Morphology of solidification front in eutectic

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Abstract
In this paper the analysis of morphology of solidification front in eutectic made. It was present influence of composition, solidification velocity, concentration micro-field and capillarity effects on the morphology of the solid/liquid interface. It was introduced phase-field model.

Keywords: Solidification, Solidification front, Solid-liquid interface, Eutectic

1. Introduction
Normally in anomalous eutectics, the faceting of one of the phases leads to uncoupled growth and, as a result, a irregular solid/liquid interface appears which produces an irregular morphology as viewed in a transverse microsection. This is true not only when the volume fraction of the faceted phase is small, but also when it is large, i.e. 40%.

The solidification of eutectic alloys generally gives rise to lamellar or fibrous structures. The spacing of the lamellae or fibers is typically very regular with a dispersion around an average value. In recent years, theoretical and experimental investigations revealed that in lamellar eutectics so-called broken-parity states can be induced, exist and prevail during directional solidification. In recent years, theoretical and experimental investigations revealed that in lamellar eutectics so-called broken-parity states can be induced, exist and prevail during directional solidification. The theoretical explanations are based on the classical description by Jackson and Hunt given as early as 1966. They analyzed lamellar and fibrous eutectic growth mainly in simplifying the problem of diffusion ahead of the solidification front assuming a planar interface and equal undercooling of both solid phases growing in a coupled mode from a melt of eutectic composition. Jackson and Hunt chose as a selection criterion for growth, the so-called minimum undercooling criterion originally proposed by Zener yielding then a series of relations between fiber (or lamellae) spacing, solidification velocity and average undercooling.

2. The morphology of front
The force balance at a three-phase (triple) junction between solid and liquid phases and the Gibbs–Thomson effect play important roles in the evolution of interface patterns during eutectic solidification [1].

Consider an equilibrium between two α grains and liquid under a constant thermal gradient, shown in Fig. 1. θ was defined as the angle between the direction normal to the solid–liquid interface and the x axis. The angle θ* at the triple junction of the groove is determined by the force balance condition:

$$\sigma_g - 2 \frac{d\sigma_{13}}{d\theta} \sin \theta - 2\sigma_{13} \cos \theta = 0$$

(1)

where the second term is the torque force originating from the anisotropy of interface energy $\sigma_{13}$; and $\sigma_g$ is the grain boundary energy assumed to be isotropic.
Fig. 1. An equilibrium between two grains and liquid, where \( \theta \) is the angle between the \( x \) axis and the direction normal to the solid–liquid interface. The angle \( \theta^* \) at the triple junction of the groove is determined by the force balance condition [2].

We assume the four fold anisotropy of the form:

\[
\sigma_{13} = \sigma_{13}^0 \left[ 1 + \delta \cos 4(\theta - \theta_0) \right]
\]  
(2)

where \( \sigma_{13}^0 \) is the average interface energy and \( \theta_0 \) is the orientation with the maximum interface energy. For given \( \delta \) and \( \sigma_{13}^0 \), the angle \( \theta^* \) can be found from the numerical solution of Eq. (1) [2].

The equilibrium interface shapes, computed using the phase-field model, at a triple junction under a thermal gradient were in good agreement with the exact solutions for both isotropic and anisotropic solid–liquid interface energies, which indicates the maintenance of force equilibrium at triple junction in present eutectic phase-field models [2].

Figure 2 present different morphology of solidification front in eutectic.

For example it was showed the influence of the amount of solute on the morphology of the solid–liquid (S/L) interface of graphitic iron as shown in Fig. 3a. This concept was partially validated through directional solidification experiments (Fig. 3b) [3].
3. Concentration micro-field

A possibility of a modification of the Jackson-Hunt theory of an oriented structure formation is analyzed in [5]. A new model for the formation of a concentration field ahead of growing regular lamellae with respect to the solid/liquid interface shape is presented. A coordinate system applied in the model is attached to the solid/liquid interface to be advancing in the \( z \) direction, identically with interface moving at a constant velocity, \( v \). The solution to a diffusion equation is given for the improved formulation of the boundary conditions. The boundary conditions are related to the interplay between the diffusion required for phase separation and the formation of the interphase between both lamellae. The boundary conditions are formulated to establish the stability of lamellar structure formation under steady-state conditions. It is assumed that stable growth of the lamellae is ensured by the separation of concentration fields within a boundary layer ahead of the solid/liquid interfaces of both the \( \alpha \) and \( \beta \) phases. Coupled lamellar growth with the presence of a leading phase protrusion is defined. The general mass balance is analyzed for a solute concentration in the liquid, taking into account a planar solid/liquid interface. A local mass balance is also ensured but it requires envisaging a protrusion of the minor eutectic phase. The existence of a lead distance is confirmed experimentally for the (Pb)-(Cd) eutectic system. The difference in undercooling is also considered as a phenomenon associated with the separation of concentration fields and the existence of a protrusion to relax the assumption of an isothermal interface (ideally coupled growth) given by the Hunt and Jackson theory.

Both separately obtained solutions for slow solidification, for an \( \alpha \)-phase lamella, and for an \( \beta \)-phase lamella, are shown schematically in Fig. 4a together with the suggested concept of coupled growth, Fig. 4b.

It is evident that both general mass balance and local mass balance should be satisfied within the considered solute concentration micro-field created at the solid/liquid interface for the lamellar eutectic growth. The separation of the liquid pre-prepared for solidification is assumed in the current model [5]. Therefore, no adjustment of the volume fractions by the movement of the three-phase junctions are necessary as this was discussed by Magnin and Trivedi. As a simplification, the density difference between eutectic phases is not taken into account when
calculating the solute concentration micro-field for lamellar eutectic growth from the separated liquids [5].

