Research on evolution of tilted eutectic structure based on phase field simulation

Jian Mo¹, Xiang-Ming Li¹, Lei Luo² and Bing-Bing Peng¹

¹ School of Materials Science and Engineering, Kunming University of Science and Technology, Kunming, People’s Republic of China
² School of Materials Science and Engineering, Beijing University of Technology, Beijing, People’s Republic of China

E-mail: lixm@kust.edu.cn

Keywords: phase field, solid-liquid anisotropy, solid-solid anisotropy, tilted eutectic

Abstract
The phase field model is established for the eutectic growth system in this paper, and the finite difference method is used to solve the model. The evolution of tilted eutectic interface morphology under isothermal solidification and directional solidification conditions, respectively, was investigated. The effects of solid-solid interface anisotropy, solid-liquid interface anisotropy, eutectic spacing and pulling speed on the evolution of the tilted eutectic structure were simulated to reveal the growth mechanism of the tilted eutectic structure. It is found that under isotropic and directional solidification conditions, eutectic growth is influenced by both the direction of heat flow and the solid-liquid interface anisotropy. When the solid-solid interface anisotropy is small, the direction of heat flow dominates the growth direction of eutectic structure, and as the solid-solid interface anisotropy increases, the growth direction of eutectic structure starts to tilt. Two kinds of instability phenomena, bifurcation or merger and fault line, are also found in the eutectic growth.

1. Introduction
Eutectic alloys are most widely used in industry, and their microstructure is characterized by coupled growth of two or more phases from liquid [1–4]. Its eutectic structure exists in the solid-liquid phase transitions of many important structural and functional materials [5–7]. The tilted eutectic structure, opposite to the direction of heat flow, is formed by the non-tilted eutectic structure under many factors. Scholars have begun to explore important issues such as the growth mechanism of tilted eutectic structures and the stability of eutectic growth interface [8–10]. It is preliminarily considered that the tilted eutectic structure is a special phenomenon of the non-tilted eutectic structure, and surface tension anisotropy has influence in the tilt angle of the eutectic structure, by both of experiments and theoretical results. The phase field method, which can continuously change the order parameters of the interface and eliminated the difficulty of tracking the interface during solidification, always is used to study the formation mechanism of crystal growth. Therefore, In this paper, we will investigate the evolution of tilted eutectic interface morphology using the phase field method. The phase field model is established for the eutectic growth system, and the finite difference method is used to solve the phase field model. Under isothermal and directional solidification, the morphology evolution of the tilted eutectic interface and non-tilted eutectic interface was considered, respectively, The influence of solid-solid interface anisotropy, solid-liquid interface anisotropy, pulling speed and temperature gradient on the morphology of the eutectic structure were obtained, and the growth mechanism of the tilted eutectic structure was revealed in essence.

2. Model
In this section, we will give the phase field model of the eutectic growth. Tilted eutectic is one of the lamellar eutectic, so our model is limited to two-dimensional phase field simulation. Because we mainly pay attention to
the effects of interface anistropy on the evolution of the tilted eutectic growth, we also neglect the effect of convection in the liquid-phase.

2.1. The phase field model

In the phase field model, the phase-field variable \( \phi \) is governed by the evolution equation describing the dynamics of solid phase and liquid phase. The phase-field variable \( \varphi \) is governed by the evolution equation describing the dynamics of the two solid phases. The phase field model for the eutectic structure based on phase field model proposed by Popov et al [11, 12].

