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Dynamical coarsening processes of microstructures in non-dendritic $AlSi_7Mg$ alloy remelted in semi-solid state ①

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Abstract: The microstructural variation in the non-dendritic $AlSi_7Mg$ samples remelted in the semi-solid state has been investigated. It is proposed that the primary α-Al phases are mainly coarsened by connecting the secondary arms or fine primary α-Al phases together at the stage of a small quantity of liquid and slowly coarsened through diffusion at the stage of a great quantity of liquid. The dynamical coarsening equation controlled by diffusion is in good agreement with the equation of $d^3 - d_0^3 = kt$ and the effect of the starting microstructures on the coarsening of primary α-Al phases is gradually decreased when the soaking time is long enough.

Key words: aluminium alloy; semi-solid; isothermal remelting; microstructure **Document code:** A

1 INTRODUCTION

The semi-solid forming technologies of non-dendritic metals or their alloys were invented in the early 1970s[1]. In particular, the thixoformation technologies of $AlSi_7Mg$ alloy billets with non-dendritic microstructures made by electromagnetic stirring during solidification had progressed greatly and been applied successfully to manufacture many kinds of automobile parts in recent years[2~5]. The non-dendritic $AlSi_7Mg$ alloy billets must be remelted to the semi-solid zone in the thixoformation and the primary α-Al particles must be coarsened during the remelting. The coarsening process of the primary α-Al particles, however, has not been very clear up to date, so the dynamical coarsening process and the effect of the starting microstructures on the coarsening process have been investigated in this paper.

2 EXPERIMENTAL

2.1 Experimental materials

An $AlSi_7Mg$ alloy used in this study consists of 7Si, 0.45Mg and 0.2Fe in mass fraction, %. The starting billets with non-dendritic microstructures were made under the following conditions: billet size of 70 mm in diameter and 130 mm in height, mold preheated to 45 ℃ or 320 ℃, pouring temperature 750 ℃, electromagnetic stirring during freezing. Fig. 1 shows the microstructures of the billets before remelting. The white primary α-Al particles are spherical or rosette, the eutectic Si is distributed between them and the equilibrium area fraction of the primary α-Al particles is about 51%.

2.2 Process of semi-solid remelting

The long tubular electric furnace was used in the remelting experiments and the temperature was controlled within an accuracy of ±1 ℃. The isothermal soaking time was started to be recorded after the surface temperature of the little samples reached the given temperature and lasted 5 min. When the remelting came to the predetermined time, the little sample was quenched in water. The soaking times of the samples were 5~ 240 min and the soaking temperatures were 578 ±1 ℃ or 589 ±1 ℃, respectively corresponding to theoretically primary α-Al area fractions 50% or 40%. The size of the samples was 10 mm in diameter and 10 mm in length.

2.3 Observation and detection of microstructures

The quenched samples were rough ground, fine ground, polished, then etched with 0.5% HF water solution and finally observed under optical microscope. In order to quantitatively describe the dynamical coarsening process of the primary α-Al particles during semi-solid remelting, the microstructures of some samples were analyzed by SEM-IPS(Image Processing System).

3 RESULT AND DISCUSSION

3.1 Microstructural evolution

The equivalent diameter d, shape factor F($F = 4\pi A / P^2$, A and P are the average area and periphery of the primary α-Al particles) and solid area fraction f_s of the primary α-Al particles in some quenched

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samples, which were cut from the billet as shown in Fig. 1(a) and remelted at 578 ℃ or 589 ℃, were detected by SEM-IPS gaining results shown in Table 1.

Table 1 Image analysis results of primary α-Al in the non-dendritic samples

Soaking temp. / ℃	Soaking time/ h	d/μm	F	f_s/%
578	0.5	70	0.68	75
	1.0	100	0.75	70
	2.0	117	0.78	71
589	0.17	80	0.75	70
	0.5	96	0.76	66
	1.0	112	0.76	64
	2.0	134	0.77	65
	4.0	168	0.79	64

The microstructural evolution of the samples remelted at 578 ℃ for different times is shown in Fig. 2. Comparing Figs. 2(a) and (b) with Fig. 1(a), even if the soaking time was short, the primary α-Al particles were quickly coarsened through connection and there were many liquid islands in them. The eutectic quantity was much less than the equilibrium eutectic quantity and part of the eutectic Si only granulated and coarsened. When the remelting lasted 1 h, the whole eutectic of low melting point had been remelted, the primary α-Al gradually became large and spherical in shape, and the shape factor F had reached 0.75, as shown in Fig. 2(c). With a time longer than 1 h, the primary α-Al became larger, more spherical and the shape factor F had been 0.78, as shown in Fig. 2(d). As a result of the low remelting temperature, 578 ℃, the driving force was small; therefore the eutectic was remelted and eutectic Si dissolved slowly and the spheroidization speed of primary α-Al was also small.

