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Effect of strontium on columnar growth of dendritic α phase in near-eutectic Al-11.6%Si alloys①

LIAO Heng-cheng(廖恒成)[1], DING Yi(丁 毅)[2], SUN Guo-xiong(孙国雄)[1]
(1. Department of Mechanical Engineering, Southeast University, Nanjing 210018, China;
2. College of Materials, Nanjing University of Technology, Nanjing 210009, China)

Abstract: For Al-11.6%Si alloy, the influence of the addition of Sr on the morphology of the dendrite α phase was investigated, and the characteristic parameters of the dendrite α phase, the primary dendrite spacing and the secondary dendrite arm spacing, were also measured. The addition of strontium promotes the columnar dendrite growth and leads to a decrease of both the primary dendrite spacing and secondary dendrite arm spacing with the increase of the content of strontium in the modified near-eutectic Al-Si alloys. It is thought that the addition of Sr leads to a reduction of the solid-liquid interfacial energy of the dendrite α phase, consequently resulting in a decrease of the growth undercooling of dendrite tips. And hence, the nucleation of the equiaxed grains in the liquid in front of the columnar dendrite tips is restrained, thus the addition of strontium in Al-Si alloys promotes the growth of the columnar dendrites. The reduction of the solid-liquid interfacial energy also leads to the decreases in the primary dendrite spacing and the secondary dendrite arm spacing.

Key words: Al-Si alloy; primary dendrite spacing; secondary dendrite arm spacing; strontium; microstructure

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1 INTRODUCTION

Though near-eutectic Al-Si alloys have got excellent castability, the undesirable strength and ductility limit their applications, especially in some important products. Investigations on improving mechanical properties of these alloys attract much attention of researchers and casting producers. Modification of eutectic silicon has become a basic practice of the near-eutectic alloys. The addition of strontium in Al-Si casting alloys causes a transition of the eutectic silicon phase from coarse flakes into fine fibers, and hence leads to a considerable improvement of the mechanical properties[1-6], which was commonly thought to be attributed to the changes of the morphology and size of the eutectic silicon phase. Many researches have focused on the modification mechanisms of sodium and strontium[1, 5, 7-16]. But whether some changes of the dendritic α phase have occurred or not during modifying process was paid less attention. The dendritic α phase, a ductile phase, has been found out to play an important role in improving the mechanical properties of the near-eutectic Al-Si casting alloys[17]. It is necessary to investigate the effect of strontium on the growth of dendrites. Although the directional solidification experiment, a good method for studying the dendrite growth behavior, is not done in the present study, it is also practically significant to discuss the effect of strontium on the dendrite growth in Al-Si alloy during casting, and to analyze its mechanism.

Depending on the constitutional and heat flow conditions in a solidifying aluminum alloy, three different grain morphologies are possible, namely, equiaxed, columnar, and twinned columnar. Twinned columnar grains(TCGs) are much less common than the other types but can occur in Al-Si casting alloys[18]. In neither of these dendritic growth modes, equiaxed or columnar, does growth occur at the equilibrium liquidus temperature. Instead the temperature of a growing dendrite tip is below the liquidus by an amount known as the growth undercooling. The temperature of the dendrite tip is mainly controlled by the solute diffusion in liquid. The movement of the isothermal front binds down the dendritic growth, the velocity of movement determines the dendrite tip undercooling[19].

In the Hunt's model of the steady state of equiaxed dendrite growth[20], a columnar dendritic front is assumed to be growing at an undercooling, ΔT_C(growth undercooling below liquidus temperature for columnar dendritic growth), and the nucleation of the equiaxed dendrites is assumed to take place instantaneously at an undercooling, ΔT_N. If $\Delta T_N < \Delta T_C$ then the equiaxed dendrites can grow in the liquid ahead of the columnar dendrite front. The competition between the columnar and equiaxed growths depends on the extent of undercooling in the liquid ahead of the columnar growth front.

