JOURNAL OF MATERIALS SCIENCE 26 (1991) 3599–3602

Effect of fluid flow on dendritic structure of Al–Si alloy

REN ZHONGMING, JIN JUNZE, GUO KEREN
Department of Materials Engineering, Dalian University of Technology, Dalian 116024, People's Republic of China

The effect of fluid flow induced by electromagnetic stirring on dendritic structure of Al–4% Si alloy has been investigated experimentally. It was found that the fluid flow modified the dendritic structure, and along with the increasing velocity of the flow, the dendrite spacing changed from large passing small to large.

1. Introduction

Fluid flow has great influence on solidification [1–12]. It can affect the shape and morphology of the solid/liquid (s/l) interface [4], and detach the branches of the dendrite, promoting the transition from columnar to equiaxed grain [5]. Fluid flow in the melt increases the positive segregation during unidirectional solidification [6, 7]. Interdendritic fluid flow produces channel segregation [8]. Forced convection may increase the lamellar spacing of eutectic [9–11], and cause the "separated eutectic" in Al–Si alloy [12].

Fluid flow also affects the dendrite spacing greatly. Burden and Hunt [1] found that the dendrite spacing in the NH_4Cl–H_2O system increased greatly due to the interdendritic fluid flow. They argued that the flow increased the interactive mass transfer between dendrite and interdendritic zone, leading to an increase of dendrite spacing. Verhoeven [2] investigated the change of primary dendrite spacing on Sn–Ag alloy and related it to the temperature gradient in front of the s/l interface. He found that the primary dendrite spacing decreased due to the stirring at low-temperature gradient, but not at higher temperature gradient. Fredriksson *et al.* [3] found that fluid flow decreased the dendrite spacing of Al–Cu alloy within the columnar zone, but increased it within the equiaxed zone. Obviously, the effect of fluid flow on the dendrite spacing needs to be investigated further.

The purpose of the present work was to investigate the structure of Al–4% Si alloy unidirectionally solidified with electromagnetic stirring, and to describe the behaviour of the dendrite spacing in the presence of stirring.

2. Experimental procedure

Al–4% Si alloy was used in this experiment. Its structure was composed of primary, secondary and tertiary dendrites, as shown later in Fig. 3a. The alloy was prepared from pure aluminium (99.8% Al) and pure silicon (98.5% Si).

The experimental apparatus is shown in Fig. 1. The heating element melted the alloy in the crucible (0.05 m i.d., 0.21 m height) and controlled its temperature. The water-cooled block froze the molten alloy directionally. By adjusting the power input to the heating element, a suitable cooling rate could be obtained.

The electromagnetic stirrer induced a rotated flow in the melt with a rotation rate, N, up to 12 rev s^{-1}. The rate, N, was obtained [10] by measuring the depth, y (m), of the meniscus surface of the melt, and calculating the rotation rate, N, in the equation

$$N = (gy)^{1/2}/(2^{1/2}\pi r) \qquad (1)$$

where, g is the gravitational acceleration (m s^{-2}), r is the radius of the crucible (m).

The procedure was as follows: first, about 0.76 kg alloy (producing a specimen of 0.15 m height) was melted in the apparatus and stirred for about 0.5 h to homogenize the melt; second, the temperature of the melt was controlled by adjusting the heating power and setting the rotation rate; finally, the water was turned on through the block to freeze the melt. At the same time, the cooling rate, R, was measured. This was performed by setting a thermal couple at a certain height in the crucible and recording the cooling curve as the solidification progressed and the s/l interface moved upwards. Meanwhile, the position of the interface was detected using an alumina rod. When the interface reached the position of the thermal couple, the gradient of the cooling curve was taken to calculate the cooling rate.

After solidification, samples were prepared from the specimen for observing macrostructure and microstructure.

Much attention was paid to the preparation of the samples for observing microstructure and measuring dendrite spacing, in order to reduce the effect of solute segregation caused by the stirring. The samples were taken at heights ranging from 3–7×10^{-2} m of the specimens, within which a maximum segregation of 0.5% was measured. It was found by experiment that this extent of segregation produced only 2% variation on dendrite spacing.

