Formation of a separated eutectic in Al–Si eutectic alloy

REN ZHONGMING, JIN JUNZE
Research Centre of Foundry Engineering, Department of Materials Engineering, Dalian University of Technology, Dalian 116024, People's Republic of China

The phenomenon of a "separated eutectic" in Al–Si eutectic alloy unidirectionally solidified with electromagnetic stirring was investigated. It was found that the eutectic silicon could be swept away from the solid/liquid (s/l) interface by the flow, and transferred by the secondary flow to the wall of the crucible, forming a silicon-rich layer on the periphery of the ingot.

Nomenclature

$\mathbf{B}$	Magnetic induction vector
B_0	Magnetic induction magnitude on the periphery of liquid column
$\mathbf{E}$	Electrical field vector
f_r, f_θ	Radial and azimuthal components of electromagnetic force
g	Acceleration due to gravity
H	Height of liquid column
$\mathbf{H}$	Magnetic field
$\mathbf{J}$	Current
N	Rotation rate of the melt
P	Pressure
r	Radial coordinate
r_0	Radius of liquid column
u_r, u_θ, u_z	Radial, azimuthal, and axial components of flow velocity
V	Speed of solidification
z	Axial coordinate
μ_0	Magnetic permeability
ν	Viscosity of liquid
ρ	Density of liquid
σ	Electrical conductivity
ω	Angular frequency of the current.

1. Introduction

During last decade, much research has been carried out on the solidification of a eutectic alloy with a fluid flow because of the pronounced influence of the flow on the solidification. One of the important phenomena found by Quensset *et al.* [1, 2], Junze *et al.* [3], and Wilcox and co-workers [4–6] is the increase in the lamellar spacing of the eutectic due to the flow. Quensset *et al.* [1], and Wilcox *et al.* [5] also established models to describe this phenomenon. More recently, Shingu *et al.* [7] found an interesting phenomenon of a "separated eutectic" occurring during the unidirectional solidification of an Al–Si eutectic alloy with strong stirring in the melt. The two coupled phases (silicon and aluminium) were separated by a distance of the order of a centimetre. In the case of rotated electromagnetic stirring, a silicon-rich layer formed on the periphery of the ingot. They attributed this phenomenon to the strong tendency to produce a solidification front with the aluminium phase as the leading phase when the stirring is applied. However, how it was formed is still unknown.

The aim of the present work was to investigate the formation of this phenomenon in the case of electromagnetic stirring (EMS), and to relate it to the flow field produced by the stirring. It was found that the secondary flow played an important role in the phenomenon.

2. Experimental procedure

The experimental apparatus is shown in Fig. 1. The heating element melted the alloy and controlled the temperature. The water-cooled block cooled the melt and moved down at a controllable speed, causing unidirectional solidification of the alloy. The electromagnetic stirrer generated a circulating flow in the melt, with a rotation rate, N, up to 12 rev s^{-1}.

The rotation rate was measured as follows: a graphic paddle was inserted into the melt, which rotated along with the melt, then the rotation rate of the paddle axis was measured. This rate was taken as the rotation rate of the melt.

The alumina crucible was 5 cm i.d. and 20 cm high. Al–Si eutectic alloy was prepared from pure aluminium (99.7% pure) and pure silicon (98.5% pure).

In the experiment, 700 g alloy was melted in the crucible and stirred for 0.5 h to homogenize the melt, then the stirring was controlled and adjusted to a certain rate; finally, the crucible was moved down at a certain speed, so that unidirectional solidification could occur. The macro- and microstructures of the ingot obtained were examined.

3. Results and discussion

The typical phenomenon of a "separated eutectic" is shown in Fig. 2. The eutectic silicon separated from

0022–2461

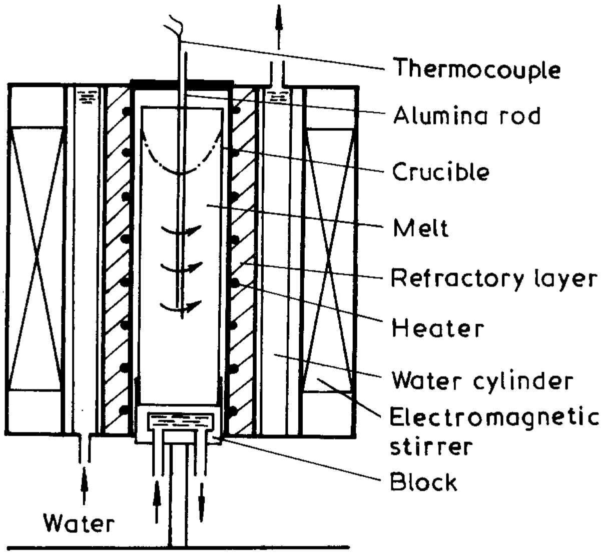

Figure 1 Schematic drawing of the experimental apparatus.

the aluminium, and accumulated at the periphery of the ingot, forming a silicon-rich layer. More strangely, in the pipe-like ingot, this layer was also formed on the inner surface of the ingot. This indicated that the wall of the curcible may have some effect on the phenomenon.

