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Effects of cooling rate on solidification process in Al–Mg–Si alloy

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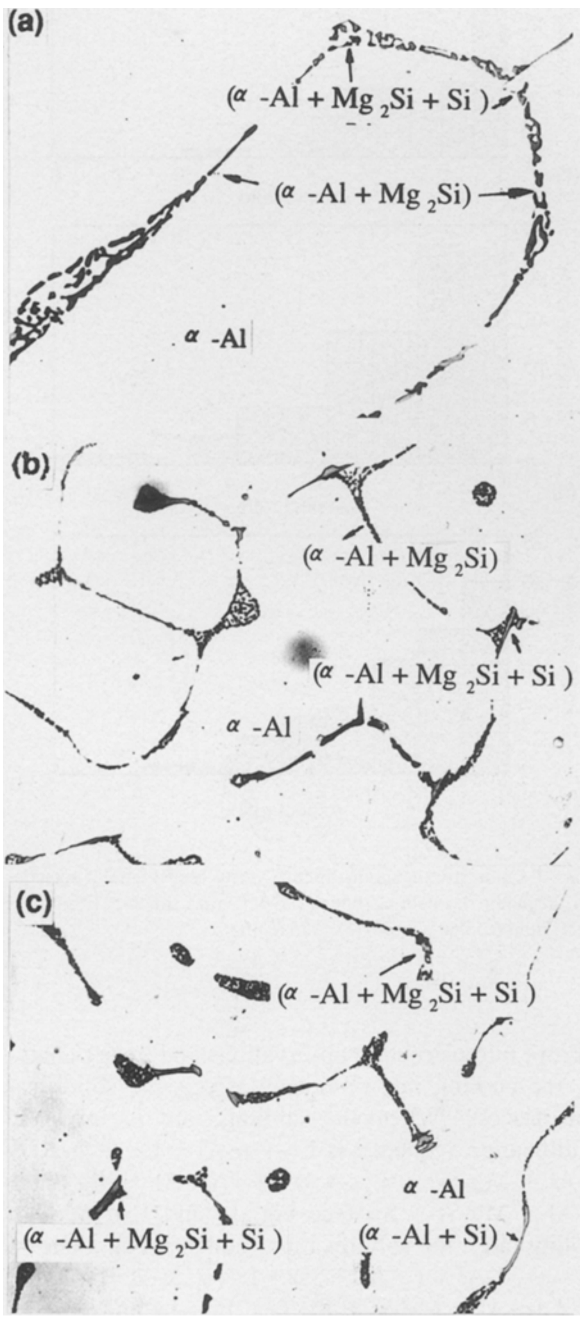
Al–Mg–Si alloys are finding increased usage in sheet applications where formability is an important requirement, e.g. transport applications. The as-cast microstructure of the alloy is mainly composed of α-Al, Si and Mg_2Si [1]. Liu *et al.* [2, 3] indicated that the cooling rate can affect the grain size, the phase composition and dendrite arm spacing in as-cast Al–Mg–Cu alloy. But there has been little study of the effect of cooling rate on the solidification process and the microstructure in Al–Mg–Si alloy. The aim of this study is to evaluate this effect.

The alloy studied here is Al-0.95 wt% Mg-1.55 wt% Si alloy. The alloy was cast using a graphite crucible at cooling rates of 70 °C/min to 1375 °C/min. The optical microstructures were observed using optical microscopy, and analysed using a LECO-200 Image Analysis System.

