Effect of rotating magnetic field and manganese on the formation of iron-containing intermetallic compounds in Al-Si alloy

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Abstract
The acicular β-AlSiFe phase is common but detrimental iron-containing intermetallic phase in Al-Si alloys. In this study, rotating magnetic field (RMF) and manganese neutralizer were used to modify the β-phase in Al-12%Si-2%Fe alloy. The results showed that the manganese addition caused the morphological transformation of iron phase from β-AlFeSi to α-AlSiFeMn with the relation of transition rate to the manganese content. The total transformation was only achieved when Mn/Fe ratio is 1.1. The application of RMF facilitated the formation of α-AlSiFeMn phase even at lower Mn/Fe ratio, economizing manganese consumption and preventing the increase in total number of intermetallic compounds. The modification and facilitation mechanisms of RMF were based on the forced convection induced by electromagnetic force.

Key words: Rotating magnetic field; Manganese neutralizer; Iron-containing intermetallic compound; Al-Si alloy

Introduction

Al-Si alloys are the most used aluminium foundry alloys due to their excellent mechanical properties. Iron is well regarded as an unavoidable impurity in these alloys and known to be detrimental to the mechanical properties, especially the ductility[1]. Iron atoms can easily interfuse into the Al-Si alloys during melting and casting process with iron tools being used. On the other hand, a large amount of brittle intermetallic compound (IMC) will form at normal cooling rates employed in permanent and sand mold casting, as long as the iron content is above 0.7 pct[2]. Such phase always presents a acicular shape, and has a poor bonding with the matrix which results in a severe loss of elongation. It is therefore important to eliminate the harmful effect of iron containing IMCs[3].

The iron-containing IMCs appear in a great variety of shapes and sizes, among which the two most common phases have been designated as α-AlFeSi phase and β-AlFeSi phase[4,5]. The α and β phases can be distinguished by their characteristic morphologies and chemical compositions. The β-phase only exhibits a needle shape, and is always denoted as Al_5SiFe or $Al_9Si_2Fe_2$. By contrast, the α-phase appears in different shapes, such as Chinese script, fish bone, star, polygon or block, etc. Its chemical formula is usually expressed as Al_8SiFe_2, $Al_{12}Si_2Fe_3$ or $Al_{20}Si_2Fe_5$. In conventional casting process, α-AlFeSi phase is metastable, it converts to primary β-AlFeSi phase, normally only acicular β-AlFeSi is present in the solidification structure.

Manganese is an efficient neutralizer and commonly used to modify the acicular iron-containing IMC. Manganese atom can replace iron without changing the crystal structure, forming quaternary IMC[6]. Among the invariant reactions in Al-Fe-Mn-Si system, the one of some interest for Al-Si alloy is[7]:

$$\textbf{Liq.} + \boldsymbol{\beta}\textbf{-AlSiFe} \rightarrow \textbf{Al} + \textbf{Si} + \boldsymbol{\alpha}\textbf{-AlSi(FeMn)} \quad (1)$$

By undergoing this reaction, the acicular β-phase converts to quaternary α-phase, which is less harmful and considered not to initiate cracks in foundry Al-Si alloys to the same extent as the acicular one. However, the replacement of β-phase by α-AlSi(FeMn) requires sufficient amount of manganese, and leading to the increased amount of IMCs, which is also disadvantageous to Al-Si alloys.

Therefore, it is of special importance to find a method to neutralize the detrimental effect of β-phase, while reducing the required content of manganese. Application of external fields may be a potential way to alter the morphology or composition of the iron-containing IMCs. It has been reported that physical fields, such as ultrasonic field, electromagnetic field, etc., are successfully used to refine and modify the microstructure of Al-based alloys[8,9]. In the present study, the rotating magnetic field (RMF) and neutralizer manganese were complexly introduced into Al-12%Si-2%Fe melt. By means of the microstructure evolution and composition change of iron-IMCs, the effect of RMF was investigated.

Experimental Procedure

Starting materials consist of commercial purity Al (99.7%), pure Si (99.9%), pure Mn(99.9%) and Al-20 %Fe master alloy. All compositions quoted in this work are in wt.% unless otherwise stated. The Al-12%Si-2%Fe alloy was smelted in a resistance furnace at 900°C and kept for 1 h in order to fully fuse iron-compounds. After holding, different amount of manganese (Mn/Fe ratio = 0, 0.5, 0.8, 1.1) was added into the melt. Then, the melt was transferred into a preheated cylindrical graphite crucible (45 mm in dia. and 100 mm in height). When the temperature lowered to 850°C, RMF was applied until the ingot was completely solidified. The cooling rate was measured to be about 38 oC/min.