0022-2461/91 $03.00 + .12 © *1991 Chapman and Hall Ltd.*

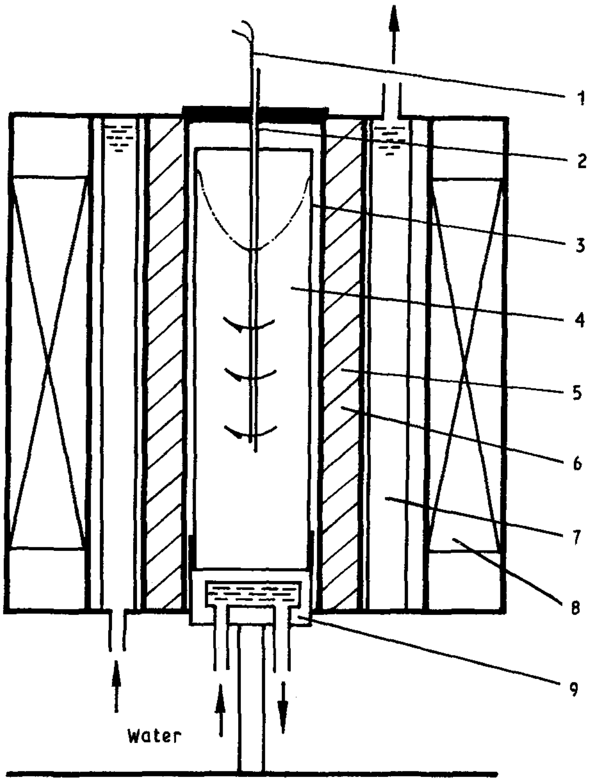

Figure 1 Experimental apparatus. 1, thermal couple; 2, alumina rod; 3, alumina crucible; 4, melt; 5, refractory layer; 6, heating element; 7, water cylinder; 8, electromagnetic stirrer; 9, water-cooled block.

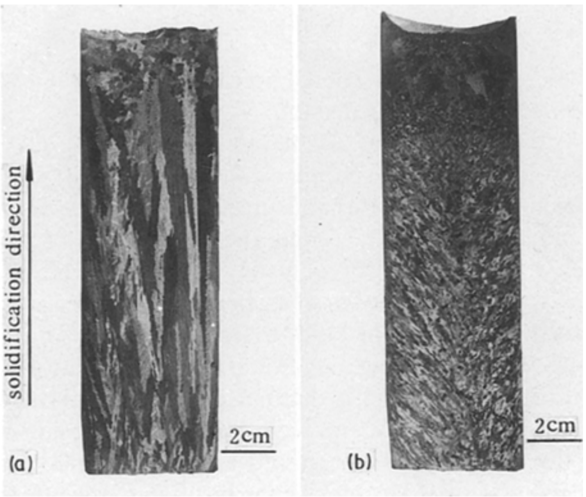

Figure 2 The macrostructures on longitudinal section: (a) without stirring; (b) with stirring, $N = 4\ \mathrm{rev\,s^{-1}}$.

3. Results and discussion

3.1. The change of structure

Fig. 2 shows the macrostructures on the longitudinal section along the centreline of the specimens under several conditions. The structure obtained with stirring was fine columnar grains inclined about 40° from the centreline, and very different from that obtained without stirring. It has been pointed out [7] that this was due to the protrusion of the s/l interface caused by the stirring.

Typical microstructures on a transverse section are shown in Fig. 3. The dendritic structure obtained without stirring was composed of regular primary, secondary, and tertiary dendrites. The structure obtained with stirring, however, was modified as irregular dendrites. The dendrite array was disorderly, and each kind of dendrite could not be distinguished. It seems that the flow disturbed the growth direction of the dendrites.

Fig. 3 also shows that with low flow velocity ($N = 4$ rev $\mathrm{s^{-1}}$, or near the centreline of specimen), the dendrites were refined, approaching the tertiary dendrite obtained without stirring; however, with high flow velocity, the dendrites were coarsened. Huang and Glicksman [13], in their experiments on succinonitrile, observed that two neighbouring dendrite arms "sintered" together and formed one dendrite arm, often leaving a liquid droplet in it. In Fig. 3 (c) and (e) show a similar coarsening. Most dendrites were connected to each other, among them were "droplets" of eutectic. It seems that in the case of stirring, this coarsening is much more likely to take place.