In order to investigate this phenomenon, a liquid-quenching experiment was conducted during solidification. The results are shown in Fig. 3. The upper

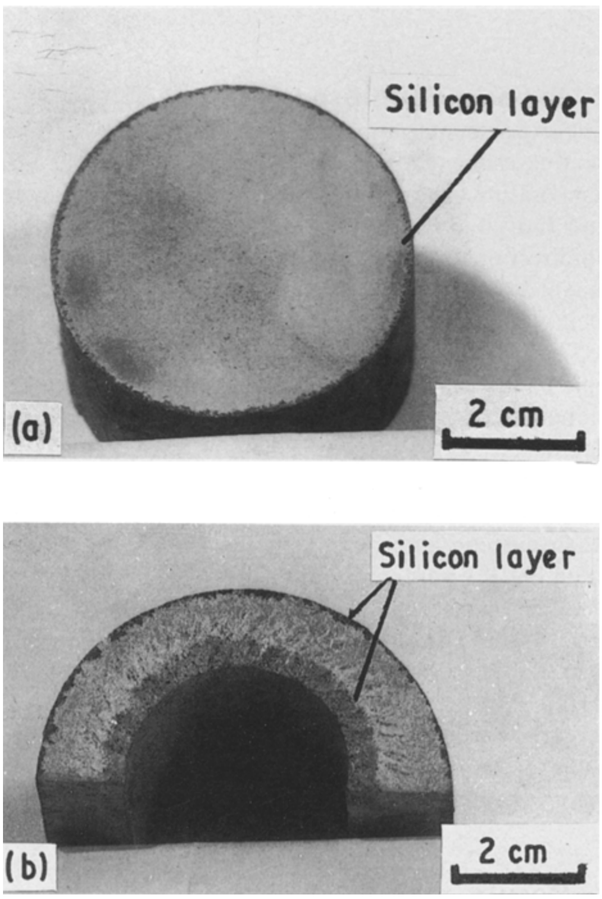

Figure 2 The "separated eutectic" phenomenon. (a) Rod specimen, (b) pipe-like specimen.

