THE INFLUENCE OF SR ADDITION ON THE MICROSTRUCTURE OF A380 ALLOY

Meng Wang
Shenzhen Key Laboratory of Advanced Materials, Department of Materials Science and Engineering, Shenzhen Graduate School, Harbin Institute of Technology, Shenzhen, China

Wilson Xu and Qingyou Han
School of Engineering Technology, Purdue University, West Lafayette, IN, USA

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Abstract

Whereas A380 series alloys are some of the most widely used aluminum alloys, iron can severely degrade the ductility of an Al–Si die-casting alloy because its presence leads to the precipitation of different AlFeSi intermetallic phases resulting in development of stress concentrations. Thus, controlling the fraction and morphology of AlFeSi phase, especially the β-AlFeSi phase, is an important way to refine the ductility of A380 die-casting alloys. This article describes how Sr element was added to A380 alloys to study the effect of Sr on the morphology change of the AlFeSi phase. The results show that high cooling rates and Sr addition can both change the morphology of β-AlFeSi and transfer β-AlFeSi to α-AlFeSi. In addition, both high cooling rates and Sr addition can modify the eutectic Al–Si phase. The study shows that the optimum Sr addition and cooling rate for the A380 series alloy are 0.1 wt% and 10 °C/s, respectively.

Keywords: *A380 alloys, strontium, Al–Fe–Si phase, cooling rate*

Introduction

A380 is one of the most widely used aluminum silicon die-casting alloys owing to its good castability, high-quality machinability, high strength–weight ratio, and ductility. Many applications of aluminum 380 can be found in aerospace craft, high-pressure resistance castings, and automotive parts.[1,2]

One important problem for the application of Al–Si die-casting alloy is the presence of iron in the alloy. In A380 series die-casting alloys, it is not unusual for iron content to be as high as 1.2–2.0 %.[3,4] Moreover, it is commonly held that the high levels of iron, compared to the iron levels in sand cast aluminum alloys and other permanent mold cast alloys, are attributed to two aspects: first, as a recycled aluminum alloy, iron is inevitably introduced during the production process and removing the iron from the alloy will severely increase the economic burden of its manufacture; second, during the die-casting process, the molten die-casting aluminum alloy will be in direct contact with the uncoated steel die and die soldering may occur. It has been shown that a high level of iron can prevent die soldering because of the limit of solubility of Fe in aluminum. However, high levels of iron significantly decrease the mechanical properties of die-casting alloys, especially ductility. The reason lies in the introduction of the Al–Fe–Si phase, especially β-Al_5FeSi phase, with increase of the Fe element. Many research studies have shown that the resulting needle or plate-like β-Al_5FeSi structure is the main cause of the degradation of mechanical properties while also acting as a stress riser.[5–7]

Since iron is inevitable and cannot be economically removed from the molten aluminum, several methods have been adopted to reduce its negative effect. The first is to increase the cooling rate. Many research studies have indicated that high cooling rates effectively suppress the formation of β-AlFeSi and change the morphology of β-AlFeSi from needle to plate.[8–10]

However, the high cooling rates cannot be achieved by permanent mold casting and sand casting, and needle-like phases can still be found whenever high cooling rates are used in die-casting applications.[11] Increasing melt heating temperatures is another method used to refine and reduce the Fe-rich β-AlFeSi. One positive aspect of the use of this method is that it also avoids the formation of sludge. Despite its benefits, increasing the casting temperature will cause oxidation and increase the porosity of the casting.[8]

Alloying is the most common way to modify the Fe-rich intermetallics in the Al–Si casting alloys. Mn, Cr, Be, etc., have crystalline structures similar to iron and can reduce the solid solubility in Al–Si die-casting alloys. In addition, these elements change β to the less harmful α phase and do not reduce the die soldering ability. However, to be effective, the amount of Mn and Cr addition must be controlled, otherwise sludge will be formed and severely reduce the casting and mechanical properties.[12–14]

Several reports examine the effect of Sr refinement on the AlFeSi phase. The key findings may be summarized in three ways. First, Sr is more effective than Mn for refining the AlFeSi phase. It is reported that the modification effect of Sr is equal to that of Mn of 10 times concentration.[15–18] Second, with low Sr addition, no extra intermetallics can be introduced. Third, Sr can simultaneously modify the eutectic silicon phase.