In the casting solidification process, many factors affect the dendritic growth and the morphology

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Correspondence: LIAO Heng-cheng, PhD; Fax: +86-25-83791414; Tel: +86-25-83792456-806; E-mail: hengchengliao@seu.edu.cn

of the dendrites. One kind of them includes the intrinsic properties of the alloy, such as m, k_0, C_0, D_L, γ and ΔS (where m is the slope of the liquidus, k_0 is the equilibrium partition coefficient of the solute between solid and liquid, C_0 is the composition of the alloy, D_L is the diffusion coefficient of the solute in liquid, ΔS is the entropy of fusion per unit volume, and γ is the solid-liquid interfacial energy), and the other includes the processing factors, such as the temperature gradient in the liquid, the pouring temperature, the heat releasing conditions and the nucleation potency in the melt. In the common casting solidification process, the temperature gradient in the liquid is fairly level after a short periodic chilling, so the tip growth undercooling, ΔT_C, which is defined as the temperature difference between the liquidus temperature of the alloy and the tip temperature, of both equiaxed and columnar dendrites can be expressed as[18, 20-22]

$$\Delta T_C = 2.83\,[\,mC_0(k_0 - 1)\,\gamma v_C / D_L \Delta S\,]^{1/2} \quad (1)$$

where v_C is the growth velocity of the dendrite tip.

2 EXPERIMENTAL

2.1 Preparation of experimental alloy and observations on microstructure

The experimental alloy with nominal composition of Al-11.6%Si-0.15%Fe was melted in an electrical resistance furnace using a graphite crucible. An Al-10%Sr master alloy was added to the melt at about 730 ℃. According to the recovery of strontium in the melts measured by ICP spectrometer, the strontium content in the alloys is obtained as 0, 0.010%, 0.015%, 0.020%, 0.025%, 0.030% and 0.0375%. After 30 min warm-keeping, the SW-RJ-1 flux was introduced for degassing. Then, the melt was poured at about 720 ℃ into a standard tensile sample mold (grey iron, preheating at 200 ℃). The metallographic samples were cut from the gage part of the tensile test bars (12 mm in diameter, 60 mm in gage length). After being etched in the Keller's reagent, the microstructure was observed and recorded using an optical microscope.

2.2 Measurement of characteristic parameters of dendritic α phase

Two characteristic parameters of the dendritic α phase, λ_1 and λ_2, were measured using the linear intercept method with an optical microscope by hand. The magnification of the visual field is fixed as 100 and the sampling number is 15 for each datum. The scale mark in the microscope was adjusted to be perpendicular to the growth direction of a given columnar dendrite groups with the same orientation, and then the number of the primary dendrites, N_1, was counted within a definite length L_1, which was not fixed and should be adjusted according to the actual cases. Then the value of λ_1 is obtained from $\lambda_1 = L_1/100(N_1 - 1)$. For λ_2, the scale mark was run parallel to the growth direction of one primary dendrite and the number of the secondary dendrite arms, N_2, was counted with a fixed length L_2 which was 4×10^4 μm (image scale) in the present study, and then, $\lambda_2 = L_2/100(N_2 - 1)$.

3 RESULTS

3.1 Morphology of dendritic α phase

The influence of the Sr content on the morphology of the dendritic α phase in Al-11.6% Si alloy is shown in Fig. 1. In the unmodified alloy, the morphology and orientation of the dendritic α are not uniform and the secondary dendrite arm spacing is large. There are some blocky primary silicon particles, and the eutectic silicon is presented as coarse flakes. With the Sr content of 0.015%, the dendritic α phase becomes more columnar. When the amount of Sr increases to 0.020%, the dendritic α becomes completely columnar and slender, and the eutectic silicon is presented as fine fibers. With more addition of Sr, both the primary dendrite spacing and the secondary dendrite arm spacing decrease. Same effects of strontium were found in Al-11.6%Si-0.4%Mg alloy[17] and Al-13.0%Si alloy[23]. From the above observations, it is rational to conclude that Sr promotes the columnar growth of the dendrites in Al-Si casting alloys. However, it fails to agree with the point of view of Lu and Hellawell[11], who pointed out that the addition of strontium or sodium has no observable influence on the dendrites in Al-Si casting alloys.

