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Investigation of Si content on the grain refinement of Al-Si alloy under pulsed magnetic field

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Abstract

The influence of Si content and pulsed magnetic field parameters on the solidification structure of the Al-Si binary alloy was investigated. Experimental results indicated that the addition of Si has a significant refinement on the macrostructure of the commercial pure aluminum. The grain size of the Al-Si binary alloy decreases first and then increases with increasing of Si content which could be caused by the constitutional-supercooling, but for the case where a PMF was applied, the grain size was further refined compared with as-cast state.

Keywords: Al-Si binary alloy; Si content; Grain refinement; PMF

Introduction

Aluminium alloys are considered the most abundant, thus important, after steel due to their light weight, physical and mechanical characteristics[1]. Among the aluminum alloys, the Al-Si alloys have shown good performance mainly for aerospace, transportation and automotive applications[1-3]. The grain refinement can reduce the hot tearing susceptibility and to improve the structure homogeneity and mechanical properties of aluminum castings. Various methods have been proposed to refine the solidification structure such as the common addition of inoculation particles in industry[4, 5]. However, the inoculation of the melt may produce undesired particle agglomerate which will contaminate the melt, the ultrasonic melt treatment [6]. Recently, the electromagnetic fields provide a contactless method to control the fluid flow in the liquid melt and achieve the fine equiaxed grains in the alloys. A large number of studies have already been reported concerning the impact of rotating magnetic fields (RMF) [7], travelling magnetic fields (TMF) [8] and Pulsed magnetic field (PMF) [9] in solidifying metals. However, few studies have been reported until now the coupling influence of the alloy composition and forced convection on the grain refinement.

In the present study, the effect of both the alloy composition and the forced convection on the grain refinement was investigated through the experimental and numerical simulation methods, and the results were discussed.

Experiment

Fig. 1 shows a schematic view of the experimental setup which consists of a straight solenoid connected with a self-prepared power which includes a capacitor bank of 1000 μ F, temperature measurement system, cylindrical graphite mold. All experiments used a pulse frequency of 10 Hz and a half sinusoidal waveform with a peak voltage 700 V. Commercial-purity (CP) aluminum (99.7 wt. %) was melted in a resistance furnace first and then added different contents of Si to the melt and held for 30 min at temperature 100 K higher than the liquidus temperature. Furthermore, the pouring temperature for each experiment was fixed at 60 K higher than the liquidus temperature, and the mold temperature was maintained at 973 K before casting. The solidification process was rendered a near isothermal condition by use of thermal insulating blanket on the lateral and bottom surfaces of the mold. The liquid melt was poured into a graphite mold with an inner diameter of 45 mm and height of 100 mm and then transferred into the PMF immediately. The K-type thermocouples were arranged vertically along the axis of the specimen to monitor the distribution of temperature during solidification process.

The specimens were sectioned longitudinally along the mid-plane and then grounded on SiC papers and polished to remove any scratches for metallographic analysis. The etching reagent used to reveal the macrostructure was a solution of 75 ml HCl, 25 ml HNO₃ and 5 ml HF. A CanoScan (LiDE120) was employed to obtain the photographs of the macrostructure. Quantitative measurements of the grain size were determined by the mean linear intercept method using Nano Measurer software package.



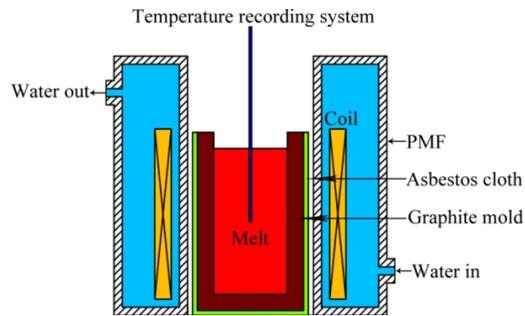


Fig. 1 The schematic view of the experimental setup

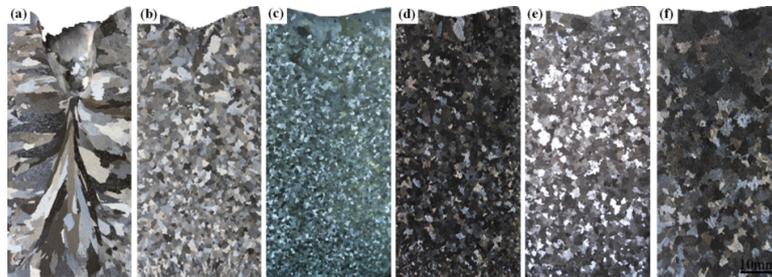


Fig. 2 As-cast macrostructure of Al-Si alloys with different Si contents: (a) Commercial-purity aluminum. (b) Al-1%Si. (c) Al-2%Si. (d) Al-3%Si. (e) Al-5%Si. (f) Al-7%Si

Result and discussion

Fig. 2 shows the as-cast macrostructures of Al-Si alloys with different Si contents. The Si contents have an obvious influence on solidification macrostructure of commercial-purity aluminum. The reference experiment conducted with commercial-purity aluminum (Fig. 2a) shows that a dominance of columnar grains growing opposite to the direction of heat flow. However, the solidification structure changes to fined equiaxed grains with addition of Si element. The corresponding average grains size is shown in Fig. 4. It can be seen that when the addition of Si content ranges from 1 % to 7 % , the average grains size of Al-Si alloys is not reduced monotonously with increasing of Si content, but decreases first and then increases. It is obvious that when the mass fraction of Si in Al-Si alloys is equal to 2 % , the average grains size is the smallest.