3.2. The change of dendrite spacing

The dendrite spacings on the transverse section of the specimens were measured by randomly intersecting the dendrites with line L_r, counting the number N_r, and calculating the spacing D_r from the equation

$$D_r = L_r/N_r \tag{2}$$

In the specimen with stirring, in view of the abovementioned inclined growth of the dendrite, cos 40° of the value calculated was taken as the spacing.

Fig. 4 shows the dendrite spacings of the same samples as shown in Fig. 3. The dendrite spacings without stirring were large and almost unvaried throughout the section. At rotation rate $N = 4\ \mathrm{rev\,s^{-1}}$, the dendrite spacing at the centreline of the specimen was minimum. This means that the dendrite spacing decreased with increasing flow velocity. However, after that point, it increased with the increasing flow velocity. At rotation rate $N = 8\ \mathrm{rev\,s^{-1}}$, the largest were approaching that obtained without stirring. So, the result demonstrated that a criterion of flow velocity existed, above which the flow showed a coarsening effect, and below which is showed a refining effect.

In order to investigate the effect of fluid flow on dendrite spacing systematically, the dendrite spacing at a site 2 cm away from the centreline of specimen under several conditions was measured, as shown in Fig. 5. It further confirmed that along with the increase in stirring rate, D_r changed from large through small to large.

The behaviour of dendrite with flow may be due to the influence of flow on heat and solute transfer in front of the s/l interface. If the thermal boundary layer at the interface is δ_T, solute boundary layer δ_S, and flow boundary layer δ_F, for aluminium the following relation holds:

$$\delta_T > \delta_F > \delta_S \tag{3}$$

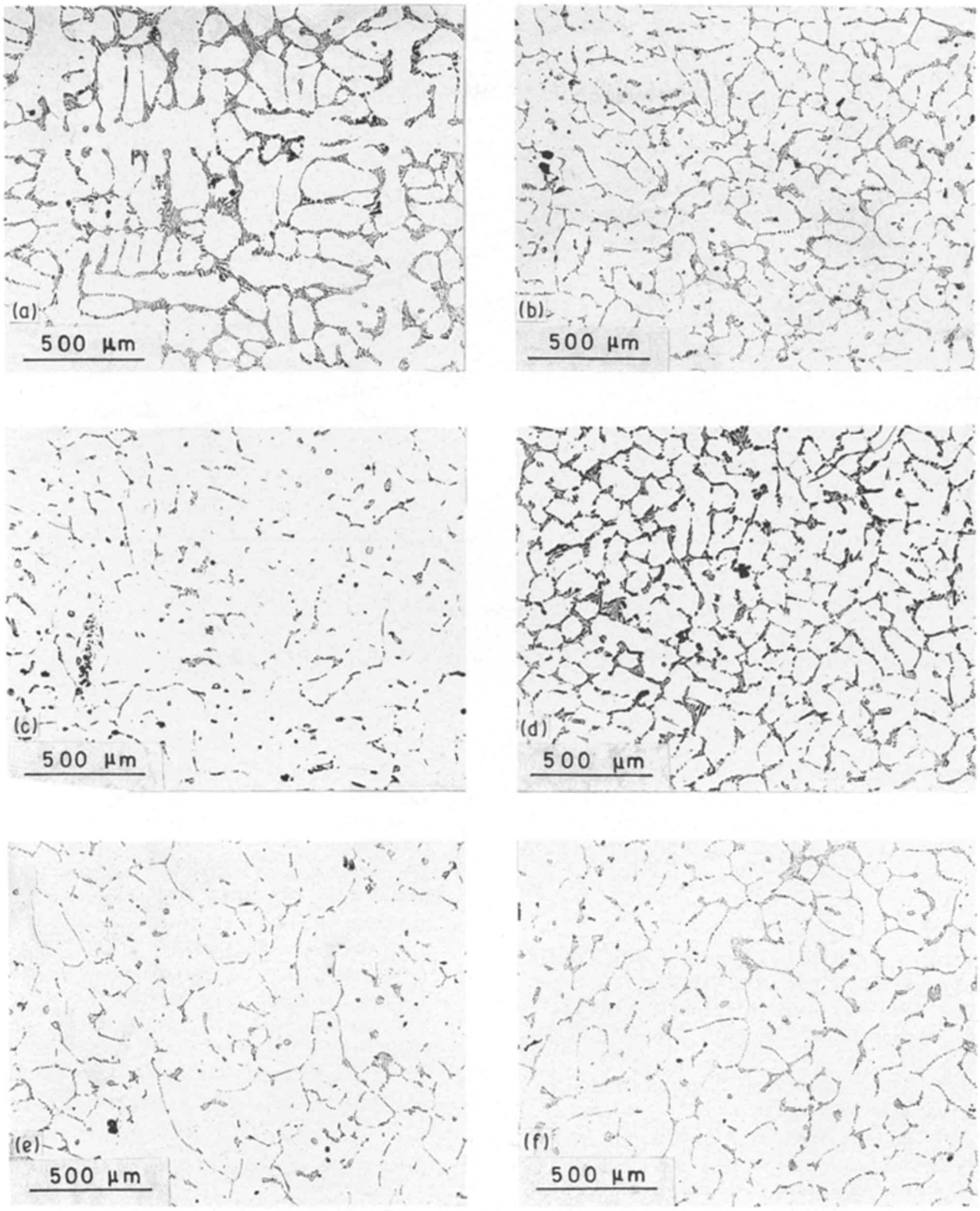

Figure 3 Dendritic structures on transverse section of specimen: (a–c, e) at the site 0.02 m away from the centreline of the specimen; (d, f) at the centreline of the specimen. (a) $N = 0\ \text{rev s}^{-1}$, $R = 6.1 \times 10^{-2}\ ^\circ\text{C s}^{-1}$; (b) $N = 4\ \text{rev s}^{-1}$, $R = 3.4 \times 10^{-2}\ ^\circ\text{C s}^{-1}$; (c, d) $N = 6\ \text{rev s}^{-1}$, $R = 4.8 \times 10^{-2}\ ^\circ\text{C s}^{-1}$; (e, f) $N = 8\ \text{rev s}^{-1}$, $R = 5.0 \times 10^{-2}\ ^\circ\text{C s}^{-1}$.

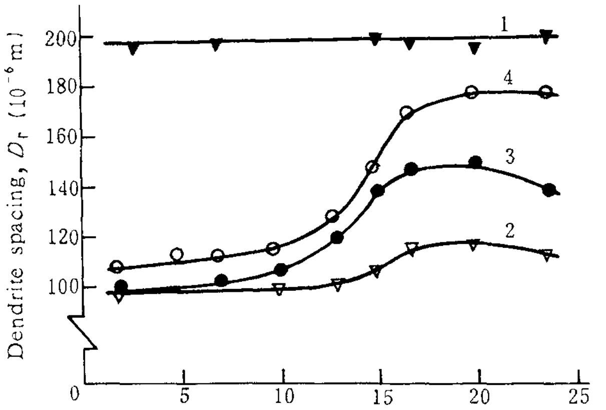

Figure 4 The change of dendrite spacing on transverse section of specimen. (1) $N = 0\ \text{rev s}^{-1}$, $R = 6.1 \times 10^{-2}\ ^\circ\text{C s}^{-1}$; (2) $N = 4\ \text{rev s}^{-1}$, $R = 3.4 \times 10^{-2}\ ^\circ\text{C s}^{-1}$; (3) $N = 6\ \text{rev s}^{-1}$, $R = 4.8 \times 10^{-2}\ ^\circ\text{C s}^{-1}$; (4) $N = 8\ \text{rev s}^{-1}$, $R = 5.0 \times 10^{-2}\ ^\circ\text{C s}^{-1}$.

Therefore, with low velocity, the flow will only reduce δ_T and increase the temperature gradient. This may lead to the refining of dendrites [14]. With high velocity, the flow will reduce δ_S and increase the transfer of solute from the interface, removing the barrier to the growth of dendrites. So, the dendrites are coarsened.

4. Conclusions

1. Stirring modifies the dendritic structure of directionally solidified Al–4% Si alloy. Together with the increase in flow velocity, the structure changes from regular passing irregularly fine to irregularly coarse dendrites.