\[
\tau \left( \frac{\delta \phi}{\delta \phi} - V_p \frac{\partial \phi}{\partial x} \right) = h(\varphi) \left\{ \varepsilon_{11}^2 \nabla^2 \phi + W_{d1} \phi - \phi^3 \right\} - \frac{\partial h(\phi)}{\partial \phi} \left\{ \varepsilon_{11}^2 \nabla^2 \phi + W_{d1} \phi - \phi^3 \right\} [\phi_f + (1 - c) f_{a2}] \\
+ [1 - h(\varphi)] \left\{ \varepsilon_{11}^2 \nabla^2 \phi + W_{d1} \phi - \phi^3 \right\} \frac{\partial h(\phi)}{\partial \phi} \left\{ \phi_f + (1 - c) f_{a2} \right\} \\
+ \frac{\partial h(\phi)}{\partial \phi} \left\{ \varepsilon_{11}^2 \nabla^2 \phi + W_{d1} \phi - \phi^3 \right\}
\]

\[
\tau \left( \frac{\delta \varphi}{\delta \varphi} - V_p \frac{\partial \varphi}{\partial x} \right) = [1 - h(\phi)] \varepsilon_{11}^2 \nabla^2 \varphi + \frac{\partial h(\phi)}{\partial \phi} \left\{ \varepsilon_{11}^2 \nabla^2 \varphi - \varepsilon_{11}^2 \nabla^2 \phi \right\} \\
- [1 - h(\phi)] \frac{\partial h(\phi)}{\partial \phi} \left\{ \phi_f + (1 - c) f_{a2} - \phi_f - (1 - c) f_{b2} \right\} \\
+ \frac{\partial h(\phi)}{\partial \phi} \left\{ \frac{1}{4} W_{d1}(1 - \phi^2)^2 - \frac{1}{4} W_{d1}(1 - \phi^2)^2 \right\}
\]

Where \( V_p \) is pulling speed, \( \varepsilon \) and \( W \) are decision by the interfacial free energy \( \sigma \) and interface width \( \delta \), where the function

\[
\varepsilon = \frac{3\sigma \delta}{2\sqrt{2}} \\
W = \frac{3\sigma}{\delta}
\]

\[
f_p(T) = \Delta H_{f1} \left( 1 - \frac{T}{T_f} \right) \\
h(\phi) = \frac{3}{4} \phi - \frac{1}{4} \phi^3 + \frac{1}{2} \\
h(\varphi) = \frac{3}{4} \varphi - \frac{1}{4} \varphi^3 + \frac{1}{2}
\]

2.2. The concentration model

\[
\frac{\partial c}{\partial t} - V_p \frac{\partial c}{\partial x} = \nabla \left\{ \left( \frac{D(\phi)\nu_m}{R} \epsilon(1 - c) \nabla \left[ \frac{\Delta u(\phi, \varphi, c, T)}{T} \right] \right) \right\}
\]

Where \( \nu_m \) is the molar volume, \( R \) is the gas constant, where the function

\[
\Delta u(\phi, \varphi, c, T) = -h(\varphi)[1 - h(\phi)] \left\{ \Delta H_{f1} \left( 1 - \frac{T}{T_{f1}} \right) - \Delta H_{f2} \left( 1 - \frac{T}{T_{f2}} \right) \right\} \\
- [1 - h(\varphi)] [1 - h(\phi)] \left\{ \Delta H_{f1} \left( 1 - \frac{T}{T_{f1}} \right) - \Delta H_{f2} \left( 1 - \frac{T}{T_{f2}} \right) \right\} + \frac{RT}{\nu_m} \ln \left( \frac{c}{1 - c} \right)
\]

\[
D(\phi) = h(\phi) D_{\text{liquid}} + (1 - h(\phi)) D_{\text{solid}}
\]

Where \( D(\phi)_{\text{liquid}} \) is liquid diffusion coefficient and \( D(\phi)_{\text{solid}} \) is solid diffusion coefficient.

2.3. The temperature model

\[
T = T_E - \Delta T
\]
Where $G$ is temperature gradient, $T_E$ is eutectic temperature, $\Delta T$ is undercooling temperature. Equation (11) is represent isothermal conditions and equation (12) is represent directional solidification.

2.4. The anisotropy model

\[
\varepsilon (\theta) = \varepsilon (1 + \varepsilon_4 \cos (m\theta))
\]

Where $\theta$ is the tilt angle of the eutectic structure.