Fig. 1 shows the optical microstructures, which can



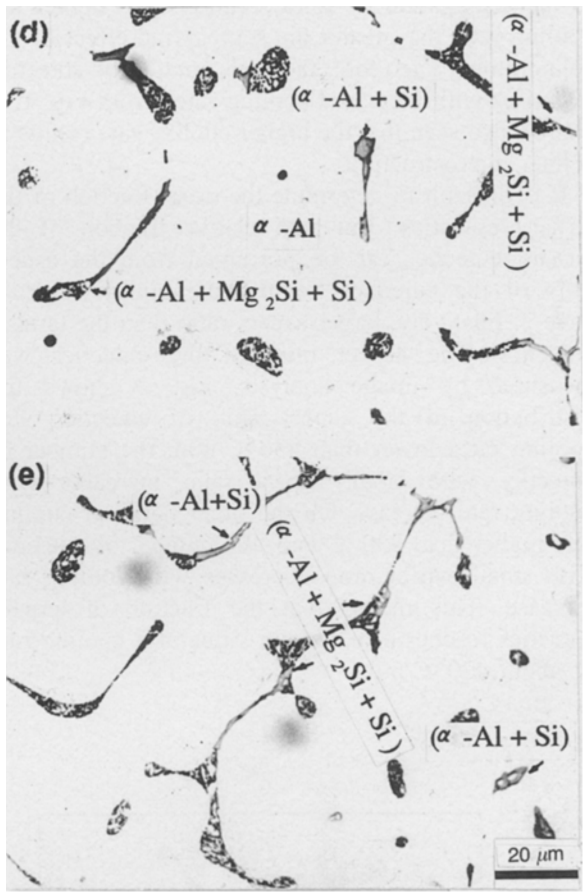


Figure 1 Optical microstructures of the Al–Mg–Si alloy obtained with changing cooling rates: (a) 70 °C/min; (b) 135 °C/min; (c) 430 °C/min; (d) 860 °C/min; (e) 1375 °C/min.

be divided into three parts, i.e. primary α-Al, binary eutectic and ternary eutectic. The binary eutectics exist mainly in the grain boundary between two α-Al grains, and the ternary eutectics exist mainly in the grain boundary among three α-Al grains. Slow cooling rate induced the formation of binary eutectic, α-Al + Mg_2Si (see Fig. 1a and 1b). Rapid cooling rate induced the formation of binary eutectic, α-Al + Si (see Fig. 1d and 1e). This means that the cooling rate has a great effect of the solidification process.

Fig. 2 shows the relationship between area fraction of eutectics and cooling rate. It can be seen that the area fraction increases with increased cooling rate and can be expressed by the following equation:

$$f = 2.04 + 2.43 \log(\dot{T}) \quad (1)$$

where f and $\dot{T}$ denote the area fraction of eutectics and cooling rate, respectively. Although the composition of the alloy is much less than the solubility limit of Al–Mg–Si system [1], the eutectics are formed due to the segregation of solid solution. The higher the cooling rate, the greater the segregation effect of the solute atom. Therefore, the area fraction of eutectics increases with increased cooling rate. From Fig. 1, it can be also seen that the higher cooling rate results in a finer microstructure.

It is difficult to determine the exact fraction of the ternary eutectics. But the relative fraction of the ternary eutectics can be presumed from the aspect ratio of the eutectics because the binary eutectics have a, relatively, larger aspect ratio than the ternary eutectics. The aspect ratio of the eutectics was measured by image analysis. Fig. 3 shows the distribution of the aspect ratio of eutectics. For cooling rates lower than 430 °C/min, the number of eutectics with small aspect ratio increases with cooling rate increase. On the other hand, at cooling rate higher than 430 °C/min, the number of eutectics with small aspect ratio decreases with cooling rate increase. This means that the fraction of ternary eutectics reaches a maximum value at a cooling rate of about 430 °C/min.

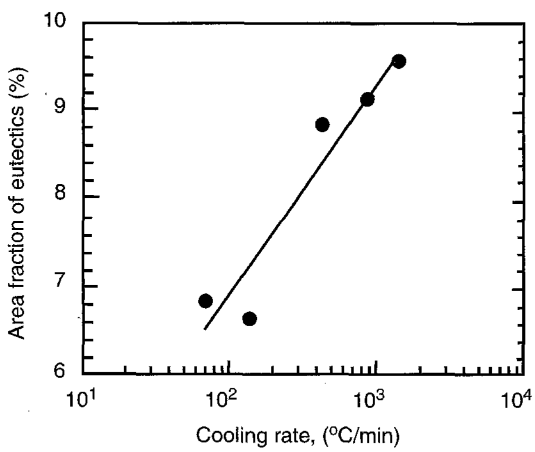


Figure 2 Relationship between area fraction of eutectics and cooling rate.