2. Dendrite spacing also changes from large through small and to large. Therefore, fluid flow shows dual, contrary effects; at small velocity, the flow

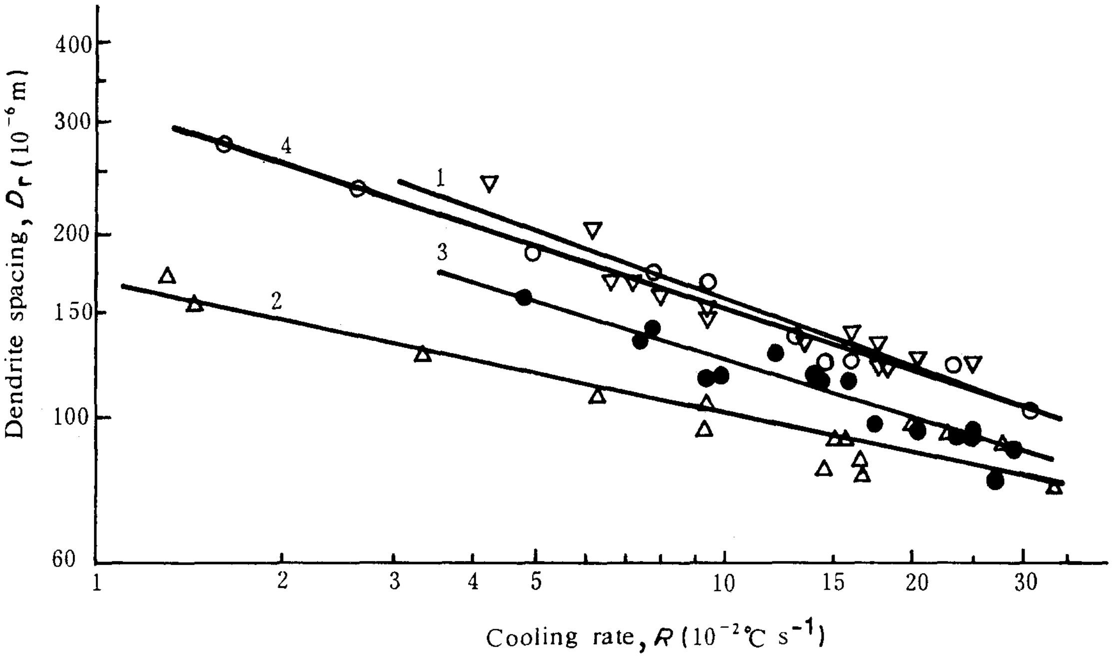

Figure 5 Dendrite spacing versus cooling rate and stirring rate. N: (▽) 0 rev s^{-1}, (△) 4 rev s^{-1}, (●) 6 rev s^{-1}, (○) 8 rev s^{-1}.

refines the dendrites, and at large velocity, the flow coarsens the dendrites.

References

1. M. H. BURDEN and J. D. HUNT, *Metals Sci.* **10** (1976) 156.
2. J. VERHOEVEN, *Metall. Trans.* **2** (1971) 2673.
3. H. FREDRIKSSON *et al. Scand. J. Metall.* **15** (1986) 127.
4. G. S. COLE, "Solidification" (American Society for Metals, Ohio, 1969) p. 222.
5. M. C. FLEMINGS, "Solidification Processing" (McGraw-Hill, New York, 1974) pp. 146, 154.
6. J. A. BURTON, R. C. PRIM and W. P. SLICHTER, *J. Chem. Phys.* **21** (1953) 1987.
7. JIN JUNZE, REN ZHONGMING and GUO KEREN, *J. Dalian Inst. Technol.* **24** (1985) 37.
8. J. J. MOORE and N. A. SHAH, *Inter. Metals Rev.* **28** (1983) 338.
9. J. M. QUENISSET and R. NASLAIN, *J. Crystal Growth* **54** (1981) 465.
10. JIN JUNZE, K. F. KOBAYASHI and P. H. SHINGU, *Metall. Trans.* **15A** (1984) 307.
11. S. CHANDRASEKHAR, G. F. EISA and W. R. WILCOX, *J. Crystal Growth* **76** (1986) 485.
12. P. H. SHINGU, M. KUROSAKI and JIN JUNZE, *Trans. Jpn Inst. Metals* **27** (1986) 546.
13. S. C. HUANG and M. E. GLICKSMAN, *Acta Metall.* **29** (1981) 717.
14. T. Z. KATTAMIS, J. C. COUGHLIN and M. C. FLEMINGS, *Trans. TMS AIME* **239** (1967) 1504.

Received 1 August 1989
and accepted 26 October 1990