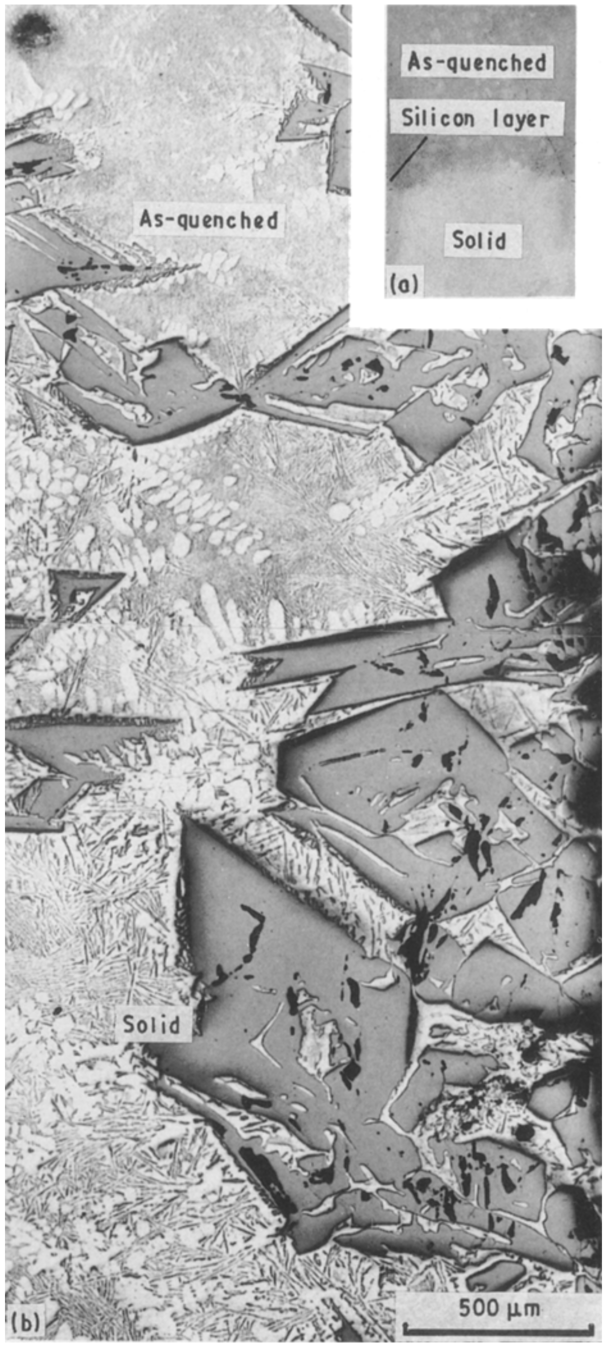

Figure 3 The result of quenching during solidification. Solidification speed $V = 1.7 \times 10^{-5}$ m s^{-1}. Rotation rate of the melt, $N = 7.5$ rev s^{-1}. (a) The macrostructure. (b) The microstructure of the silicon layer around the s/l interface.

portion of the ingot was quenched, the lower unidirectionally solidified. The solid/liquid (s/l) interface was visible. As can be seen, the silicon-rich layer extended over the interface into the liquid about 1 cm. This indicated that the layer was formed in the liquid ahead of the s/l interface, that is, before solidification took place there.

The microstructure of the layer in the above ingot shows that the layer was composed of large silicon granules, the size of which were several ten times larger than that of the eutectic silicon in the matrix. It is noticed that the size of the granules was basically the same throughout the layer, whether in the quenched portion or in the solid portion. Thus quenching had

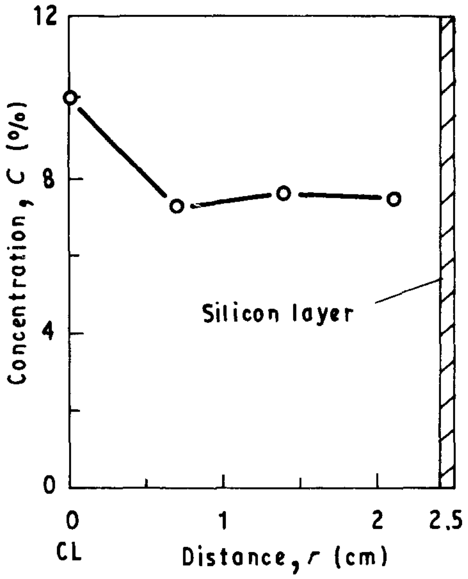

Figure 4 The distribution of silicon content along the radius of the specimen.

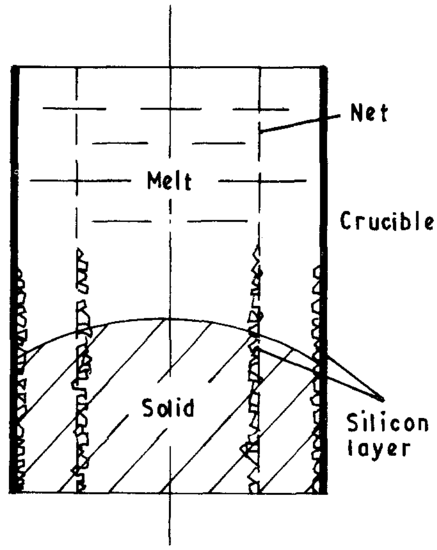

Figure 5 Schematic drawing of the experimental results with a refractory net coaxially inserted in the crucible.

little effect on the granules. In contrast, the matrix was considerably refined by the quenching. Therefore, it is confirmed that the silicon in the layer was in the solid state in the melt, and not crystallized from a silicon-rich liquid during solidification. Only if silicon was in the solid state did it remain unrefined by the quenching.

The distribution of the solute along the radial direction of the ingot demonstrated that its centre part was hypoeutectic, as shown in Fig. 4. Additionally, the experimental results of Shingu *et al.* [7] showed that the quenched portion was still eutectic. These results indicated that the silicon granules in the layer came from the s/l interface. This figure also shows that the silicon content in the solid portion decreased along the radial direction of the ingot. At the layer, however, it increased sharply to near pure silicon content. This apparently ruled out the possibility of redistribution or diffusion of solute as the cause of the formation of the layer, and strongly suggested the transport of silicon granules from the interface to the wall of the crucible.

In order to confirm the suggestion, the following experiment was carried out. A refractory net cylinder was positioned coaxially in the crucible, and unidirectional solidification was carried out as usual; the structure of the ingot was then examined. As can be seen in Fig. 5, a silicon-rich layer was also formed on the net. This confirmed the transport of granules in the melt during the formation of the layer.