2.5. Thermophysical parameters

We will solve the model above based on the physical properties of Pb-Sn eutectic growth system, shown in table 1. In our study, we mainly investigate effects of the interface anisotropy on the growth of tilted eutectic. Therefore, the anisotropy of the Pb-Sn system is not included in table 1. We will obtain a general law of tilted eutectic growth by varying these parameters.

### Table 1. Pb-Sn material parameters [11–14].

| Parameter | Value | Unit |
|-----------|-------|------|
| $C_E$     | 0.739 | mol% |
| $C_{\alpha}$ | 0.968 | mol% |
| $C_{\beta}$ | 0.29  | mol% |
| $T_E$     | 456.0 | K    |
| $\Delta H_1$ | $626.7 \times 10^{-12}$ | $1 \mu m^{-3}$ |
| $\Delta H_2$ | $876.4 \times 10^{-12}$ | $1 \mu m^{-3}$ |
| $D_S$     | 10.0  | $\mu m^2 s^{-1}$ |
| $D_L$     | $1.0 \times 10^3$ | $\mu m^2 s^{-1}$ |

\[
T = T_E + G^2(z_e - V_p t)
\]

3. Results and discussion

In this section, we will reveal the effects of solid-solid interface anisotropy, solid-liquid interface anisotropy, and pulling speed on the evolution of the tilted eutectic structure under isothermal solidification and directional solidification conditions, respectively. Meanwhile, we will consider the two cases of the eutectic evolution: a large initial eutectic spacing and small initial eutectic spacing, respectively.

3.1. Morphology of tilted eutectic structure under isothermal conditions

Figure 1 shows the morphology of the tilted eutectic structure under different solid-solid interface anisotropy at the same time. The initial tilt angle is $30^\circ$ and the temperature is $420$ K. Figures 1 (a)–(d) shows the morphology of the tilted eutectic structure when the initial eutectic spacing is $6.67 \mu m$ and solid-solid interface anisotropy is $0.01$, $0.03$, $0.05$ and $0.06$, respectively. Figures 1(e)–(h) shows the morphology of the tilted eutectic structure when the initial eutectic spacing is $3.33 \mu m$ and solid-solid interface anisotropy is $0.01$, $0.03$, $0.05$ and $0.06$, respectively. In the figure, the red area is the $\alpha$-phase, and the blue area is the $\beta$-phase.

For the eutectic structure with a large initial eutectic spacing, when solid-solid interface anisotropy is small, as shown in figure 1(a), the $\alpha$-phase solid-liquid interface is a concave interface. The reason for this is that solid-liquid interface of $\beta$-phase grown faster, which destroyed the coupled and stable growth of the eutectic, and made $\beta$-phase solid-liquid interface have the characteristics of single-phase alloy. Eutectic coupling growth actually is dependent on the constituents of each phase. According to the phase diagram of Pb-Sn eutectic growth, for example, the growth of the $\alpha$-phase, which is rich of constituent Sn, depends on the release of the component Pb and the absorption of the component Sn from the $\beta$-phase, which is rich of constituent element Pb. However, the faster growth rate of the $\alpha$-phase solid-liquid interface led to the enrichment of Pb at the front of the $\beta$-phase solid-liquid interface, which promoted the solid-liquid interface of the $\alpha$-phase become unstable and concave. In the red area of the figure, the $\alpha$-phase bifurcation has a big difference between the growth speed of the 1-end tissue and the 2-end tissue. The 1-end tissue grown at the original tilt angle, and the growth direction of the 2-end tissue grown from the tilted angle direction changed to non-tilted angle direction. The $\beta$-phase structure in the blue region also kept the tilted angle direction. Increased solid-solid interface anisotropy, as shown in figure 1(b), the $\alpha$-phase bifurcation phenomenon disappeared. In figure 1(b), the eutectic structure has a tilt angle, and the eutectic structure grown in coupled. As shown in figure 1(c), the tilt
angle of the $\alpha$-phase in the red region became significantly larger, and the $\beta$-phase in the blue region also remained in the tilt angle direction. Due to the changed in the tilt angle of $\alpha$-phase structure in the red region, some $\beta$-phase crystals in the blue region begin to nucleate away from the initial tilted growth direction, resulted in the tilt angle changed of $\beta$-phase in the blue region. In strong solid-solid interface anisotropy in figure 1(d), the rapid growth of $\beta$-phase in the blue region merged and $\alpha$-phase in the red region is closed. The unstable growth of $\beta$-phase with the characteristics of single-phase alloy resulted in more Sn cumulated at the front of the concave interface and promoted the nucleation of $\alpha$-phase. Eventually, the bifurcation of $\beta$-phase occurred. Under the conditions of large eutectic spacing and strong solid-solid interface anisotropy, the tilted eutectic structure began to appear as shown in figure 1(c).

