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STEREOMETRIC CHARACTERISATION OF UNIDIRECTIONALLY SOLIDIFIED DENDRITIC STRUCTURE

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ABSTRACT

The dendritic microstructure of an unidirectionally solidified Al-4.4 wt% Cu alloy has been characterised by automatic image analysis. A geometric model has been developed to describe this microstructure. Eutectic was formed between the primary and secondary dendrite arms at the end of solidification independing on the conditions of solidification. The eutectic covered 10-12% of the dendrite surface.

Key words: dendrite, eutectic, microstructure, solidification, Al-4.4wt% Cu.

INTRODUCTION

Unidirectional solidification of aluminium-copper solid solution alloys normally begins with the formation of α-solid solution dendrites and is completed by the development of an eutectic which consists of an α-solid solution and an Al_2Cu compound. The aim of this work is to explain the connection between the stereological parameters of the dendrites and the eutectic volume parts.

EXPERIMENTS

Al-4.4 wt% Cu alloys have been unidirectionally solidified under steady-state conditions. The experimental parameters (the temperature gradient at the solid/liquid interface, G_L(K/mm), and the interface growth velocity, R(mm/s)) were determined using a measuring probe equipped with thermocouples.

Longitudinal and transverse microsections were embedded into an epoxy-resin and grind with SiC paper in four different grades, then polished with diamond pastes. The dendritic structure was examined on specimens etched in 1% HF solutions. Dendritic structure of the specimen is shown in Fig. 1. Parameters of the eutectic were measured on microsections prepared with an aqueous solution of 25% HNO_3. Metallographic sections were analysed by computer controlled image analyser.

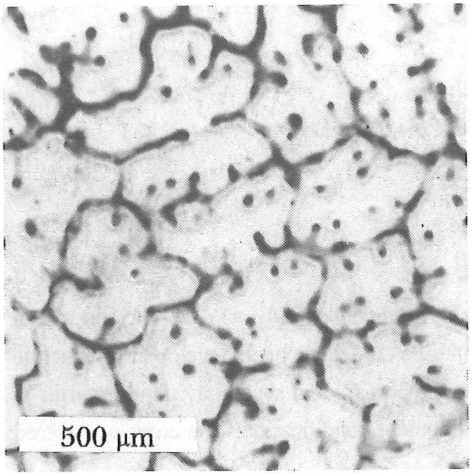


Fig.1. Primary dendrite arms.

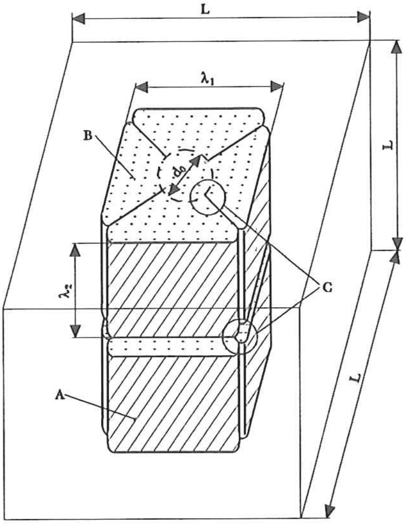


Fig. 2. Interfacial surface in volume of the dendritic structure.

The primary dendrite arm spacing was determined on the computerized image from its transverse section. For each specimen about 100-120 primary arms were circumscribed by using the computer mouse and their perimeters, K_1, were measured. The primary dendrite arm is approximated by a square parallelepiped the side-length of the square (the primary dendrite arm spacing, λ_1) can be determined from the perimeter, which is measured on the perpendicular intersection. This approach is very similar to Schievenbusch's (1993) except for their geometry which was a cylindrical one. Hence the average primary arm spacing, λ_1, was given as:

$$\lambda_1 = \frac{K_1}{4} \quad [\mu m] \tag{1}$$

The average of the secondary dendrite arm spacing, λ_2, was determined from the projected image of the longitudinal sections by measuring the distances between the neighbouring arms. On each specimen approximately 120-150 dendrite arms were processed.