It is well known that during the solidification of an Al–Si eutectic, the silicon phase is the leading phase and protrudes into the liquid. Miwa *et al.* [8] found that when vigorous stirring was applied to the melt, the flow could sweep away the silicon phase from the interface, forming free granules in the liquid. From this result, it is easy to understand how these granules may be transferred elsewhere by the flow, for instance, to the net, or the wall of the crucible, and be trapped there.

From Fig. 2 it can be seen that neither the centrifugal force of the rotated flow nor the electromagnetic attractive or repulsive force are capable of transferring the granules to the wall of the crucible, because these forces are one directional.

To gain a full understanding of the transport of the granules, the flow field was numerically analysed. For simplicity, the following assumptions are made.

1. The s/l interface is static, because of its very slow movement compared with the flow.
2. The temperature, viscosity, density and electrical conductivity of the melt are constant.
3. The electromagnetic stirrer is infinitely long.
4. The liquid column is so long that its top can be considered to be a horizontal free surface.
5. Turbulent flow is not considered.
6. The roughness of the crucible wall is ignored.

The Navier–Stokes equation for cylindrical geometry and rotational symmetry is given by the following expressions:

$$u_r\frac{\partial u_r}{\partial r} + u_z\frac{\partial u_r}{\partial z} - \frac{u_\theta^2}{r} = -\frac{1}{\rho}\frac{\partial P}{\partial r} + \nu\left(-\frac{u_r}{r^2} + \frac{1}{r}\frac{\partial u_r}{\partial r} + \frac{\partial^2 u_r}{\partial r^2} + \frac{\partial^2 u_r}{\partial z^2}\right) + \frac{1}{\rho}fr \quad (1)$$

$$u_r\frac{\partial u_\theta}{\partial r} + u_z\frac{\partial u_\theta}{\partial z} + \frac{u_r u_\theta}{r} = \nu\left(-\frac{u_\theta}{r^2} + \frac{1}{r}\frac{\partial u_\theta}{\partial r} + \frac{\partial^2 u_\theta}{\partial r^2} + \frac{\partial^2 u_\theta}{\partial z^2}\right) + \frac{1}{\rho}f_\theta \quad (2)$$

$$u_r\frac{\partial u_z}{\partial r} + u_z\frac{\partial u_z}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial z} + \nu\left(\frac{1}{r}\frac{u_z}{\partial r} + \frac{\partial^2 u_z}{\partial r^2} + \frac{\partial^2 u_z}{\partial z^2}\right) + g \quad (3)$$

The continuity equation for constant density is

$$\frac{u_r}{r} + \frac{\partial u_r}{\partial r} + \frac{\partial u_z}{\partial z} = 0 \quad (4)$$

The electromagnetic force $\boldsymbol{f} = \boldsymbol{J} \times \boldsymbol{B}$. The $\boldsymbol{J}$ and $\boldsymbol{B}$ are obtained by solving Maxwell equations

$$\nabla \times \boldsymbol{H} = 0 \quad (5)$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \quad (6)$$

$$\nabla \cdot \boldsymbol{B} = 0 \quad (7)$$

$$\boldsymbol{B} = \mu_0 \boldsymbol{H} \quad (8)$$

The approximate solution of Equations 5–8 is [9] (for the stirrer with four poles)

$$f_r = -\frac{1}{58} B_0^2 \sigma^2 \mu_0 \frac{r^5}{r_0^2}\left(\omega - \frac{u_\theta}{r}\right)^2 \quad (9)$$

$$f_\theta = \frac{1}{4} B_0^2 \sigma \frac{r^3}{r_0^2}\left(\omega - \frac{u_\theta}{r}\right) \quad (10)$$

The boundary conditions are

$z = 0$, on the bottom of the liquid column,

$$u_r = u_z = u_\theta = 0 \quad (11a)$$

$z = H$, on the top surface of the liquid column,

$$\partial u_r/\partial z = u_z = \partial u_\theta/\partial z = 0 \quad (11b)$$

$r = 0$, along the centreline (CL) of the liquid column, $u_r = \partial u_z/\partial r = u_\theta = 0$ (11c)

$r = r_0$, on the wall of the crucible,

$$u_r = u_z = u_\theta = 0 \quad (11d)$$

These equations were computed in a finitive difference method on an NEC–9801 personal computer, with the result as shown in Fig. 6. In addition to the rotated flow, there is a secondary flow in the axial and radial directions. Near the s/l interface, this flow is from the wall of the crucible to the centreline of the liquid column, and then back to the wall. This flow is just in front of the interface, with a velocity comparable to the tangential one.