Although the reason why Sr can refine the Al–Fe–Si phase is not clearly understood, a research study to gain further knowledge of the influence of Sr addition on the microstructure of A380 alloy has been made and is described in this paper. Briefly, this research consists of a series of experiments with different levels of addition of Strontium in A380 die-casting alloy at different cooling rates. The resulting morphology change of Fe-intermetallics is described, and the reasons for refinement of the AlFeSi phase due to the presence of the element Sr are discussed.

Experimental Procedure

The A380-Sr alloys were prepared by using 380 aluminum alloy in unmodified form supplied by ALCOA (See compositions in Table 1). About 180 g A380 alloy was remelt in the Kerr furnace. Casting samples consist of A380 with additions of 0.01, 0.05, 0.10, 0.30 wt% Sr in the form of Al–10Sr master alloy, holding temperature at 710 °C for 2 h and casting at 650 °C. The molten alloy was then poured into:

(a) a steel mold, inner dimension 3 × 1 × 1 in., which was expected to resemble cooling rates close to a slow permanent mold casting (∼5 °C/s);
(b) a copper mold, inner diameter Φ1 × 1 in., and placed in a tank with water. The cooling rates can be assumed to be close to the ones from a fast permanent mold casting (∼10 °C/s);
(c) cold water directly. This process of melt quenching is used to produce a fine grain structure with secondary dendrite arms 6–8 μm, resembling those obtained from a die-casting process (∼20 °C/s).

Samples for metallographic observation were prepared using standard procedures (mounted into standard samples, followed by grinding and polishing) and etched by a 0.5 % HF solution. Metallographic observation was made by the combination of optical microscopy (optical microscopy (OM, Leca) and SE imaging from a scanning electron microscope (FEI XL40) using energy dispersive X-ray spectroscopy. ImageJ software was used to determine the influence of Sr content and cooling rate on the microstructure of the A380 alloy. Particle size and shape were characterized with statistics software. The 380-xSr phase diagram and cooling curves were developed using Thermal-Calc™ software.

Theoretical simulations of A380-Sr phase diagram were conducted by Thermo-Calc Software. Poly_3 module and ALT database of aluminum alloy were used for thermo-calculation and prediction of the precipitation of Al–Fe–Si phase.

Results

From Figure 1, A380-Sr phase diagram shows that Sr does not have an effect on the formation on AlFeSi phase. But the Sr addition will lead to the formation of Al_2SrSi_2 phase, which is a hard intermetallic and detrimental to the ductility of alloy.

From Figures 2, 3 and 4, it can be seen that Sr is an effective modifier to reduce the amount of β-AlFeSi phase and to transfer β-AlFeSi to α-AlFeSi phase. With the addition of Sr, the following phenomena have been observed:

Table 1. Chemical Compositions of A380 Alloy

	Si	Fe	Cu	Mn	Mg	Ni	Zn	Al
Specific conc. (wt%)	9.0	1.0	3.6	0.4	0.1	0.3	0.35	Bal.