The RMF of 50 Hz frequency was induced by a three-phase–three-pole magnetic generator. The voltage was set as 0 V, 40 V, 60 V and 80 V, with the corresponding magnetic flux density in the center of the crucible 0 mT, 12 mT, 18 mT and 24 mT, respectively.

The ingots obtained were cut along the central vertical plane and grounded to examine the macrostructure. Small samples taken from the cross-section of ingot at 20 mm distance from the bottom were prepared for the microstructure observation by optical microscope MEF-4A. The electron probe microanalyzer (EPMA) was used to measure the chemical composition of IMCs.

Results

Figure 1 shows the macrostructure of Al-12%Si-2%Fe alloy smelted with different content of manganese. The typical as-cast coarse acicular iron phase is presented in Fig. 1a, which can be observed by naked eye. As shown in Fig. 1b and 1c, with the increasing Mn/Fe ratio to 0.5 and 0.8, there is some granular iron IMCs found in the bottom of the ingot. The shape of particles suggests that they probably are manganese IMCs, especially that manganese is more powerful than iron in causing gravity separation[7,10]. However, lots of large acicular phase still can be observed in the section. When Mn/Fe ratio is 1.1, acicular inclusions are fully substituted by the granular phase. It can be concluded that the addition of manganese causes the morphological transformation of iron phase from needle to compact, and the increasing Mn content is beneficial for facilitating the transformation. Such results are consistent with earlier reports.

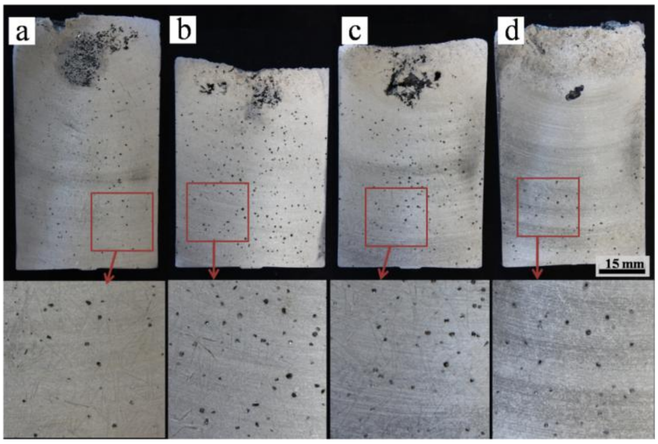

Fig. 1: Macrostructure of Al-12%Si-2%Fe-x%Mn alloy (x=0, 1.0, 1.6, 2.2)

Figure 2 shows the influence of RMF and manganese on the microstructure evolution of iron-containing IMCs in Al-Si-Fe alloy. Without Mn and RMF, the iron phase is crystallized in an acicular shape, as mentioned above. The quantitative element analysis by EPMA (table 1) shows clearly that the acicular phase (highlighted by arrow 1) is β-$Al_9Si_2Fe_2$. The RMF applied singly induces some changes to the morphology of IMCs reducing their size, rather than affects its composition. It is notable that the rod-like phase is still β-phase with the chemical formula $Al_9Si_2Fe_2$. Figure 3 shows the comparison of the iron phase average size under different conditions, the data is calculated from more than fifty iron-containing IMCs for each condition, and based on more than five metallographs those are not totally displayed in Fig.2. The size and length-width ratio of β-phase are reduced significantly by RMF.

When the manganese is added (Mn/Fe ratio is 0.5 and 0.8) without the application of RMF, a number of star-like iron-containing IMCs of α-type (Table 1) appear in the microstructure (Fig. 2). However, the acicular intermetallics are still present in the matrix, although their amount decreases with increasing the manganese content. With the Mn/Fe ratio of 1.1, there is only star-like iron-containing IMC in the microstructure. The average composition of this phase at highlighted points 4, 7, 9 (Fig.2) is similar. The content of manganese is close to that of iron, and the approximate compound chemical formula is $Al_{12}Si_2Fe_{1.5}Mn_{1.5}$.

Following treatment by RMF results in an evident change in the alloy microstructure. Both, star-like and acicular compounds are replaced by the blocky ones. More important, when the manganese is added and RMF is applied, the trend in the IMCs morphology evolution in the case of Mn/Fe ratio 0.5 and 0.8 is similar to the case of Mn/Fe ratio 1.1. Furthermore, the slight changes in the iron phase morphology can be observed with different voltage of RMF. With the increasing input voltage, the compounds shape trends toward hexagonal with smooth edges.