4. Phase-field model

Directionally solidified MnBi/Bi eutectic has a quasi-regular MnBi rod structure at freezing rates. As with many other eutectics, the average rod spacing \( \lambda \) depends on the freezing rate \( V \) such that \( \lambda^2 V = \text{constant} \). The influence of convection on the microstructure of the MnBi–Bi eutectic was reviewed. Thus the two solid phases may be seen along with the composition field in the melt. When the freezing rate is increased, the supersaturation in front of lamellae increases, causing formation of a deep depression, followed by nucleation, instability, and volume fraction adjustment that eventually stabilizes the freezing interface. Vice versa, with a decrease in freezing rate, an instability develops that changes the local growth direction and provokes volume fraction adjustment with subsequent elimination of lamellae. With freezing rate oscillations, back melting becomes important, especially for large lamellar spacings [6].

Fig. 5. Phase-field simulation of the evolution of a lamellar microstructure caused by a) decreasing the freezing rate b) increasing the freezing rate (top to bottom) [6]

Directional solidification experiments with eutectic Al+Al\(_3\)Ni alloys were performed in which the solidification fronts were moved with constant accelerations and decelerations. The temperature gradients were kept constant and the samples were analyzed at positions where the velocity of the solid/liquid interface always was equal. New methods for the analysis of fiber-eutectic structures were employed giving not only the average fiber-fiber distance but also the number of neighbors for each fiber as well as distributions of these parameters. It was found that with increasing acceleration the fiber-fiber distance decreases and the order in the arrangement of fibers increases. It was shown variation of the average fiber-fiber distance. The cause for the changes of the order itself is related to the acceleration and the resulting changes of areas of stable eutectic growth. that the changes in the order are the cause for the variation of the average fiber-fiber distance. The cause for the changes of the order itself is related to the acceleration and the resulting changes of areas of stable eutectic growth. [7].

5. Capillarity effects

While the model presented above accounts for the development of haloes in directionally solidified off-eutectic alloys, the liquid (and, consequently, also the solid) compositions predicted by the model are based on the assumption that the growth undercoolings of the phases are produced entirely by the diffusion of solute. Capillarity undercoolings have been neglected. The relative contribution of capillarity to the total growth undercooling of each microstructural constituent depends,
naturally, on the degree of curvature of the solid–liquid interface. For the $\alpha$ dendrites, the radius of curvature at the tip of each dendrite is sufficiently large that capillarity undercooling may be neglected, except under rapid solidification conditions. Consequently, for normal growth rates the composition of the liquid at the tip of each dendrite is given quite accurately by the equilibrium liquidus composition ($C_d$ in Fig. 7) at the dendrite tip temperature ($T_d$ in Fig. 7).

**Fig. 7.** The variation in the morphology of the solid–liquid interface during directional solidification at a given growth rate, as the nominal composition of the alloy, $C_\infty$, moves to the left, away from the eutectic composition. $T_d$, $T_h$, and $T_c$ represent the growth temperatures of the primary $\alpha$-phase, $\beta$ haloes and coupled eutectic, respectively. The position of $T_c$ has been emphasised by a change in the shading of the coupled zone at $T_c$. The compositions of the liquid at the interface with the primary $\alpha$ phase, $\beta$ haloes, and $\alpha$ and $\beta$ phases in the coupled eutectic are $C_\alpha$, $C_\beta$, $C_c$ and $C_\beta$, respectively [8].

Furthermore, the curvature of the solid–liquid interface decreases very rapidly moving away from the tip, down the “side” of each dendrite, so the contribution of capillarity to the total growth undercooling is even less away from the dendrite tip. This is true even in dendrites with fully developed side branches, since the side branches coarsen towards the roots of the dendrites. Thus, the assumption of the model that the composition of the liquid adjacent to the primary phase follows the zero curvature equilibrium liquidus is valid at normal growth rates. Since the radius of curvature at the tip of each lamella in the coupled eutectic is relatively small, the contribution of capillarity undercooling to the growth undercooling of the eutectic is significant. Consequently, the compositions of the liquid at the tips of the $\alpha$ and $\beta$ lamellae are not given by the compositions of the zero curvature equilibrium $\alpha$ liquidus ($C_\alpha$ in Fig. 7) and $\beta$ liquidus ($C_\beta$ in Fig. 7) at the coupled eutectic growth temperature, $T_c$. Rather, the actual compositions of the liquid at the centres of the $\alpha$ and $\beta$ lamellae tips are given by the compositions of the $\alpha$ liquidus and $\beta$ liquidus, each depressed by the capillarity...
undercooling for coupled eutectic growth, at the coupled eutectic growth temperature, $T_c$ (Fig. 7) [8].

Fig.7a show coupled eutectic growth, 6b. some $\alpha$ lamellae grow ahead of the eutectic growth front, overgrow adjacent $\beta$ lamellae and join forming cellular protrusions. The liquid adjacent to these protrusions is enriched in solute, causing adjacent $\beta$ lamellae to thicken and advance ahead of the eutectic growth front. Fig.7c the cellular protrusions increase their lead over the coupled eutectic interface and thicken, developing side branches if the lead over the coupled eutectic growth front is sufficient. In the solute-rich diffusion boundary layer adjacent to the primary $\alpha$-phase, the $\beta$-phase that is growing ahead of the coupled eutectic overgrows adjacent $\alpha$ lamellae and thickens into $\beta$-phase haloes surrounding the $\alpha$ dendrites [8,9].

7. Conclusions

The crucial role of three-phase junctions is emphasized, showing that this leads to a control of the volume fractions of the phases formed during the solidification process.

The shape of the solidification front influence on the kinetic of the transformation and about the structure eutectic.

References


