Interface morphology evolvement and microstructure characteristics of hypoeutectic Cu–1.0 wt%Cr alloy during unidirectional solidification

Rui Hu *, Xiaoqin Bi, Jinshan Li, Hengzhi Fu

State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi’an 710072, People’s Republic of China

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Abstract

Effect of unidirectional solidification rate on microstructure of hypoeutectic Cu–1.0%Cr alloy was investigated. The microstructure evolution of Cu–1.0%Cr alloy was noticed especially during the unidirectional solidification with the different solidification rates. It is shown that eutectic (α + β) and primary α(Cu) phase grew up equably in parallel to direction of solidification. A kind of fibiform microstructure will appear when unidirectional solidification rate is up to some enough high certain values. When temperature gradient was changeless, the interface morphology evolution of the primary α(Cu) phase underwent to a series of changes from plane to cell, coarse dendrite, and fine dendrite grains with increasing the solidification rates. Primary dendrite arm spacing (λ1 of α(Cu) phase increases with increasing the solidification rate where the morphology of the solid/liquid (S/L) interface is cellular. However, λ1 decreases with further increasing the solidification rate where the S/L interface morphology is changed from cell to dendrite-type. Its rule might accord with Jackson–Hunt theory model. An experience equation obtained is as follows: λ1 = −0.0052 + 0.061G1/2V−1/3. On the other hand, secondary dendrite spacing (λ2 of primary α(Cu) phase will thin gradually with increasing the solidification rate. Moreover, secondary dendrite will become coarse in further solidification. Another experience equation about relationship among secondary dendrite arm spacing (λ2), temperature gradient G1 and the velocity of the S/L interface (V) is that: λ2 = −0.0003 + 0.0027(G1V)−1/3. In addition, the volume fraction of eutectic will decrease with the increase of solidification rate.

Keywords: Unidirectional solidification; Cu–Cr alloy; Interface morphology

1. Introduction

Hypoeutectic Cu–Cr alloy is an important material with high strength and high conductivity, which is generally used to make electrical contactors and electrical leads for power net in high railway system [1]. Hypoeutectic Cu–Cr alloy with unidirectional microstructure is called as a kind of in situ composite material [2]. Due to a high strength of Cr-rich phase, the eutectic part has higher strength than matrix. Eutectic with fibrous shape can reinforce the copper matrix in direction parallel to these fibrous microstructures and keep a good conductivity [3]. However, it should be noticed that most of the previous researches mainly focus on the effect of the microstructure of the unidirectional solidified Cu–Cr alloys on conductivity [4,5]. Moreover, some early works thought the fibrous microstructure was Cr whisker in eutectic alloy [6]. But in fact, authors indicated that ‘Cr whisker’ should be ‘Cr-rich β phase’ in a former work [7]. The certainly orientated microstructure in hypoeutectic alloy is eutectic except for Cr-rich β phase because of effect of primary α phase growth. Orientation of Cr-rich β phase in the unidirectional solidified eutectic-like microstructure of hypoeutectic alloy is also disorder [7]. Authors think that this result is related with evolvement characteristics of interface morphology. In the present work, the effect of unidirectional solidification rate on microstructure and evolvement characteristics of interface morphology of hypoeutectic Cu–1.0 wt%Cr alloy was investigate by LMC method (liquid metal cooling).

2. Experiment procedure

The binary Cu–1.0 wt%Cr alloy was smelted from the Cu–25 wt%Cr mid-alloy and electrolytic pure Cu (99.94%) in a middle-frequency vacuum induction furnace with 25 kg capacity by using a high-purity graphite crucible. Then, original sample (φ8 mm × 100 mm rods) were obtained when Cu–1.0 wt%Cr alloy melt solidified in a die model. These sample rods were treated with unidirectional solidification method in equipment with high temperature gradient [7]. When
these samples were melted, they were moved downward with several different velocities into a Ga–In alloy pool with water-cooling located below heat region. Some of adiabatic refractory material plates were set at position between heat region and cooling pool in order to make a higher temperature gradient on the S/L interface. By using thermocouples [7], cooling curve of sample can be recorded during solidification process. In this work, the temperature gradient ($G_L$) is about 200 K/cm. Based on the constant temperature gradient, this work adopted a serial of solidification rates ($G_L V$). Where the velocity of the advancing S/L interface ($V$) are about 3.7, 6.7, 12, 30, 60, 100, 200, 400, 600 and 1000 m/s, in order to investigate the influence of the solidification parameters on the microstructure. The samples were cut along axial direction of samples by line incising technique. The morphology evolution and microstructures were observed with optical microscope and SEM methods.