From this result, one can learn that the secondary flow will carry the silicon granules separated from the interface to the wall of the crucible, as shown in Fig. 7. There, they may be trapped and accumulate within the boundary of the flow. In this way, the silicon-rich layer

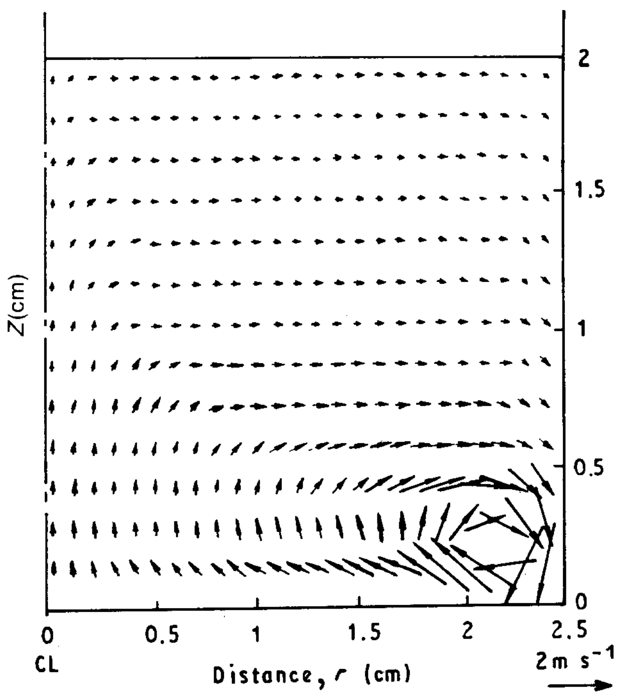

Figure 6 Vector diagram of secondary flow (u_r, u_z). Magnetic induction $B_0 = 20$ mT. Rotation rate of the melt $N = 12$ rev s^{-1}.

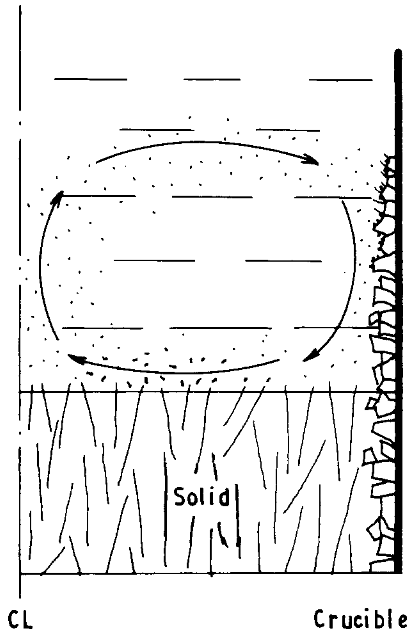

Figure 7 Schematic illustration of the formation of the "separated eutectic".

is formed. The granules may coarsen to reduce their surface area.

In this way it is easy to understand the formation of the inner silicon-rich layer in the pipe-like ingot. The separated granules would also be carried to the inner surface of the "pipe" by the secondary flow, and trapped there. So the inner silicon-rich layer is formed.

4. Conclusion

Under the influence of strong rotating EMS, the eutectic silicon was swept away and separated from the s/l interface, forming free silicon granules; the free granules were transferred to the wall of the crucible by the secondary flow. There they were trapped, and they accumulated and coarsened on the wall. Therefore, a silicon-rich layer composed of large silicon granules was formed.

Acknowledgement

The authors acknowledge the support of National Natural Science Foundation of China.

References

1. J. M. QUENSSET and R. NASLAIN, *J. Crystal Growth* **54** (1981) 465.
2. J. M. QUENSSET, *ibid.* **63** (1983), 389.
3. JIN JUNZE, K. F. KOBAYASHI and P. H. SHINGU, *Metall. Trans.* **15A** (1984) 307.
4. V. BASKARAN and W. R. WILCOX, *J. Crystal Growth* **67** (1984) 343.
5. G. F. EISA, W. R. WILCOX and G. BUSCH, *ibid.* **78** (1986) 159.
6. S. CHANDRASEKHAR, G. F. EISA and W. R. WILCOX, *ibid.* **76** (1986) 485.
7. P. H. SHINGU, M. KUROSAKI and JIN JUNZE, *Trans. Jpn Inst. Metals* **27** (1986) 546.
8. K. MIWA, T. KAKAMU and T. OHASHI, *ibid.* **26** (1985) 549.
9. K. H. SPITZER, M. DUBKE and K. SCHWERDTFEGER, *Metall. Trans.* **17B** (1986) 119.

Received 29 April and accepted 2 August 1991