The composition of the iron phase obtained with various concentrations of manganese differs considerably. When Mn/Fe ratio is 1.1, the ratio of manganese and iron content in the hexagonal blocks is nearly 1. The approximate chemical formula can be expressed as $Al_{12}Si_2Fe_{1.5}Mn_{1.5}$, similar to the star-like phase formed without RMF. When the Mn/Fe ratio is 0.5 or 0.8, the content of Mn in the blocky compounds (arrowed as 5 and 8 in Fig.2) is only half of iron amount. The approximate chemical formula of this phase is $Al_{12}Si_2Fe_2Mn_1$. It indicates that the application of RMF can facilitate the formation of α-AlSiFeMn phase, as well as its transformation to hexagonal blocks even at lower manganese content. Therefore, with the application of RMF the consumption of neutralizer can be reduced and the amount of iron-containing IMCs in modified alloys can be decreased.

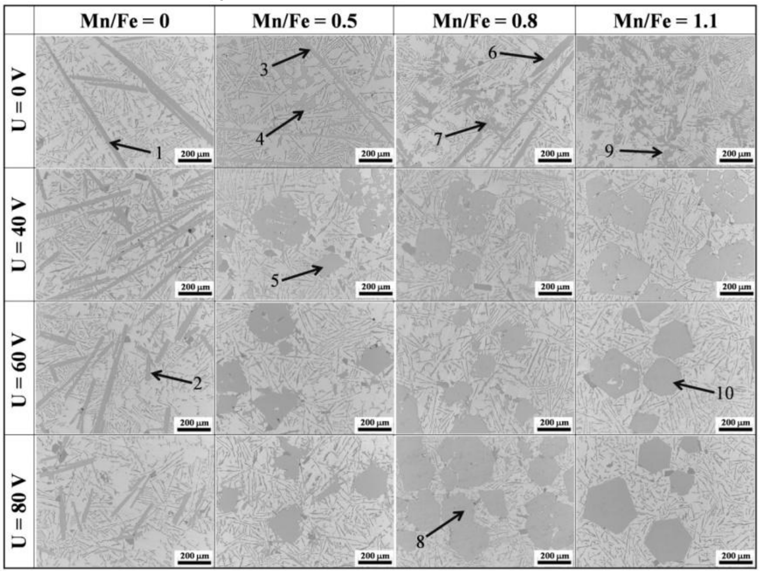

Fig. 2: Microstructure of Al-12%Si-2%Fe-x%Mn alloy (x=0, 1.0, 1.6, 2.2) smelted with RMF of different voltage

Table 1 Composition analysis of the iron phases in Fig.2 by EPMA (mol.%)

Point	Al	Si	Fe	Mn	Average-chemical formula
1	67.126	16.763	16.111	0	β-$Al_9Si_2Fe_2$
2	67.931	16.354	15.715	0	β-$Al_9Si_2Fe_2$
3	65.308	19.012	14.222	1.458	β-$Al_9Si_2Fe_2$
4	71.395	10.371	10.104	8.131	α-$Al_{12}Si_2Fe_{1.5}Mn_{1.5}$
5	68.647	12.291	12.652	6.410	α-$Al_{12}Si_2Fe_2Mn_1$
6	65.120	18.728	14.906	1.245	β-$Al_9Si_2Fe_2$
7	70.967	10.659	10.271	8.103	α-$Al_{12}Si_2Fe_{1.5}Mn_{1.5}$
8	68.113	10.850	14.280	6.757	α-$Al_{12}Si_2Fe_2Mn_1$
9	70.632	11.274	10.084	8.010	α-$Al_{12}Si_2Fe_{1.5}Mn_{1.5}$
10	70.583	11.478	8.876	9.064	α-$Al_{12}Si_2Fe_{1.5}Mn_{1.5}$