3.2 Characteristic parameters λ_1 and λ_2

Fig. 2(a) shows that the secondary dendrite arm spacing decreases with the addition of strontium increasing. When the addition of strontium increases from 0.020% to 0.0375%, λ_2 decreases by about 30% in the Al-11.6% Si alloy. Fig. 2(b) indicates that increasing the strontium content from 0.020% to 0.0375% leads to about 23.1% reduction of λ_1. The results above suggest that the addition of strontium in Al-Si casting alloys can refine the primary dendrites and the secondary dendrite arms. It is beneficial to the improvement of the mechanical properties.

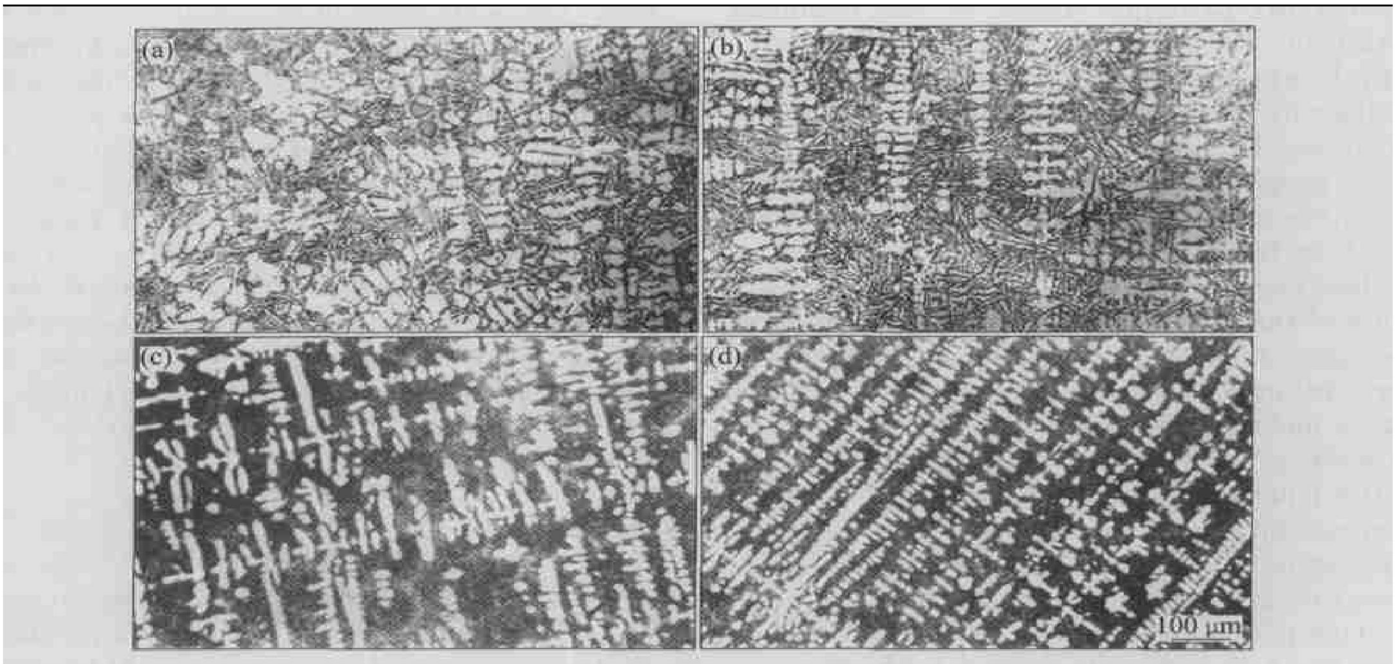

Fig. 1 Influence of Sr content on morphology of dendritic α in Al-11.6%Si alloy
(a) —0%Sr; (b) —0.015%Sr; (c) —0.020%Sr; (d) —0.0375%Sr

