Al-20% Cu and Al-7% Si alloys results in a forced fluid flow that causes the dendrite arm spacing increase, and further the change from equiaxed dendrites to globular grains if the magnetic field is strong enough.

2) In the eutectic growth, electromagnetic stirring leads to an increase of lamellar spacing of the Al-$CuAl_2$ and Al-Si eutectic structures, enhancing the transition of lamellar to rod-like eutectic and proeutectic growth of α(Al) phase.

3) Electromagnetic stirring induces Si flakes in the Al-Si eutectic coarsening, which is related to a reduction of branching frequency.

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