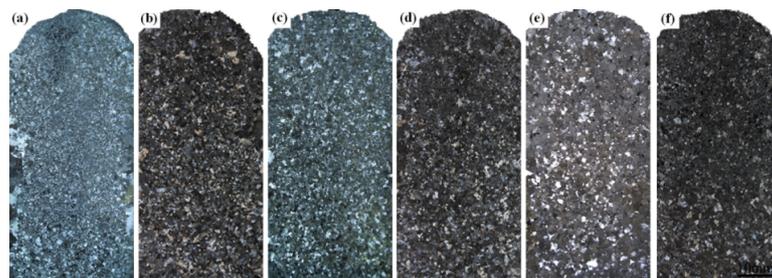


Fig. 3 The macrostructure of Al-Si alloys with different Si contents under PMF: (a) Commercial-purity aluminum. (b) Al-1%Si. (c) Al-2%Si. (d) Al-3%Si. (e) Al-5%Si. (f) Al-7%Si

The representative macrostructures of Al-Si alloys with different Si contents under PMF are shown in Fig. 3. The average grains size under PMF is much smaller compared with the macrostructure as cast but it should be mentioned that the grains size of commercial-purity aluminum is the smallest which is different from the as-cast condition.

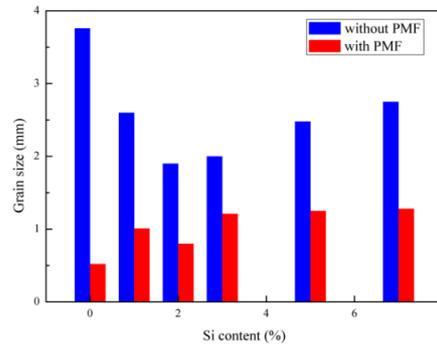


Fig. 4 Grain size of Al-Si alloys with different Si content

In order to yield a better understanding of the refinement mechanism of both Si content and the treatment with PMF, a numerical simulation method was performed to obtain the distribution of Lorentz force in the liquid melt.

According to Maxwell's equations, the eddy current J is induced in case of applying PMF in the liquid melt. The equation can be expressed as follows:

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (1)$$

$$J = \sigma E \quad (2)$$

where B is magnetic flux density, E is intensity of electric field, J is eddy current density, σ is electrical conductivity.

The above equations are solved by the magnetic vector potential method:

$$B = \nabla \times A \quad (3)$$

$$E = -\frac{\partial A}{\partial t} \quad (4)$$

where A is magnetic vector potential.

As a consequence, the Lorentz force acting on the liquid melt during early stage of solidification can be determined by:

$$F = J \times B \quad (5)$$

Where F is Lorentz force.

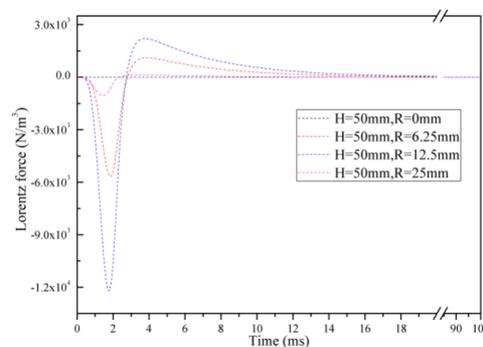


Fig. 5 Variations of the radial Lorentz force with time

Fig. 5 shows the radial Lorentz force induced by the PMF at five points along the radius of the middle section. All of those forces arise as a pressure force, and then turn into a pull force, and finally become negligible before 0.002 s. Due to the inhomogeneous distribution of Lorentz force, there exists a forced convection in the melt. The fluid flow in the bulk of the unsolidified melt promotes an effective homogenization of temperature distribution in the liquid phase, which is beneficial for the formation of the fine equiaxed grain. The refinement effect of PMF can be attributed to the nuclei dissociation from the wall by the melt variation.

Conclusions

In the present study, the coupling effect of Si content and forced convection induced by the PMF on the refinement was investigated. The results show that the average grains size of Al-Si alloys are not reduced monotonously with increasing of Si content, but decreases first and then increases. Furthermore, due to

the inhomogeneous distribution of Lorenz force, there exists a forced convection in the melt. The refinement effect of PMF can be attributed to the nuclei dissociation from the wall by the melt variation.

Acknowledgment

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