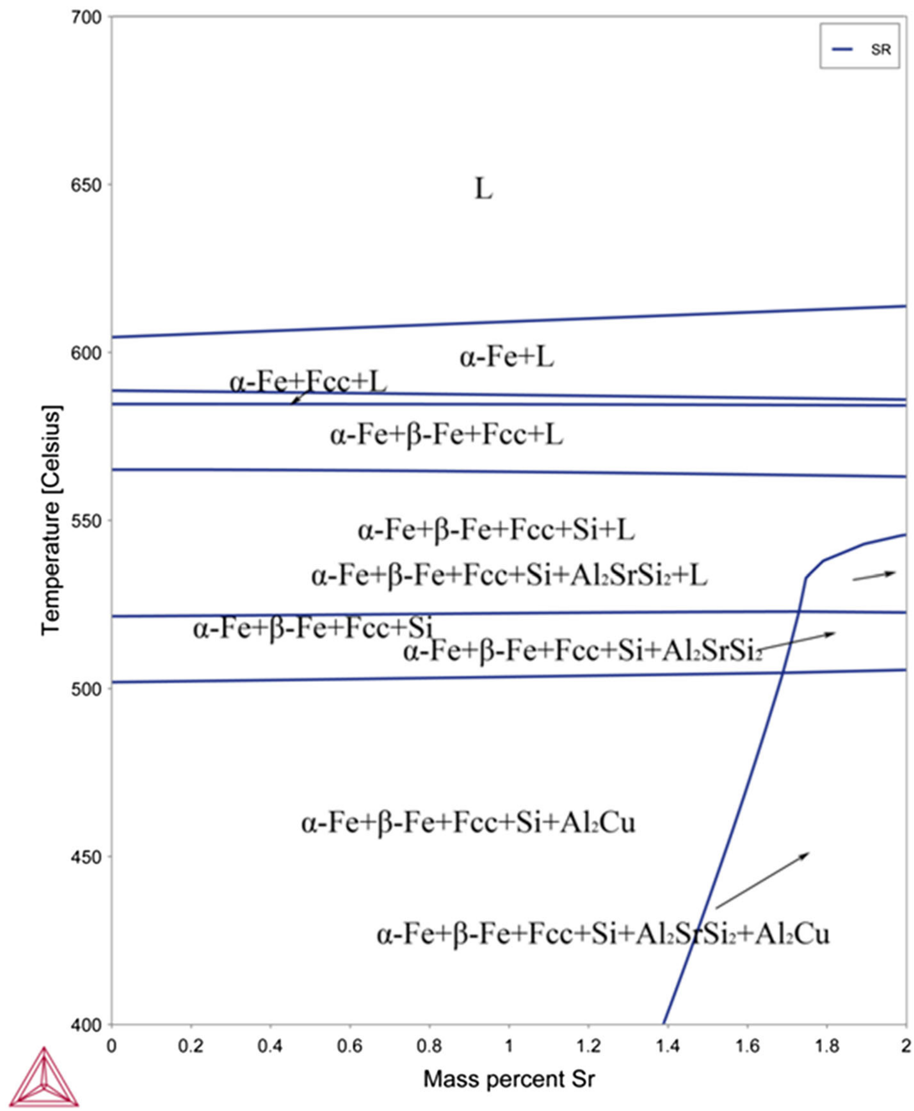

Figure 1. Al–Si–Cu–xSr phase diagram (Si = 9 %, Cu = 3.5 %, Mn = 0.4 %, Fe = 1 %, Mg = 0.2 %, Zn = 0.35 %, Al = bal.).

1. The cooling rates affect the transformation of β-AlFeSi to the α-AlFeSi phase. With 5 °C/s, even with 0.01 % Sr addition, no obvious β-AlFeSi can be found (see Figure 2). With a cooling rate of 10 °C/s, even 0.01 % Sr addition can effectively reduce the fraction of β-AlFeSi formed. The optimized condition can be obtained when the Sr content is 0.1 %. If the Sr contents go up, more platelate phase would form (see Figure 3). The 20 °C/s cooling rate sample has a similar trend to that of using a 10 °C/s rate. However, even with the optimized condition (0.1 Sr%), obvious β-AlFeSi can still be viewed (see Figure 4).
2. It is noted that if the Sr content is lower than 0.1 %, the size and fraction of β-AlFeSi is reduced with Sr addition; however, if the Sr content is higher than 0.1 %, the size and fraction of β-AlFeSi is increased with Sr addition. Thus, the high Sr content introduced more β-AlFeSi phase (Tables 2, 3, 4, 5).

Other phenomena have also been observed. When the cooling rate is about 20 °C/s, some polygon α-AlFeSi sludge is formed. The sludge is trapped by α-AlFeSi, taken to mean a primary phase. From this point of view, it is apparent that a higher cooling rate can transfer β-AlFeSi phase to α-AlFeSi, while very high cooling rates can also introduce sludge. The reason is attributed to the fact that high cooling rates facilitate the formation of the metastable α-AlFeSi while reducing the formation temperature of α-AlFeSi. Therefore, the first nucleated α-AlFeSi can grow without the restriction of α-Al.