3. Results and discussions

3.1. Effect of solidification rate on interface morphology and microstructures characteristics

Based on having a constant temperature gradient ($G_L = 200$ K/cm), by changing the velocity of the advancing S/L interface ($V$), an effect of solidification rate on solidification microstructure was investigated in this work. The interface morphologies under different solidification rate are as follows:

As shown in Fig. 1, the S/L interface morphology underwent changes from planar interface to cell and dendrite ones with increasing the solidification rate. In particular, the microstructure of hypoeutectic alloy is not composed of single $\alpha$ phase but primary $\alpha$ phase and eutectic phase. When the advancing unidirectional solidification interface is carried through with a lower velocity, the hypoeutectic alloy will be made up of whole eutectic-type microstructure, where the S/L interface is characterized with planar, intergrowth growth of eutectic and stability growth. The growth of primary $\alpha$(Cu) phase will be restrained completely [8]. In hypoeutectic alloy, when unidirectional solidification S/L interface is a low velocity planar interface, constitutions of liquid near front edges of intergrowth interface of two phases in eutectic are so obviously different that solute atoms can diffuse easily each other. The solute concentration near S/L interface is further less than one near S/L interface of single-phase alloy. Therefore, whole

Fig. 1. The longitudinal cross-section of unidirectional solidified and quenched samples showing the S/L interface morphologies of Cu–1.0 wt%Cr alloy under different solidification rate. (a) the planar front; (b) the cell interface; (c) the dendrite interface.

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Fig. 2. Microstructure for the planar interface of Cu–1.0%Cr alloy.
eutectic microstructure without primary \( \alpha \) phase may be obtained at low unidirectional solidification rate in hypoeutectic alloy as shown in Figs. 1(a), 2, and 3(a).

However, the increase in \( V \) causes the S/L interface morphology to be unstable and interface morphology will change from cell to dendrite type as shown Fig. 1(b) and (c). When S/L interface morphologies are cell or dendrite, solidification microstructure before melt quenching will be made up of eutectic (\( \alpha + \beta \)) and primary \( \alpha \) (Cu) phase.

It is the kind of interface morphology evolution that brought on a serial of multiplex unidirectional solidification microstructure change in Cu–1.0 wt%Cr alloy. Solidification microstructures of Cu–1.0 wt%Cr alloy under different solidification rates also were shown in Fig. 3.

When the S/L interface morphology changes from plane to cell type, the \( \alpha \) (Cu) primary phase will appear inevitably. At the same time when the growth velocity is kept at a lower level and constitutional supercooling region at the front edge of interface is very narrow, the secondary dendrites are not able to appear on the salient of interface. Therefore, the primary \( \alpha \) (Cu) phase will grow up as cell style. The cell-grain microstructures of primary \( \alpha \) (Cu) phase are shown in Fig. 3(b). The increase of solidification rate causes the secondary dendrite arm to appear on branch salient edge of cell grains and then to come into

![Fig. 3. Microstructures of directionally solidified Cu–1.0 wt%Cr alloy at different solidification rates (\( G_l = 200 \) K/cm).](image-url)
growing dendrite grains. In alloys which have a less quantity of solution and a narrow temperature range, the morphology of cellular dendrite look like that there are many length and thick second dendrite arms on trunks of cell, as shown on Fig. 3(c) and (d). With increasing the solidification rate continuously, the constitutional supercooling degree near S/L interface will increase so that the morphological changes from cell to dendrite type appears. At the same time, cellular dendrite grain will evolve to columnar dendrite grain with high divarication as shown on Fig. 3(e). When solidification rate come to the critical rate of cell/dendrite transition, dendrite morphology or primary (Cu) phase becomes fine gradually with the increase of solidification rate and the decrease of local solidification time as shown from Fig. 3(f)–(j). All things accord with completely classical theory model of dendrite growth [9]:

\[ \lambda = b t_f^n = b(G_L V)^n \]  \hfill (1)

\[ VR^2 = \text{const.} \]  \hfill (2)

where \( V \) is velocity rate; \( \lambda \) is dendrite arm spacing; \( R \) is curvature radius of dendrite top; \( t_f \) is local solidification time; \( n \) is a power with negative value.

3.2. Effect of solidification rates on cell/dendrite arm spacing

3.2.1. Primary dendrite arm spacing of cell or dendrite

Primary dendrite arm spacings of cell or dendrite are measured in the present paper. The relationship between primary dendrite arm spacing \( \lambda_1 \) and solidification rate are shown on Fig. 4.

At present, there are Jackson–Hunt [10], BH [11] and Trivedi models [12]. It is very different that \( \lambda_1 \) value calculated separately by these models. But, there are still some common

![Fig. 3 (continued)](image)

![Fig. 4. The relation between the primary arm spacing \( \lambda_1 \) and solidification rate \( G_L V \).](image)
features: (1) there exist a maximum value in the primary dendrite arm spacing \( l_1 \) versus solidification rate \( G_L V \) curve. This is a result of cell/coarse-dendrite transition. (2) When solidification rate is enough high, \( l_1 \) must obey to the following equation: 
\[
\lambda_1 = \beta(G_L V)^{-0.25}
\]

where the correlation coefficient \( R \) is 0.99, and the standard deviation is 3%. It is shown that the result accords with Jackson–Hunt model. During coarse dendrite/fine dendrite transition, constitutional supercooling becomes more and more obvious with the increase of solidification rate. At the same time, the second dendrite or the third dendrite will grow up so that the primary dendrite spacing \( l_1 \) decreases and becomes fine any more.