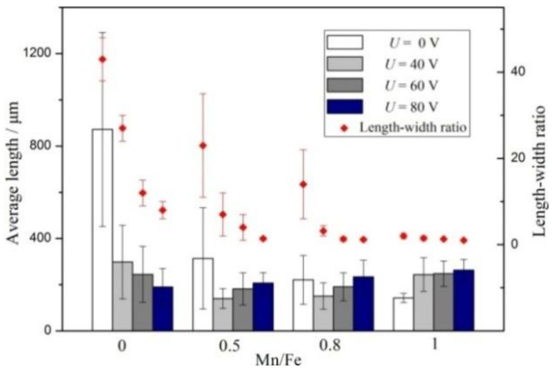

Fig. 3: Morphological analysis of theiron-containing phases with RMF and Mn

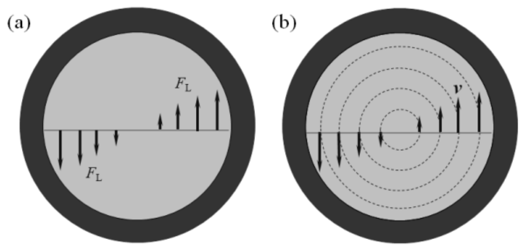

Fig. 4: Schematic illustration of the Lorentz force and flow direction under RMF on the top view, (a) Lorentz force, and (b) flow direction

Discussion

In the case of RMF applied without addition of manganese, the electromagnetic stirring most likely to be responsible for the transformation of β-phase from acicular shape to the rod-like. It is well known that RMF induces fluid flow in the treated melt, leading to thermal and solute transfer. When RMF is applied, there is a Lorentz force generated in the melt[11,12], the azimuthal component of which is written as F_L. A schematic illustration of this magnetic force and flow direction of a melt under RMF is shown in Fig. 4. In the cross-section, the Lorentz force has a tangential direction, and thus the liquid metal mainly exhibits a primary motion in the form of a swirl. This electromagnetic stirring is useful in assisting dendrite fragmentation and abscission of secondary dendrite arms during solidification[11]. For this reason, the strong stirring is considered to fragment the brittle acicular β-phase. With the increasing voltage, the magnetic force F_L and the corresponding magnetic flux density will increase. The average length of β-phase therefore reduces along with increase in stirring effect. In addition, rotating followed by the fluid flow during the solidification is also useful to the inhibition of β-phase growth. These should be the reasons for the change in the morphology of β-phase.

According to the microstructure of alloy, the influence of RMF on the morphology and type of iron-containing IMCs depends on the presence of manganese. Under conventional casting condition, the acicular iron phase can be neutralized only by the additions of sufficient amount of manganese (Mn/Fe ratio is 1.1 in this study) which converts the β-$Al_9Si_2Fe_2$ into the more compact star-like α-$Al_{12}Si_2Fe_{1.5}Mn_{1.5}$. But at lower manganese concentrations (Mn/Fe<1.1), only part of β-phase gets neutralized. Some star-like α-$Al_{15}Si_2Fe_{1.5}Mn_{1.5}$ appear by undergoing reaction 1. At the same time, the formation of α-phase consumes most manganese present in the melt and shifts the local chemical composition. As a result, part of iron IMCs grow to α-$Al_{15}Si_2Fe_{1.5}Mn_{1.5}$ due to manganese segregation, while in the regions depleted with manganese, the more stable β-phase is formed.

With using RMF, a forced convection is generated in the melt as soon as it is applied. The presence of the electromagnetic driven flow promotes the uniform distribution of alloying elements, leading consequently to the componential homogenization. The manganese segregation during neutralization is thus restrained. By the contribution of RMF, each piece of β-phase platelet can be provided sufficient manganese for the transformation to α-AlSi(FeMn). Since the manganese concentration in the melt is lower, the product is α-$Al_{12}Si_2Fe_2Mn_1$ rather than α-$Al_{12}Si_2Fe_{1.5}Mn_{1.5}$. Therefore, the facilitation of α-AlSiFeMn phase formation under RMF should be related to the solute homogenization by electromagnetic stirring.

Conclusions

Effect of RMF and neutralizer manganese on the morphology and composition of AlFeSi IMCs formed in the Al-12%Si-2%Fe alloy were studied. The main conclusions can be formulated as following:

(1) The manganese addition causes the transformation of β-$Al_9Si_2Fe_2$ IMC to the α-α-$Al_{12}Si_2Fe_{1.5}Mn_{1.5}$ IMC with subsequent changes in morphology of iron phase from acicular to star-like. The increasing manganese content is beneficial for the converting, and the total transformation is achieved when Mn/Fe ratio is 1.1.

(2) In the absence of neutralizer, the RMF only affects the size and morphology of β-$Al_9Si_2Fe_2$, single RMF makes the iron phase crystallized in rod-like. When the manganese is introduced, the application of RMF facilitates the formation of $Al_{12}Si_2Fe_2Mn_1$ at lower Mn/Fe ratio (0.5 and 0.8).

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