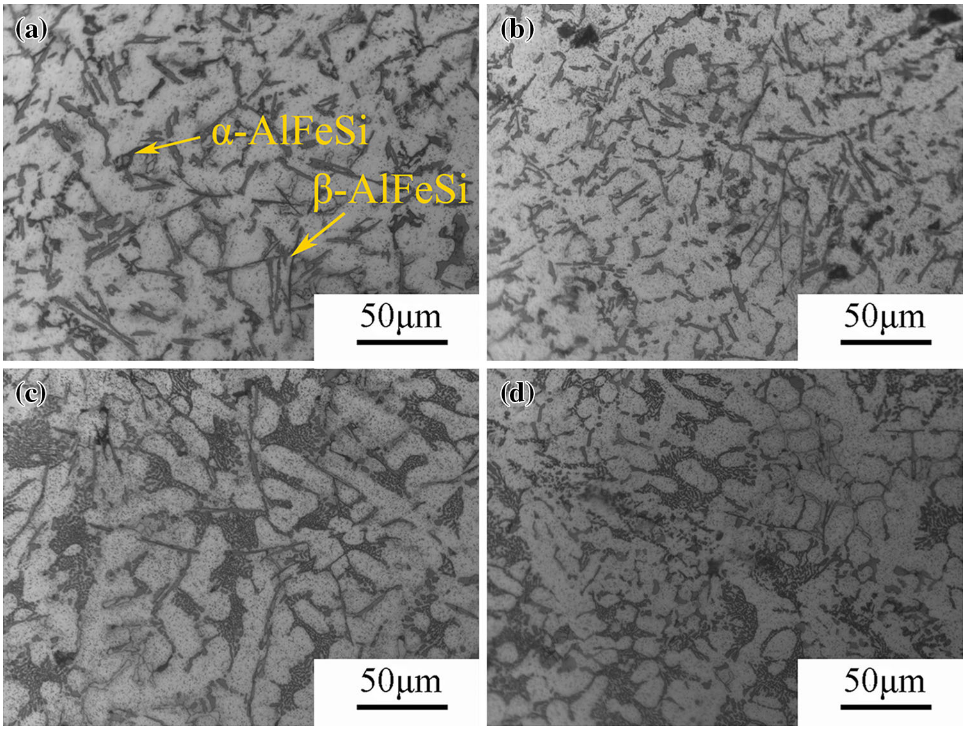

Figure 2. Microstructure of 380 alloys with different Sr addition at 5 °C/s. (a) 0.01, (b) 0.05, (c) 0.1, and (d) 0.3.