For the eutectic structure with a small initial eutectic spacing. The tilt angle of the eutectic structure in figures 1(e)–(h) gradually decreased from the initial tilt angle. In figures 1(e)–(g), the eutectic structure is still stable coupled growth. The solid-liquid interface of eutectic structure changed from convex interface to flat interface. When solid-solid interface anisotropy is large, as shown in figure 1(h), the blue area $\beta$-phase structure meshed the red area $\alpha$-phase structure. The reason for its annexation is similar to figure 1(d). Figure 1 shows that when the eutectic spacing is small, the tilt angle gradually decreased. Only when the solid-solid interface anisotropy is strong, the eutectic structure will be merged; when the eutectic spacing is large, the tilt angle changed not large, the solid-solid interface anisotropy has greater effect on the eutectic structure.

As shown in figure 2, the morphology of the tilted eutectic structure under different solid-liquid interface anisotropy at the same time. Figures 2(a)–(d) shows the morphology of the tilted eutectic structure when the initial eutectic spacing is 6.67 $\mu$m and solid-liquid interface anisotropy is 0.01, 0.03, 0.05 and 0.08 respectively. Figures 2(e)–(h) shows the morphology of the tilted eutectic structure when the initial eutectic spacing is 3.33 $\mu$m and the solid-liquid interface anisotropy is 0.01, 0.03, 0.05 and 0.08 respectively.

When the initial eutectic spacing is large, the tilted eutectic structure is still unstable growth. The bifurcation phenomenon of the tilted eutectic structure in figure 2(a) is similar to that of the tilted eutectic structure in figure 1(a). Under the influence of small solid-solid interface anisotropy or small solid-liquid interface anisotropy, the effect on the morphology of the tilted eutectic structure is not obvious. In figure 2(a), the bifurcation tissue is divided into 1-end tissue and 2-end tissue. The growth speed of the bifurcation tissue at 1-end is significantly faster than that at 2-end, and the growth direction of 1-end is maintained at tilt angle direction, while the growth direction of 2-end tissue is changed from the tilt angle direction to the non-tilted angle direction. When solid-liquid interface anisotropy increased, the bifurcation phenomenon is disappeared that is different from the non-tilted eutectic structure at solid-liquid interface anisotropy of 0.03. As shown in figure 2(b), the morphology of bifurcation tissue is similar to the morphology of bifurcation tissue in figure 2(a). While 1-end tissue grown in preference to 2-end tissue grown. In figure 2(c), the 2-end tissue of the bifurcation tissue is disappeared, and only 1-end tissue is existed. This is because $\beta$-phase structure in the blue region in preference to 2-end tissue grown, and the crystallization core begun generated at the front of 2-end tissue, meshed the 2-end tissue and caused the 2-end tissue to disappear. In figure 2(d), Solid-liquid interface of $\beta$-phase in the blue region remained straight interface, and $\alpha$-phase solid-liquid interface in the red region