If the remelting temperature was raised, the remelting speed of the eutectic and the connection coarsening speed of the primary α-Al were increased obviously, as shown in Fig. 3. Fig. 3(a) shows that when the sample was soaked for 0.17h at 589 ℃, the connection coarsening process had not only performed rapidly, the primary α-Al shape had been very spherical and the shape factor F had been 0.75, but the whole eutectic had been remelted. If the sample was soaked at 578 ℃, completion of the above process required 1h. Fig. 3(b) shows that after continued soaking, the primary α-Al particles had become larger, more spherical and the shape factor F was 0.79.

Another phenomenon was found from Fig. 2 and Fig. 3, that is to say when soaked at 578 ℃, fine primary α-Al dendrites did not appear on the large primary α-Al particles or in the former liquid area, but when soaked at 589 ℃, many fine primary α-Al dendrites that were pointed out with arrows in Fig. 3 grew out of the large primary α-Al particles or the former liquid area. This phenomenon may be related to the composition of the remelted liquid. If the samples were remelted at 578 ℃, the liquid composition was close to the equilibrium eutectic composition and the tendency of separating fine primary α-Al dendrites was small; when the samples were quenched, the liquid was changed to fine eutectic. However, if the samples were remelted at 589 ℃, the liquid composition was apart from the equilibrium eutectic composition and the tendency of freezing fine primary α-Al dendrites from the liquid or growing out of the large primary α-Al particles was large; when the samples were quenched, many fine primary α-Al dendrites emerged finally.

When the samples were soaked in the semi-solid region, they might gradually deform like the metals creep at high temperatures. The longer the soaking time, the more serious the deformation, but the effect of temperature on the deformation was more significant and the higher the temperature, the more serious the deformation. The experiments showed that the time for the samples to start to clearly deform at 578 ℃ was 1.5h and that at 589 ℃ was only 0.5h.

3.2 Dynamical coarsening process

The primary α-Al particle's coarsening was an

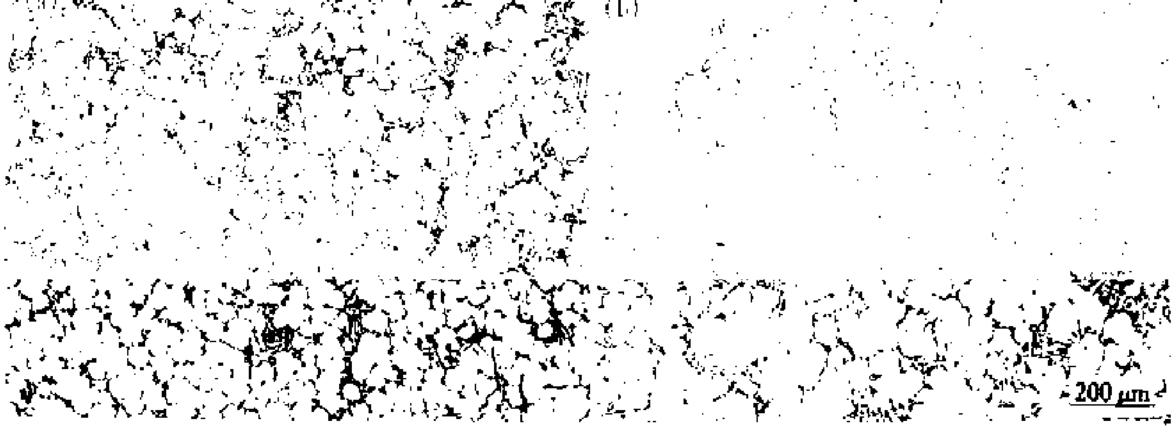

Fig. 1 Microstructures of non-dendritic billets before remelting in semi-solid state
(a) —Mold preheated to 45 ℃ before pouring; (b) —Mold preheated to 320 ℃ before pouring