3.2.2. Second dendrite arm spacing
Kattamis–Flemings had analyzed approximately the second dendrite arm spacing [13]. According to their results, the second dendrite arm spacing \( l_2 \) may be described as 
\[
l_2 = \beta(G_L V)^{-1/3}
\]

which \( \lambda_2 = AG_L^{-1/2}V^{-1/4} \). An example is shown in Fig. 5.

An experimental equation is obtained by fitting the data by the method of least squares:
\[
l_1 = -0.0052 + 0.061G_L^{-1/2}V^{-1/4}
\]

where the correlation coefficient \( R \) is 0.99, and the standard deviation is 3%. It is shown that the result accords with Jackson–Hunt model. During coarse dendrite/fine dendrite transition, constitutional supercooling becomes more and more obvious with the increase of solidification rate. At the same time, the second dendrite or the third dendrite will grow up so that the primary dendrite spacing \( l_1 \) decreases and becomes fine any more.

3.3. Effect of solidification rate on volume fraction of eutectic

The unidirectional solidification microstructures of hypo-eutectic Cu–1.0 wt%Cr alloy consist of primary \( \alpha(Cu) \) phase and eutectic \( (\alpha + \beta) \). A more quantity of eutectic \( (\alpha + \beta) \) is hoped because they may reinforce the alloy. Generally, morphology changes and volume fraction of eutectic \( (\alpha + \beta) \) must decrease with the increase of solidification rate (as shown on Fig. 8). In fact, the volume fraction of eutectic \( (\alpha + \beta) \) is laid on component at top of dendrite of primary \( \alpha \) and minimum supercooling degree for eutectic solidification [14]. With the increase of solidification rate, constitutional supercooling degree will increase the solute enrichment at top of dendrite so that transverse diffusion of solute atoms is limited and elevate component concentration at top of dendrite of primary \( \alpha \) phase [8].

According as Cu–Cr phase diagram, a equation can be gotten for volume fraction of eutectic \( f_E \) [15]:

\[
\lambda_2 = -0.0003 + 0.0027(G_L V)^{-1/3}
\]
where $f_a$ is volume fraction of primary $\alpha$ phase. This equation means that $f_E$ will decrease with the increase of solidification rate since the $C_i$ would increase as described above. The experimental data of the relation between volume fraction of eutectics and solidification rate is shown in Fig. 8.

In addition, as Jackson/Hunt theory, the relation between the minimum supercooling degree $\Delta T_E$ and solidification rate $V$ is as follows [8]:

$$\Delta T_E = AV^{1/2}$$

(6)

So minimum supercooling degree $\Delta T_E$ will increase with increasing the solidification rate. It will cause that eutectic grown just appear under a further low temperature and it will lead to decrease volume fraction of eutectic but more amount of primary $\alpha$ phase will appear due to eutectic line move toward down.

4. Conclusions

Under a fixed temperature gradient $G_L=200$ K/cm, the unidirectional solidification was carried out for the microstructural study of hypoeutectic Cu–1.0 wt%Cr alloy. The results obtained are as follows:

1. Eutectic ($\alpha + \beta$) and primary $\alpha$(Cu) phase grew up equably in parallel to direction of solidification. A kind of fibrous microstructure will appear when unidirectional solidification rate is up to some enough high certain values. At least when temperature gradient was changeless, the interface morphology evolution of the primary $\alpha$(Cu) phase has been changed from plane to cell, coarse dendrite and fine dendrite grains with the increase of solidification rates.

2. First dendrite arm spacing $\lambda_1$ of $\alpha$(Cu) phase increases with the increase of solidification rate during cellular grown and decreases with increasing the solidification rate during dendrite grown. Its rule might accord with Jackson–Hunt theory model. An experience equation obtained is as follow:

$$\lambda_1 = -0.0052 + 0.061G_L^{1/2}V^{-1/4}$$

3. Second dendrite spacing $\lambda_2$ of primary $\alpha$(Cu) phase will thin gradually with the increase of solidification rate. Moreover, the secondary dendrite will become coarse in further solidification. The relationship among dendrite arm spacing, temperature gradient and solidification rate is that: $\lambda_2 = -0.0003 + 0.0027(G_LV)^{-1/3}$. It meets with Kattamis–Flemings model.

4. Volume fraction of eutectic will decrease with the increase of solidification rate.

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