Figure 1. Morphology of tilted eutectic structure under different solid-solid interface anisotropy at the same time : (a)–(d) initial lamellar eutectic spacing is 6.67 $\mu$m, solid-solid interface anisotropy is 0.01, 0.03, 0.05 and 0.06; (e)–(h) initial lamellar eutectic spacing is 3.33 $\mu$m, and solid-solid interface anisotropy is 0.01, 0.03, 0.05, and 0.06.
remained concave. In the unstable growth state, under the influence of solid-liquid interface anisotropy, the tilt angle of the tilted eutectic structure remained almost unchanged. When the initial eutectic spacing is small, as shown in figures 2(e)–(h), the tilt angle of the tilted eutectic structure gradually decreased from the initial tilt angle. By comparing figures 1(e)–(h) with figures 2(e)–(h), it was found that the eutectic structure maintained coupled growth with small lamellar eutectic spacing. And solid-liquid interface changed from convex interface to flat interface of the eutectic structure. Figure 2 shows that with small lamellar eutectic spacing, the increased in the solid-liquid interface anisotropy has the effect of stabilized the solid-liquid eutectic interface; as the eutectic interface grown and evolved, the tilted eutectic tilt angle gradually decreased.

3.2. Morphology of tilted eutectic structure under directional solidification
Figure 3 shows the morphology of the tilted eutectic structure under the different solid-solid interface anisotropy at the same time. The pulling speed is 1.5 μm s⁻¹, the temperature gradient is 8.0 × 10⁵ K m⁻¹, and the initial tilt angle is 30°. Figures 3(a)–(d) shows the morphology of the tilted eutectic structure when the initial eutectic spacing is 6.67 μm and the solid-solid interface anisotropy is 0.01, 0.03, 0.05, and 0.06 respectively.
Figures 3(e)–(h) shows the morphology of the tilted eutectic structure when the initial eutectic spacing is 3.33 μm and solid-solid interface anisotropy is 0.01, 0.03, 0.05 and 0.06 respectively.

For the eutectic structure with large initial eutectic spacing: when solid-solid interface anisotropy is small, as shown in figures 3(a), (b), the eutectic spacing is also adjusted by bifurcation. In figures 3(a), (b), the tilted eutectic structure is affected by small solid-solid interface anisotropy and the heat flow direction. It can be seen from the figure that the tilt angle of the tilted eutectic structure gradually decreased from larger initial tilt angle, and it is closer to the opposite direction of the heat flow direction. It shows that under the influence of small solid-solid interface anisotropy, the heat flow direction played major role in the growth direction of the tilted eutectic structure. Under the influence of strong solid-solid interface anisotropy, the tilted eutectic structure is affected by the coupling effect of solid-solid interface anisotropy and heat flow direction. The morphology of the tilted eutectic structure as shown in figures 3(c), (d) is different from that of figures 3(a), (b). In figures 3(c), (d), the bifurcation phenomenon of the tilted eutectic structure is disappeared, and the tilt angle of the tilted eutectic structure changed simultaneously.

For the eutectic structure with small initial eutectic spacing: as shown in figures 3(e)–(h), the tilted eutectic structure maintained the coupled growth. Under the influence of small solid-solid interface anisotropy, as shown in figures 3(e), (f), the tilt angle of the tilted eutectic structure is not obvious. However, under the influence of strong solid-solid interface anisotropy, as shown in figures 3(g), (h), the tilt angle of the tilted eutectic structure and the eutectic spacing is obviously changed. Figure 3 also shows that when solid-solid interface anisotropy is small, the imposed heat flow direction is the major factor for eutectic growth, and the eutectic interface grown in the opposite heat flow direction. When solid-solid interface anisotropy increased to certain extent, the eutectic growth reflected the anisotropy direction in preference to growth and caused the eutectic growth direction to deviate. At small eutectic spacing, as solid-solid interface anisotropy increased, the tilt angle of the tilted eutectic structure increased, and the eutectic spacing became smaller.