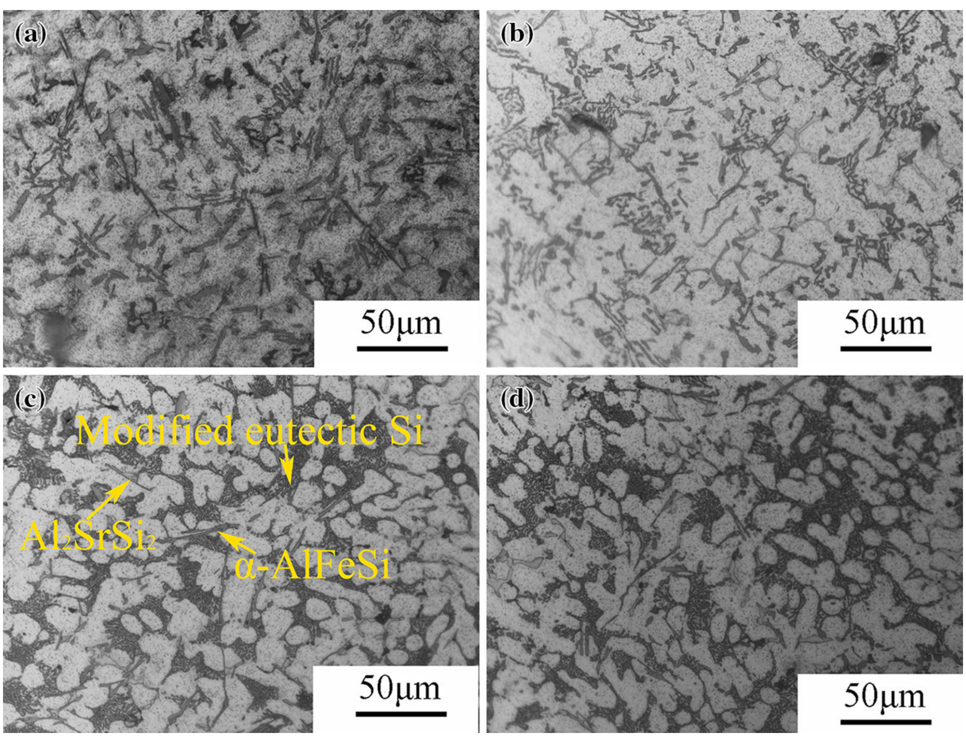

Figure 3. Microstructure of 380 alloy with different Sr addition at 10 °C/s. (a) 0.01, (b) 0.05, (c) 0.1, and (d) 0.3.

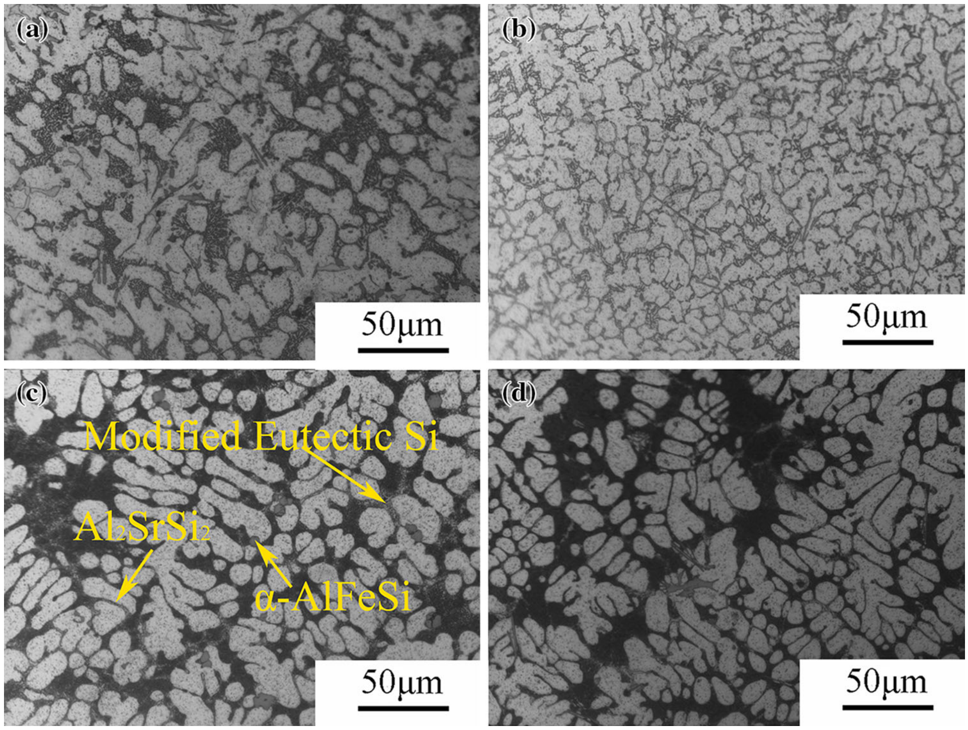

Figure 4. Microstructure of 380 alloy with different Sr addition at 20 °C/s. (a) 0.01, (b) 0.05, (c) 0.1, and (d) 0.3.