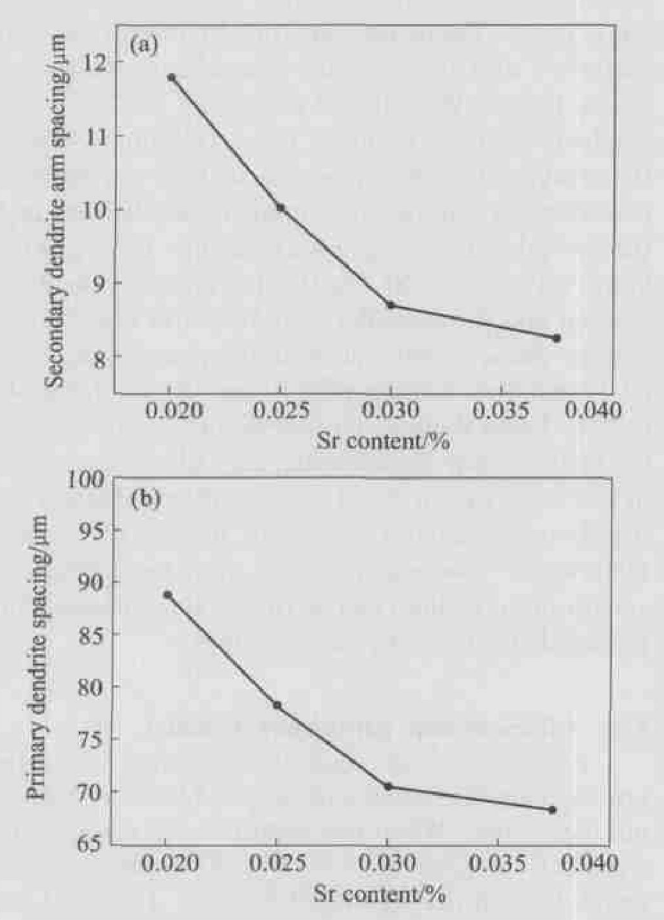

Fig. 2 Effects of Sr content in Al-11.6%Si alloys on λ_2(a) and λ_1(b)

4 ANALYSIS AND DISCUSSION

Tashis[24] has found out by experiment that the refinement of alloying elements has a relation to the parameter, $mC_0(k_0-1)/k_0$. The grain size decreases remarkably with the increase of the value of it. This refining effect is related to the constitutional undercooling caused by the solute rejected from the dendrite tips and accumulating in the liquid ahead of the tips. From the point of view of the constitutional undercooling criterion, the larger the ΔT_0 is, the larger the constitutional undercooling is. It is validated by the experimental data of Gowri and Samuel[25]. They reported that the additions of Zn, Mg, Cu, Mn or Fe in 380 Al alloys led to a decrease in the secondary dendrite arm spacing. Kearns and Cooper[26] and Apelian et al[27] thought that this effect of alloying elements could be cumulated simply. The effect of strontium is also assumed to cumulate simply in the present work.