Figure 4 shows the relationship between the average lamellar spacing of the tilted eutectic structure and solid-solid interface anisotropy under directional solidification. The abscissa is solid-solid interface anisotropy strength, and the ordinate is the average lamellar spacing. The black solid line in the figure represents the change of the eutectic spacing under the influence of different solid-solid interface anisotropy when the initial eutectic spacing is 3.33 μm. Figures 4(a)–(c) show the average lamellar spacing, the average lamellar width of α-phase structure and the average lamellar width of β-phase structure, respectively. It can be seen from the figure that, as solid-solid interface anisotropy increased, the average lamellar eutectic spacing, the average lamellar width of α-phase structure and the average lamellar width of β-phase structure decreased simultaneously.
Figure 5 shows the relationship between the tilt angle of the tilted eutectic structure and solid-solid interface anisotropy. The abscissa in the figure is the solid-solid interface anisotropy strength, and the ordinate is the tilt angle. The red solid line represents the curve of the tilt angle of the tilted eutectic structure with solid-solid interface anisotropy when the initial eutectic spacing is 6.67 μm, and the black solid line represents the curve of the tilt angle of the tilted eutectic structure with different solid-solid interface anisotropy when the initial eutectic spacing is 3.33 μm. In the figure, as solid-solid interface anisotropy increased, the tilt angle of the tilted eutectic structure also increased. At the same time, under the influence of small solid-solid interface anisotropy, the eutectic structure is mainly affected by the heat flow direction. Under the influence of strong solid-solid interface anisotropy, the eutectic structure is affected by the coupled of the heat flow direction and solid-solid interface anisotropy, and the eutectic structure is tilted at a large angle. Overall, as the solid-solid interface anisotropy increased, the tilt angle of the eutectic structure also increased.

Figure 6 shows the morphology of the tilted eutectic structure under the different solid-liquid interface anisotropy at the same time. The pulling speed is 1.5 μm s⁻¹, the temperature gradient is 8.0 × 10⁵ K m⁻¹, and the initial tilt angle is 30°. Figures 6(a)–(d) shows the morphology of the tilted eutectic structure when the initial eutectic spacing is 6.67 μm and solid-liquid interface anisotropy is 0.01, 0.03, 0.05 and 0.08; Figures 6(e)–(h) shows the morphology of the tilted eutectic structure when the initial eutectic spacing is 3.33 μm and solid-liquid interface anisotropy is 0.01, 0.03, 0.05, and 0.08.
For the eutectic structure with a large initial eutectic spacing: the growth direction of the tilted eutectic structure in figure 6 changed from tilt angle direction to the opposite heat flow direction. It shows that under the influence of solid-liquid interface anisotropy and the heat flow direction, the heat flow direction played major role in the growth direction of tilted eutectic structure. When solid-liquid interface anisotropy is small, as shown in figures 6(a), (b), the tilted eutectic structure has a primary bifurcation phenomenon and a secondary bifurcation phenomenon. However, when solid-liquid interface anisotropy is large, as shown in figures 6(c), (d), the tilted eutectic structure produced only primary bifurcation phenomenon, and no secondary bifurcation phenomenon. It shows that lamellar tilted eutectic spacing changed due to changed of solid-liquid interface anisotropy. Under the influence of solid-liquid interface anisotropy, the morphology of the tilted eutectic structure evolved from a convex eutectic structure to a plat eutectic structure.

For the eutectic structure with small initial eutectic spacing: the tilted eutectic structure is no longer a stable coupled growth. When solid-liquid interface anisotropy is small, the bifurcation phenomenon occurred in the tilted eutectic structure as shown in figures 6(e), (f). However, when solid-liquid interface anisotropy is large, as shown in figures 6(g), (h), the bifurcation phenomenon does not occur, which completely shows that under solid-liquid interface anisotropy, the lamellar eutectic spacing changed. In figures 6(e)–(h), the eutectic structure also evolved from cellular eutectic structure to plat eutectic structure. Figure 6 shows that when solid-liquid interface anisotropy is small, the eutectic structure has a secondary bifurcation phenomenon and has the effect of adjusting the lamellar eutectic spacing.