Table 2. Parameters of α-AlFeSi and β-AlFeSi Morphology in A380-0.01Sr Alloy with Different Cooling Rates

Cooling rate (°C/s)	β-length (μm)	β-width (μm)	Aspect ratio	β-fraction (%)	α-fraction (%)
5	28.95	1.87	15.48	1.12	2.22
10	16.87	1.88	8.97	0.73	2.51
20	–	–	–	–	3.13

Table 3. Parameters of α-AlFeSi and β-AlFeSi Morphology in A380-0.05Sr Alloy with Different Cooling Rates

Cooling rate (°C/s)	β-length (μm)	β-width (μm)	Aspect ratio	β-fraction (%)	α-fraction (%)
5	31.85	2.10	15.17	1.01	2.32
10	10.15	1.55	6.35	0.51	2.63
20	–	–	–	–	3.22

Table 4. Parameters of α-AlFeSi and β-AlFeSi Morphology in A380-0.1Sr Alloy with Different Cooling Rates

Cooling rate (°C/s)	β-length (μm)	β-width (μm)	Aspect ratio	β-fraction (%)	α-fraction (%)
5	23.67	1.64	14.43	0.62	2.68
10	20.56	1.79	11.49	0.31	3.12
20	–	–	–	–	3.31

On the other hand, the combined use of a high cooling rate and Sr addition can facilitate the modification of eutectic silicon. There is an obvious modification effect present using a 5 and 10 °C/s cooling rate with 0.1 wt% Sr addition, while a 0.1 wt% Sr concentration for a 20 °C/s cooling rate is sufficient for Al–Si modification.

Table 5. Parameters of α-AlFeSi and β-AlFeSi Morphology in A380-0.3Sr Alloy with Different Cooling Rates

Cooling rate (°C/s)	β-length (μm)	β-width (μm)	Aspect ratio	β-fraction (%)	α-fraction (%)
5	30.43	1.81	16.81	1.23	2.86
10	29.73	1.92	15.48	1.31	3.02
20	–	–	–	–	3.51

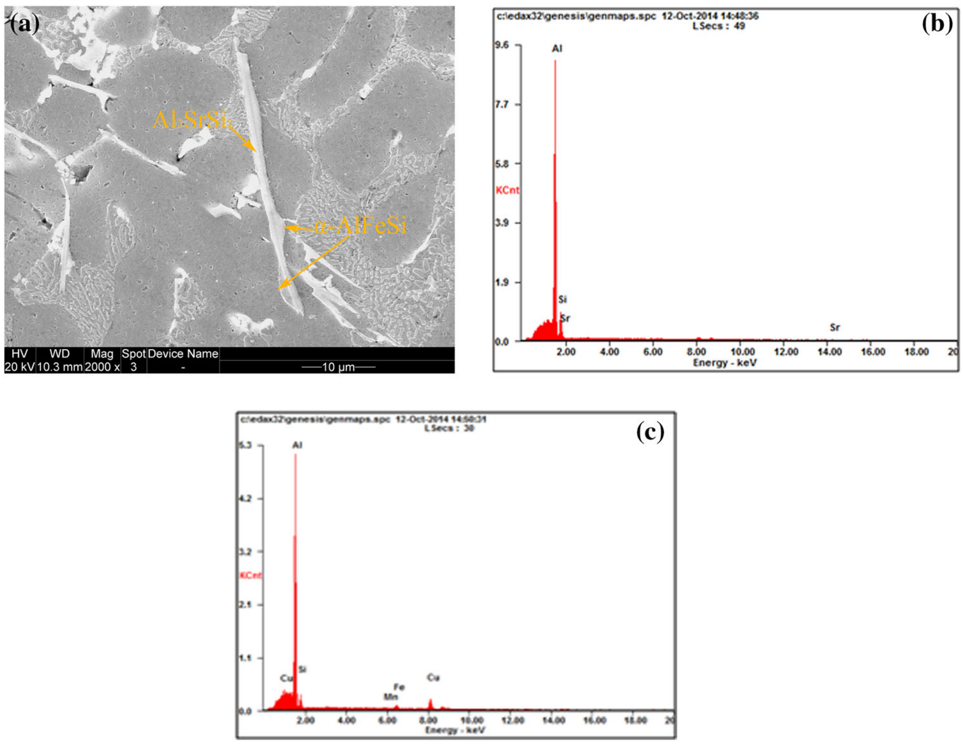

Figure 5. Relations of Al_2SrSi_2 and α-AlFeSi. (a) SEM images showing nucleation of α-AlFeSi from Al_2SrSi_2, (b) EDS of Al_2SrSi_2 and (c) EDS of α-AlFeSi.