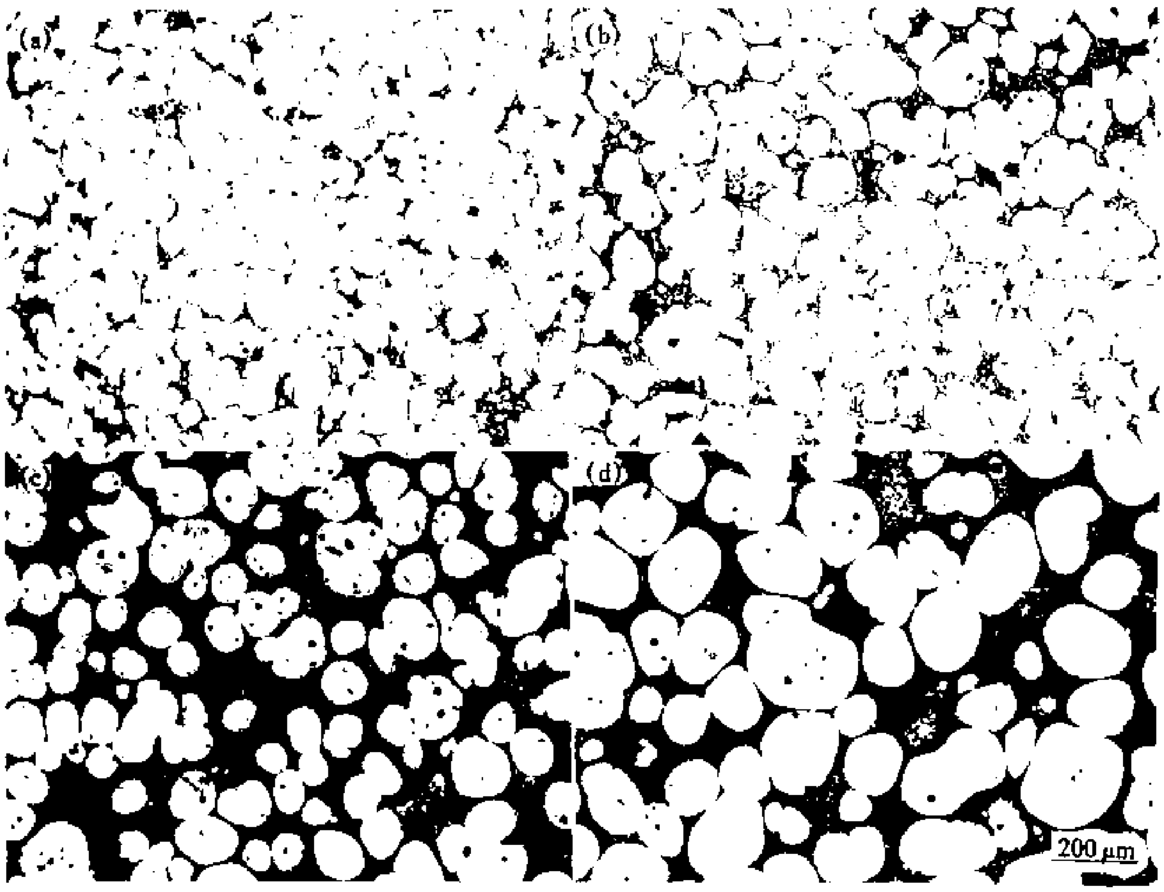

Fig. 2 Microstructures of non-dendritic samples remelted in semi-solid state at 578 ℃ for (a) 0.17h, (b) 0.5h, (c) 1.0h and (d) 2.0h

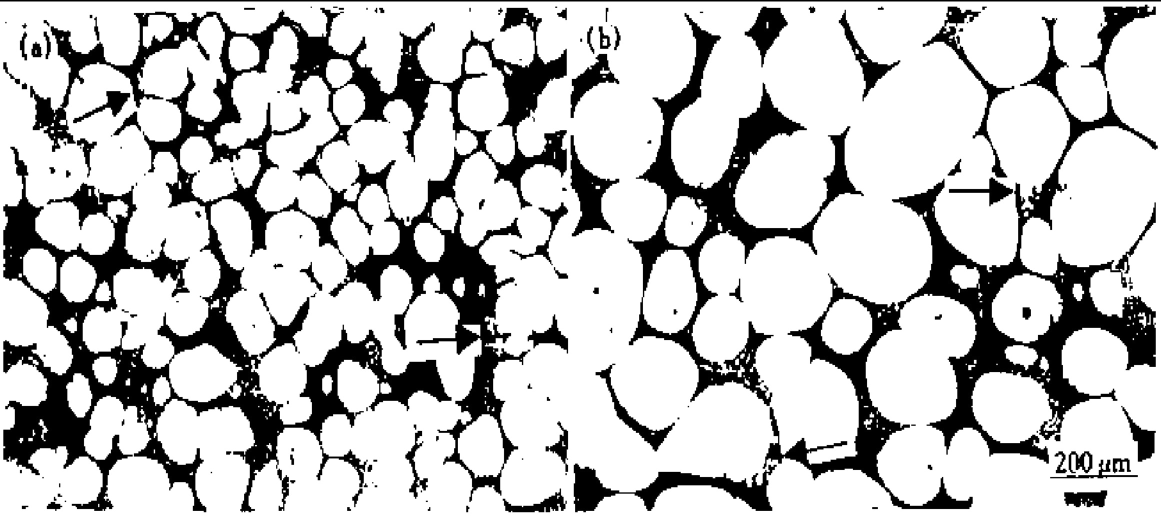

Fig. 3 Microstructures of non-dendritic samples remelted in semi-solid state at 589 ℃ for (a) 0.17h and (b) 4.0h