Figure 7 shows the relationship between the average lamellar spacing of the tilted eutectic structure and solid-liquid interface anisotropy under directional solidification: (a) average lamellar eutectic spacing \( \lambda_E \), (b) \( \alpha \)-phase average lamellar width \( \lambda_{\alpha} \), (c) \( \beta \)-phase average lamellar width \( \lambda_{\beta} \).

Figure 8 shows the morphology of the tilted eutectic structure at the same time with different pulling speed. The temperature gradient is \( 8.0 \times 10^5 \) K m\(^{-1}\), the initial tilt angle is 30\(^{\circ}\), and solid-liquid interface anisotropy is set to zero. Figures 8(a)–(d) show the effect of different pulling speeds (1.0 \( \mu \)m s\(^{-1}\), 2.0 \( \mu \)m s\(^{-1}\), 3.0 \( \mu \)m s\(^{-1}\) and
4.0 μm s⁻¹, respectively) on the evolution of tilted eutectic with the small solid-solid interface anisotropy, 0.03. Figure 8(e) shows the morphology of the tilted eutectic structure when solid-solid interface anisotropy is 0.05 and the pulling speed is 4.0 μm s⁻¹. Figure 8(f) is fault line which is discovered by Jackson et al. [15] in the experiment. When solid-solid interface anisotropy is small, figures 8(a)–(c) shows that the tilted eutectic structure is coupled growth. When pulling speed is increased to a certain extent, as shown in figure 8(d), the growth of the tilted eutectic structure is unstable, resulting in fault line. And there have been bifurcation and mesh. When solid-solid interface anisotropy is increased, as shown in figure 8(e), the tilted eutectic structure growth is more unstable, and fault line is more obvious. Comparing figures 8(e) and (f), the simulation results are similar to those obtained by Jackson experiments, proved the true reliability of fault line. Jackson did not put forward specific experimental conditions in this article, but this paper found fault line under large pulling speed and strong solid-solid interface anisotropy. It can be predicted that fault line is mainly affected by large pulling speed and strong solid-solid interface anisotropy. Figure 8 shows that as pulling speed increased, the tilted eutectic structure grown unstable, and fault line are found in the instability. The greater the pulling speed or the greater the solid-solid interface anisotropic strength, the more likely caused fault line [16–21].

4. Conclusion

In this paper, the morphological characteristics of tilted eutectic structure under anisotropy conditions are studied. Mainly under isothermal conditions and directional solidification conditions, the evolution of tilted eutectic structure morphology such as solid-solid interface anisotropy, solid-liquid interface anisotropy and eutectic structure initial lamellar spacing were studied. The laws of tilted eutectic evolution revealed in the study are similar, therefore, it can be used for other eutectic growth systems. The conclusion is as follows:

(1) When solid-solid interface anisotropy is small, the α-phase bifurcation phenomenon occurred in the eutectic structure with large initial eutectic spacing. The increased in anisotropy promoted the eutectic coupled growth, and the larger solid-solid interface anisotropy promoted the eutectic growth to tilt. When solid-solid interface anisotropy increased to a certain degree, the β-phase bifurcation phenomenon occurred in the eutectic structure. The increased of solid-liquid interface anisotropy has the effect of stabilized solid-liquid interface of the eutectic structure.

(2) Under directional solidification conditions, the eutectic growth direction is mainly affected by the coupled effect of the heat flow direction and solid-solid interface anisotropy. When solid-solid interface anisotropy
is small, the heat flow direction dominated the eutectic structure growth direction, and the eutectic interface grown in opposite heat flow direction. When solid-solid interface anisotropy increased to a certain extent, there will be a tilted eutectic structure. As solid-solid interface anisotropy increased, the lamellar eutectic spacing decreased and the tilt angle increased. The increased of solid-liquid interface anisotropy made stabilizing the eutectic structure, and solid-liquid interface eventually evolved into flat interface. As solid-liquid interface anisotropy increased, the lamellar eutectic spacing increased.