Discussion

Mechanism of AlFeSi Phase Refinement by Sr Addition

There are three hypotheses dealing with the effect of addition of Sr on the category and morphology of the AlFeSi phase. These include:

1. Sr can be absorbed on the surface of primary α-AlFeSi phase to act as a barrier for dissolution. Thus, the peritectic reaction $L + \alpha$-AlFeSi = Al + β-AlFeSi will be hindered. If this situation happens, α-AlFeSi phase can be the reactant of the peritectic reaction. From the observation of samples without Sr addition, there is no β-AlFeSi to grow from and entrapped by α-AlFeSi. Thus, no obvious peritectic reaction can be found. Except for the low cooling rates, there is not sufficient time for the primary α-AlFeSi phase to form, while fast cooling rates can contribute to better modification of β-AlFeSi. Thus, this theory cannot support the current experimental results or explain the phenomenon observed in the experiment.
2. Sr can cause the super saturation of the elements Fe and Si. With the super saturated Si and Fe, the primary β-AlFeSi phase will nucleate first prior to the formation of α-Al. After that, α-Al begins to nucleate on the surface of the primary β phase and Fe is rejected. The secondary β-AlFeSi phase then grows on the interdendrite zone.[19] The growth rate of the secondary phase is much lower than that of the primary phase; thus, the smaller β-AlFeSi phases can be found. However, no obvious primary β-AlFeSi phases can be found in the samples. For A380 alloys in general, the β-AlFeSi formation temperature is much

lower than the liquidus temperature so that even with the assistance of Sr, primary β-AlFeSi phase cannot form.

3. The third hypothesis is presented as an opinion and can be stated as follows: the Sr can be absorbed on the possible nucleation positions of the β phase, a phenomenon referred to as poisoning. Thus, the quantity of the β phase is reduced. No evidence of this condition was observed in the experiment.

Instead, our experimental results indicate the presence of an increased double-size oxidation layer and the formation of Al_2SrSi_2 phase during solidification. Figure 5 shows that α-AlFeSi grew from Al_2SrSi_2. The Al_2SrSi_2 has an effect similar to that of Al_2CaSi_2 which is also a good substrate of the α-AlFeSi phase. However, the Sr can also introduce an oxidation layer, which is a source of the nucleation of β-AlFeSi. Thus, the amount of Sr addition should be controlled.

In summary, the optimum Sr addition in A380 alloy to reduce the detrimental β-AlFeSi phase and avoid the formation of Al_2SrSi_2 sludge and SrO oxide layer is 0.1 %.

The Combination Effect of Sr and High Cooling Rates

The combination of using high cooling rates and addition of the element Sr may be summarized in the following three effects: (1) transfer β-AlFeSi to α-AlFeSi, for β-AlFeSi is a stable phase and is prone to form in an equilibrium situation while α-AlFeSi is metastable; (2) a high cooling rate can reduce the formation of β-AlFeSi; (3) a high cooling rate can reduce the size of β-AlFeSi for reducing the starting formation temperature of β-AlFeSi.

It was also found that a high cooling rate can facilitate the modification of Si with a lower concentration of Sr. This is because an undercooling rise by higher cooling, combined with the undercooling introduced by Sr addition, facilitate the modification of the Al–Si eutectic phase.

Conclusion

This paper has examined the effect of Sr addition on the formation of the AlFeSi phase in A380 alloys. The effect of different Sr concentrations and cooling rates on the quantity and morphology of the AlFeSi phase was investigated. The following conclusions based on the outcomes of the study are presented:

1. High cooling rates and Sr addition can both change the morphology of β-AlFeSi and the transfer of β-AlFeSi to α-AlFeSi. However, high cooling rates can introduce polygon α-AlFeSi sludge and a high Sr content can also introduce an oxidation layer, which will be the substrate of β-AlFeSi.
2. The use of both high cooling rates and Sr addition can modify the eutectic Al–Si phase. High cooling rates can facilitate the modification of eutectic Al–Si phase with low Sr addition.
3. The optimum Sr addition and cooling rate for A380 series alloy is 0.1 wt% and 10 °C/s, respectively.

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