From the data in Table 1, it is seen that in Al-11.6%Si alloy the variation of $mC_0(k_0-1)$, even with the maximum addition of strontium in the present study (the strontium content is 0.0375%), is quite little, which can be neglected. But the addition of strontium may cause the intrinsic property of alloy melt to change considerably. The influence of atomic volume on the surface tension has been well established by many researchers[28, 29]. As modifiers, the atomic radii of sodium and strontium are long[5], $r_{Na}/r_{Al}=1.86/1.4310=1.30$ and $r_{Sr}/r_{Al}=2.16/1.4310=1.51$, and the solubility of them in the α (Al) solution is very low. So the atoms of strontium or sodium are rejected from the solid, accumulating in the liquid ahead of the dendrite tips during the growth of the dendritic α phase, and, consequently, the solid-liquid interfacial energy is decreased. The data in Table 2 illustrate that the addition of sodium in Al-Si alloy leads to a considerable reduction in the surface tension of the alloy melt. Though the effect of strontium on the surface tension of the Al-Si alloy melt has not been measured, it is rational to think that the addition of strontium in Al-Si alloy melts also causes the solid-liquid interfacial energy to decrease according to the effect of sodium. Suppose that the influences of strontium on D_L and ΔS are tiny, since the effect of strontium on $mC_0(k_0-1)$ can be neglected, it can be obtained that the addition of strontium in Al-Si alloys leads to a decrease in the tip growth undercooling of columnar dendrite from Eqn. (1), under the same processing conditions. It is the reduction in the growth undercooling of the dendrite tip that restrains the nucleation of the equiaxed grains in the liquid ahead of the columnar dendrite tips. Thus the columnar growth of dendrite is promoted.

Table 1 Properties of Al alloys with a sort of solute elements[11]

Element	m	k_0	$m(k_0-1)$	$mC_0(k_0-1)^*$ / K	ΔT_0^* / K
Si	− 6.7	0.13	5.83	67.63 (C_0= 11.6)	6.59
Sr	− 2.4	0.12	2.11	0.079 (C_0= 0.037 5)	0.66

* The data of these two columns are obtained by calculating with the alloy compositions in the present study.

Table 2 Influence of Na on surface tension of Al and Al-Si alloy melts[24] (10^{-3}N·m^{-1})

Pure Al	Pure Al+ 0.1% Na	Al-10% Si	Al-10% Si+ 0.1% Na	Al-10% Si+ 0.2% Na
849	695	842 - 831	619	560

Using the scaling law $\lambda_2/R = 2$, the variation in the secondary dendrite arm spacing, in small Peclet number conditions, can be presented as[30]

$$\lambda_2^2 = 8\gamma L D_L / v_C \Delta T_0 k_0 \Delta S \qquad (2)$$

where L is a constant which depends on the harmonic of perturbation. For cubic crystals, $L = 28$ has been shown to be operative for the dendrite growth[31, 32].

For the primary dendrite spacing, a lot of work has been done by Flood and Hunt[21], Hunt[22], Trivedi and Somboonsuk[30], and Somboonsuk, Mason and Trivedi[32]. The following equation is deduced according to the previous results by the present authors above[33]

$$\lambda_1 = 6.506(\gamma D_L m(k_0-1)C_0/\Delta S v_C G_L^2)^{1/4} \qquad (3)$$

From Eqn. (2) and Eqn. (3), the relationships, $\lambda_2 \propto \gamma^{1/2}$ and $\lambda_1 \propto \gamma^{1/4}$, can be concluded. So the reduction of the solid-liquid interfacial energy, caused by the addition of strontium, is also the main reason for the secondary dendrite arms refining and the primary dendrite spacing decreasing.

5 CONCLUSIONS

1) The addition of strontium in near-eutectic Al-Si alloys promotes the columnar growth of dendrite. Both the primary dendrite spacing and the secondary dendrite arm spacing decrease with the increase of the strontium content. Strontium is beneficial to the refinement of the dendritic α phase.

2) It is thought that the addition of strontium in Al-Si casting alloys leads to the decrease of the solid-liquid interfacial energy, which causes the growth undercooling of the dendrite tip to be lower, and consequently the nucleation of the equiaxed grains in the liquid ahead of the columnar dendrite tips is restrained. Thus the columnar growth of dendrite is promoted. The same reason causes the primary dendrite spacing and the secondary dendrite arm spacing to decrease too.

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