(3) Under directional solidification conditions, two types of instability occurred during the growth of eutectic structure. The first kind of instability phenomenon is bifurcation or mesh phenomenon, adjustment of eutectic structure spacing. The second kind of instability phenomenon is fault line, which is mainly affected by large pulling speed and strong solid interface anisotropy.

Acknowledgments

This work was supported by National Natural Science Foundation of China (No. 51561016 and No. 51961018).

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

ORCID iDs

Xiang-Ming Li © https://orcid.org/0000-0002-1784-2592

References

[1] Vermede S, Donze J and Rappaz M 2009 A mesoscale granular model for the mechanical behavior of alloys during solidification Acta Mater. 57 1354–69
[2] Perrut M, Parisi A and Akamatsu S 2010 Role of transverse temperature gradients in the generation of lamellar eutectic solidification Acta Mater. 58 1761–9
[3] Akamatsu S and Plapp M 2016 Eutectic and peritectic solidification patterns Mater. Sci. 20 46–54
[4] Akamatsu S, Fairev G, Plapp M and Karma A 2004 Overtstability of lamellar eutectic growth below the minimum-undercooling spacing Acta Mater. 53 1815–28
[5] Schleier A, Kuhn U and Eckert J 2011 Anisotropic mechanical behavior of ultrafine eutectic Ti–Fe cast under non-equilibrium conditions Internetsylicles 19 327–35
[6] Zhu F, Fria M, Dick A and Grabowski B 2012 First-principles study of the thermodynamic and elastic properties of eutectic Fe–Ti alloys Acta Mater. 60 1594–602
[7] Kurz W 1991 Eutectic growth under rapid solidification conditions Metall. Trans. A 22 3051–7
[8] Perrut M, Parisi A and Akamatsu S 2010 Role of transverse temperature gradients in the generation of lamellar eutectic solidification patterns Acta Mater. 58 1761–9
[9] Quensinet J M and Naslain R 1981 Effect of forced convection on eutectic growth J. Cryst. Growth 54 465–74
[10] Akamatsu S, Fairev G, Plapp M and Karma A 2004 Overtstability of lamellar eutectic growth below the minimum-undercooling spacing Mater. Trans. A 53 1815–28
[11] Popov D and Regel L I 2001 Influence of freezing rate oscillations and convection on eutectic microstructure Acta Astronaut. 48 101–8
[12] Popov D 1999 Modeling of Detached and Unsteady Eutectic Solidification (Clarkson University)
[13] Cadipli E and Gündüz M 2000 The dependence of lamellar spacing on growth rate and temperature gradient in the lead–tin eutectic alloy J. Mater. Process. Technol. 97 74–81
[14] Verhoeven J D, Gibson E D and Mourer D P 1977 The morphology and crystallography of directionally solidified pb–sn eutectic alloys Metall. Trans. A 8 1239–47
[15] Jackson K A and Hunt J D 1988 Lamellar and rod eutectic growth Dynamics of Curved Fronts 236 363–76
[16] Meng S, Zhang A and Guo Z 2020 Phase-field-lattice Boltzmann simulation of dendrite motion using an immersed boundary method Comput. Mater. Sci. 184 109784
[17] Yadav V, Vanherpe L and Mols L 2016 Effect of volume fractions on microstructure evolution in isotropic volume-conserved two-phase alloys: a phase-field study Comput. Mater. Sci. 125 297–308
[18] Hinrichs F et al 2020 Calibration of a concentration-driven nucleation mechanism for phase-field simulations of eutectic and off-eutectic compositions in AlCu-5Ag Sc. Mater. 186 89–94
[19] Grandi D et al 2019 A phase-field approach to eulerian interfacial energies Arch. Ration. Mech. Anal. 234 351–73
[20] Yue P, Zhou C and Feng J J 2017 Spontaneous shrinkage of drops and mass conservation in phase-field simulations J. Comput. Phys. 223 1–9
[21] Dennstedt A et al 2015 Large scale phase-field simulations of directional ternary eutectic solidification Acta Mater. 93 194–204