The structure of the eutectic has been described by their following characteristics:

a,) Volume fraction, X: the average area fraction of the eutectic determined by the image analyser.

b,) Surface in volume, S_v^E : surface in volume of the eutectic volume parts is therefore given as (Exner and Hougardy, 1985):

$$S_v^E = \frac{4}{\pi} K_P \quad [1/\mu m] \tag{2}$$

The perimeters, K_p, of the eutectic volume parts per unit area were measured with the image analyser. Another important parameter, S_x^E, which is the surface in volume of the given eutectic part can be derived from the following expression:

$$S_x^E = \frac{S_v^E}{X} \quad [1/\mu m]. \tag{3}$$

c,) Number of eutectic volume part in volume, N_V^E : this parameter can be relatively easily determined in polydispersed system for spherical particles by the Fullman (1953) method:

$$N_v^E = \frac{2 N_a \overline{m}}{\pi} \quad [1/\mu m^3] \tag{4}$$

where N_a is the number of colonies per unit area $[1/\mu m^2]$,

$\overline{m}$ is the mean of the reciprocal of the diameters of equivalent sphere and can be calculated as follows:

$$\overline{m} = \frac{\sum_{i=1}^{n} \frac{1}{D_{eq}^i}}{n} \quad [1/\mu m] \tag{5}$$

and:

$$D_{eq}^i = \sqrt{\frac{T^i}{\pi}} \quad [\mu m] \tag{6}$$

where D_{eq}^i is the equivalent diameter of the area,

T^i is the area of the ith volume part and n the number of parts.

Equations (4-6) are only valid if the shape of eutectic colonies is nearly spherical.

GEOMETRIC MODELLING

The dendritic structure of an unidirectionally solidified sample is shown in Fig. 2. The main two structural parameters are the distances between the primary, λ_1, and secondary, λ_2, dendrite arms. Considering the positions and morphology of the eutectic volume parts the following parameters are important (Gácsi, 1992):

(i) the interfacial area between the primary dendrite arms (denoted with "A" in Fig. 2.),

(ii) the interfacial area between the secondary dendrite arms (marked with "B" in Fig. 2.),

(iii) the number of the places where the eutectic probably forms (indicated with "C' in Fig. 2).

The number of the primary dendrite arms (N_1) are:

$$N_1 = \frac{L^3}{\lambda_1^2 L} \tag{7}$$

and the surface of the one primary dendrite arm (S_1) is:

$$S_1 = 4\lambda_1 L \quad [\mu m^2] \tag{8}$$

The "A"-type surface in volume, S_v^A is given as (see Fig. 2.):

$$S_v^A = \frac{N_1 S_1}{L^3} = \frac{L^3}{\lambda_1^2 L} 4\lambda_1 L \frac{1}{L^3} = \frac{4}{\lambda_1} \quad [1/\mu m] \tag{9}$$

where L^3 is the investigated volume.

The number of the secondary dendrite arms (N_2) are:

$$N_2 = \frac{L^3}{\lambda_1^2 L} \frac{L}{\lambda_2} \tag{10}$$

and the surface of the secondary dendrite arm (S_2) is:

$$S_2 = 2(\lambda_1^2 - \frac{d_0^2 \pi}{4}) \quad [\mu m^2] \tag{11}$$

The "B"-type surface in volume is then given by:

$$S_v^B = \frac{N_2 S_2}{L^3} = \frac{L^3}{\lambda_1^2 L} \frac{L}{\lambda_2} 2(\lambda_1^2 - \frac{d_0^2 \pi}{4}) \frac{1}{L^3} \quad [1/\mu m] \tag{12}$$

By approximating $\lambda_1^2 >> d_0^2$ it follows that:

$$S_v^B = \frac{2}{\lambda_2} \quad [1/\mu m] \tag{13}$$

The total interfacial surface in volume of the dendritic structure, S_v^{AB}, becomes equal to:

$$S_v^{AB} = S_v^A + S_v^B = \frac{4}{\lambda_1} + \frac{2}{\lambda_2} \quad [1/\mu m] \tag{14}$$

For calculating the number of "C"-type sites per unit volume, N_V^C, the method developed for the characterisation of lamellar structure (Roósz et al., 1983) was applied:

$$N_V^C = \frac{L^3}{\lambda_1^2 L} \frac{L}{\lambda_2} K_V \frac{1}{L^3} = \frac{K_V}{\lambda_1^2 \lambda_2} \quad [1/\mu m^3] \tag{15}$$

Here K_v is a proportionality factor depending on the symmetry conditions.

RESULTS

Within the range of cooling rates (0.01 K/s < ($\dot{T}_L = GR$) < 4 K/s) investigated here, the solidification of the Al - 4.4 wt% Cu alloy will be completed by formation of eutectic. This deviation from the equilibrium type solidification is caused by the too slow diffusion in the solid phase (Roósz and Exner, 1990). The volume fraction and the morphology of the developed eutectic have considerable effects both on the mechanical properties and the parameters of the homogenization treatment.