important process during semi-solid soaking and this process could be divided into two stages, the first stage with a small quantity of liquid and the second stage with a great quantity of liquid. At the first stage, the eutectic liquid was not distributed between the whole primary α-Al particles and the coarsening mechanism of the primary α-Al particles was quick connection between the secondary arms of the rosette, especially the fine primary α-Al particles because the systematic energy could be fast decreased. At the second stage, the regions between the primary α-Al particles were full of eutectic liquid and the connection coarsening was more difficult, so the coarsening mechanism controlled by atoms diffusion was dominant. Suppose the liquid-solid interface is in equilibrium state at the second stage, then the small primary α-Al particles are in equilibrium with lower melting point and the large primary α-Al particles are in equilibrium with higher melting point, that is the small primary α-Al particles reach equilibrium with the liquid of low Si content and the large one with the liquid of high Si content. Therefore the Si in the liquid near the large primary α-Al particles diffuses to the liquid near the small ones and in the meantime the

Al diffuses in the reverse direction, which leads to continuous dissolving of small primary α-Al particles and growing of large primary α-Al particles[6]. Because the coarsening process requires Si and Al to diffuse remotely and there is no convection in the liquid, the coarsening process at the second stage was very slow[7,8].

The chart between the cubic of equivalent diameter d^3 and the soaking time t in Table 1 at 589 ℃ was shown in Fig. 4 and the regression line was very straight. The linear regression equation about d^3 and

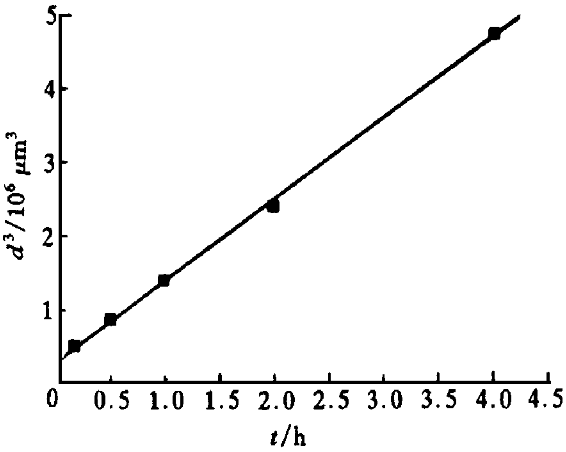

Fig. 4 Relation between cubic of equivalent diameter d^3 of primary α-Al particles and soaking time t

t was made as equation (1) or equation (2), which describes the dynamical process of the grain coarsening at the second semi-solid stage, and d_0, k in equation (2) are respectively equal to 67.29 μm, 1.09856 × 10^6 μm³/h and the correlation coefficient r was 0.9995.

$$d^3 - 67.29^3 = 1.09856 \times 10^6 t \quad (1)$$

$$d^3 - d_0^3 = kt \quad (2)$$

Equation (1) and Fig. 4 indicate that the coarsening process indeed agree with the Ostwald mechanism. Equation (1) also shows the starting average diameter of the primary α-Al particles before Ostwald coarsening is about 67.29 μm. The dynamic equations between d^2 and t or d^4 and t in Table 1 were also made and the correlation coefficients were respectively 0.9973, 0.9939, so the analysis result shows that the dynamical coarsening equation is not only one and the correlation coefficients were very high, but more agreeable with the cubic relation. Grant[6], Yamaguchi[9] and Zhang[10] have studied the microstructural variation of Al-4%Cu, N707, 2618, 6066, Al-Si alloys deposited by spraying method in semi-solid state and also it is shown that the primary solid coarsening process in liquid-solid zone agrees with the cubic Ostwald mechanism.

When the starting grain size in non-dendritic $AlSi_7Mg$ alloy is large as shown in Fig. 1(b), the coarsening process of the primary α-Al particles in semi-solid state also follows the quickly connecting coarsening with low liquid quantity and the slow diffusion coarsening with great liquid quantity. The linear regression equation of d^3 and t in this group samples soaked at 589 ℃ was made according to equation (2) and d_0, k and r were respectively equal to 95.11 μm, 865766.55 μm³/h, 0.9927. This value k was smaller than the value k in equation (1) because the primary α-Al particles related to equation (1) are smaller and the diffusion distance is shorter so that the coarsening speed is fast. However, when the soaking time is longer and the grain size becomes large enough, the diffusion distance is greater, the diffusion ability falls, the coarsening speed decreases and the primary grain sizes of the two kinds of samples would be similar in the end, no matter how the starting grain sizes are different.

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