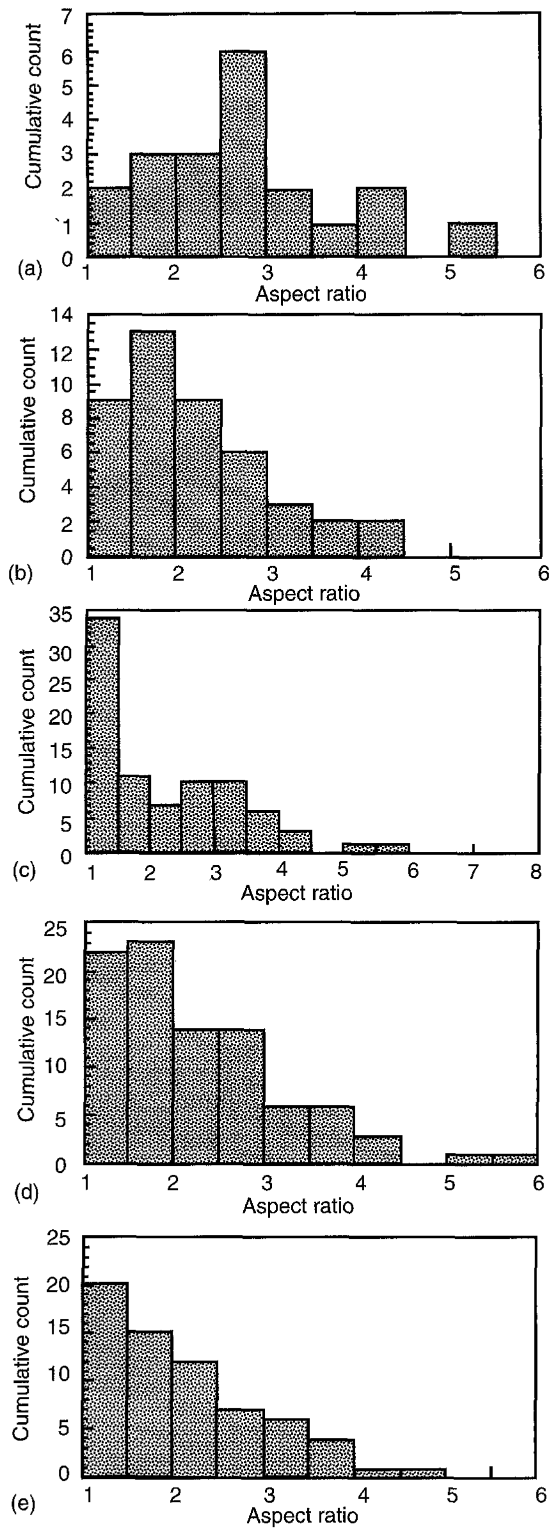


Figure 3 Cumulative count distribution versus aspect ratio of eutectics with changing the cooling rate: (a) 70 °C/min; (b) 135 °C/min; (c) 430 °C/min; (d) 860 °C/min; (e) 1375 °C/min.

From microstructure observations and image analysis, the cooling rate obviously affects the solidification process. When the cooling rate is low, the solidification sequence is L → α-Al + L_1 → α-Al + (α-Al + Mg_2Si) + L_2 → α-Al + (α-Al + Mg_2Si) + (α-Al + Mg_2Si + Si) (see Fig. 1a and 1b). At high cooling rates, the solidification sequence is L → α-Al + L_1 → α-Al + (α-Al + Si) + L_2 → α-Al + (α-Al + Si) + (α-Al + Mg_2Si + Si) (see Fig. 1d and 1e).

The diffusion rate of Si atoms is much slower than that of Mg atoms in aluminium alloy [4]. During solidification processing, the concentration of Si atoms in the liquid phase near the solid–liquid interface increases with cooling rate increase. Therefore, the solidification path moves form line OS to line OF with the cooling rate increase as described in Fig. 4.

A study of the effects of cooling rate on the solidification process in Al–Mg–Si alloy provides the following conclusions:

(1) The fraction of eutectics increases with cooling rate increase in the range of 70 °C/min to 1375 °C/min.

(2) When the cooling rate is low, the solidification sequence is L $\rightarrow$ α-Al + L_1 $\rightarrow$ α-Al + (α-Al + Mg_2Si) + L_1 $\rightarrow$ α-Al + (α-Al + Mg_2Si) + (α-Al + Mg_2Si + Si). When the cooling rate is higher, the solidification sequence is L $\rightarrow$ α-Al + L_1 $\rightarrow$ α-Al + (α-Al + Si) + L_2 $\rightarrow$ α-Al + (α-Al + Si) + (α-Al + Mg_2Si + Si).

(3) The image analysis of eutectics shows that the relative fraction of ternary eutectics reaches a maximum value at a cooling rate of about 430 °C/min.

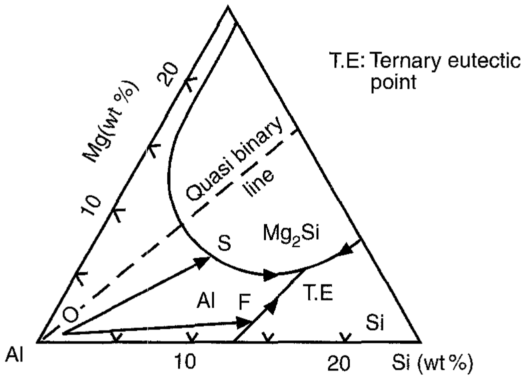


Figure 4 Schematic illustration of solidification path.

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