During the final step of solidification (after the dendritic structure has been fully developed), the eutectic volume parts solidify. It is believed that the liquid phase, which becomes more and more concentrated in the alloying element, is constrained into less and less space between the primary and secondary dendrite arms, then solidify as eutectic along the dendritic interface through a nucleation and growth type process mostly at sites shown by "C" in Fig. 2. Eutectic is also formed in a smaller amount, at the contact sites of the secondary arms and the trunk. According to this hypothesis the morphological parameters of the eutectic should depend on the morphological characteristic of the dendrite expressed by the functions:

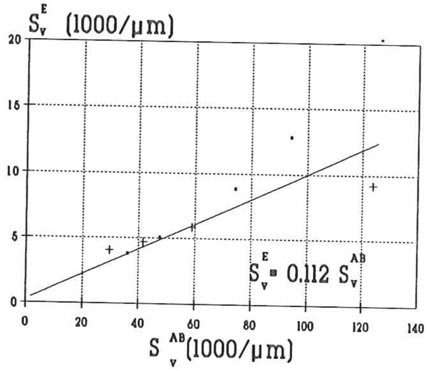
$$S_v^E = f(S_v^{AB}) \qquad (16)$$

$$N_v^E = f(N_v^C) \qquad (17)$$

This hypothesis can be proved by the following experimental results. It is shown in Fig. 3 that there is a linear relationship between the S_v^E and S_V^{AB}:

$$S^E = K_S S^{AB} \quad [1/\mu m] \qquad (18)$$

The proportionality factor, K_S gives that fraction of the dendritic surface which is in direct contact with the eutectic, in this case K_S =0.112.



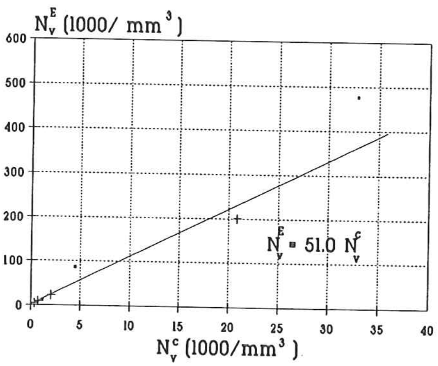


Fig. 3. Eutectic surface (S_v^E) as a function of dendrite surface (S_v^{AB}); () G_L= 5.05 K/mm and + G_L= 1.42 K/mm).

Fig. 4. The number of eutectic's parts (N_v^E) as a function of the number of contact points (N_v^C).

Equation (18) shows that, irrespective of the conditions of solidification, about 10-12 % of dendritic surface becomes covered by eutectic colonies by the end of solidification.
Figure 4 confirms the assumption that number of the eutectic volume parts in volume depends on the number of the most favourable sites (denoted with "C" in Fig. 2.) for heterogeneous nucleation. As previously, the functional relationship is approximately linear, so the relevant term of Eq.(18) can be written as:

$$N_V^E = K_C N_V^C = K_C \frac{K_V}{\lambda_1^2 \lambda_2} = K_C^V \frac{1}{\lambda_1^2 \lambda_2} \quad [1/\mu m^3] \qquad (19)$$

where K_C^V is a proportionality factor which was determined as 51.0

CONCLUSION

It was shown that the stereometrical microscopic characteristics of the eutectic colonies depend on the structural parameters λ_1 and λ_2 as well as the symmetrical and geometrical conditions of the solidified structure. It was also found that:

(i) the structure can be characterised by the surface in volume of primary and secondary arms as well as by the number of volume parts occupied by the eutectic;

(ii) the extent of surface in volume of primary and secondary arms, as well as the number of volume parts occupied by the eutectic depend on the arm spacing and the geometry of growth as well as its symmetry conditions;

(iii) the eutectic develops in the area between the primary and secondary arms at the end of the dendritic solidification, its morphological characteristics are determined by the parameters of the dendritic structure;

(iv) the spatial number of the eutectic parts is proportional to the number of contact points of primary and secondary arms;

(v) the surface in volume of the eutectic depends on the surface in volume of the dendrite. Independently on the solidification conditions, about 10 - 12 % of the surface of a dendrite is covered by non equilibrium eutectic at the solidification of Al - 4.4 wt% Cu alloy.

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