

Study on the *in situ* composites microstructure of the directionally solidified hypoeutectic Cu–Cr alloys

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Because the *in situ* composite microstructures come into being “automatically” during the solidification process, avoiding interfacial defects in the traditional synthetic composites, they possess important application value on structural materials, especially on functional materials [1, 2]. Cu–Cr *in situ* composites are a kind of Cu-based functional materials, which utilize the compound structures to strengthen tensile properties, and possess high conductivity [3–5]. In this letter, Cu–Cr *in situ* composites were prepared by the method of directional solidification, and the focus is placed on the evolution of solid/liquid (S/L) interfacial morphology, eutectic morphology, and the directionally solidified structural characteristics of hypoeutectic Cu–0.74wt%Cr alloy.

The Cu–0.74wt%Cr alloy used in this study was smelted from the Cu–25%Cr mid-alloy and electrolytic Cu (99.94% purity) in a MBD-3M middle-frequency vacuum induction furnace of 25 kg capacity by using a high-purity graphite crucible. The original rods ($\phi 8$ mm \times 100 mm) were made by investment casting.

Specimen rods of the Cu–Cr *in situ* composite were prepared on the self-made equipment [6]. The temperature gradient ahead of the S/L interface in this experiment is about 200 K/cm by measure. During the experiment, the specimen rods were first heated to 1250 °C, which were preserved for 30 min, then were immersed into the cooling liquid at constant rates of 20, 60, and 100 μ m/s respectively, and finally quenched quickly into the cooling liquid after being immersed to about 40 mm.

The specimens were incised along the axial line, then polished, eroded and finally observed and photographed by optical microscopy and scanning electron microscope (SEM). The aim was to review the varying rule of microstructure.

The evolution of S/L interfacial morphology is shown in Fig. 1. It can be seen from Fig. 1 that the morphol-

ogy of S/L interface undergoes the change from planar to cellular to dendritic in turn as the solidification rates increase. The control of S/L interface is important during directional solidification. Solidification theory points [7] that only when interfacial morphology takes on planar or cellular, regularly eutectic can be obtained; planar or cellular morphology changing to dendritic induces the whole eutectic to split to dendritic and lose the direction. Stability criterion of planar is as follows [8]:

$$G_L/R \geq m_L C_S^* (1 - K_0) / D_L K_0 = m_L (C_E - C_0) / D_L \quad (1)$$

where, G_L is temperature gradient; R is solidification rate; m_L is relevant liquidus slope; C_S^* is equilibrium composition of solid phase in the solidification interface; K_0 is the equilibrium distribution coefficient; C_0 is initial solute composition; C_E is eutectic composition; D_L is diffused coefficient of the solute in the liquid phase. Crystal solidifies as planar when G_L/R is greater than the critical value. When G_L/R is lower than the critical value, crystal solidifies gently as cellular and dendritic with the decrease of G_L/R .

It can be known, based on the equilibrium phase diagram of binary Cu–Cr alloy (see Fig. 2) [9], that the eutectic of Cu–Cr alloy is ($\alpha + \beta$), where α is the content of 0.65%Cr and β is taken as Cr phase (because of the solubility of Cu in β phase being very small). The eutectic point of binary Cu–Cr alloy deflects mostly to the Cu-rich corner. When the eutectic point deflects mostly to one component, the divorced eutectic is easy to come into being [10]. Fig. 3 shows the morphology of the divorced eutectic of Cu–0.74%Cr *in situ* composite. The growth of primary α and eutectic ($\alpha + \beta$) is a reciprocally competitive and selective process during directional solidification of Cu–0.74%Cr alloy. Because the growth undercooling of primary α and eutectic ($\alpha + \beta$)

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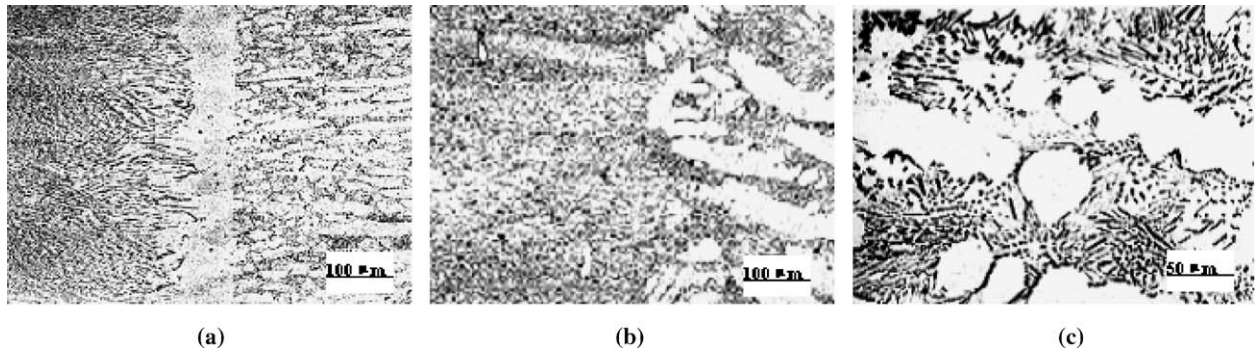


Figure 1 Solid/liquid (S/L) interfacial morphology for different solidification rates: (a) $R = 20 \mu\text{m/s}$, planar (b) $R = 60 \mu\text{m/s}$, cellular, and (c) $R = 100 \mu\text{m/s}$, dendritic.

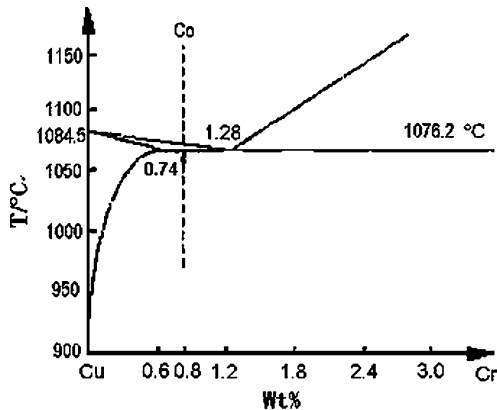


Figure 2 Equilibrium phase diagram of binary Cu-Cr alloy (Cu-rich corner).

are different, the crystal with a smaller undercooling will grow preferably. For Cu-0.74%Cr alloy, when the temperature gradient is certain, the growth undercooling of eutectic ($\alpha + \beta$) is greater than that of primary

α , and so the growth of eutectic is restricted to a certain extent. Therefore, when liquid is cooled to the eutectic temperature and the component turns into eutectic component, the growth of eutectic just begins. In this case, the crystal nucleus of the α phase in eutectic does not form directly from the remainder liquid, but basing on the primary α , because this way needs smaller undercooling and the diffusion of atoms in liquid becomes easier. When the solute of the remainder liquid is enriched to a certain degree, β phase separates out. From the point of view of crystallography, the volume fraction of β phase is less than 33%, so rod-like structure is easy to form, and the exposure relation between rod-like eutectic and matrix is not so strict as the exposure relation between patch-like eutectic and matrix, so the divorced eutectic morphology of Cu-0.74%Cr alloy shows that β phase distributes as rod-like structure on the α matrix phase.

The evolution of the divorced eutectic morphology is shown in Fig. 4. From the Fig. 4, the rod-like eutectic

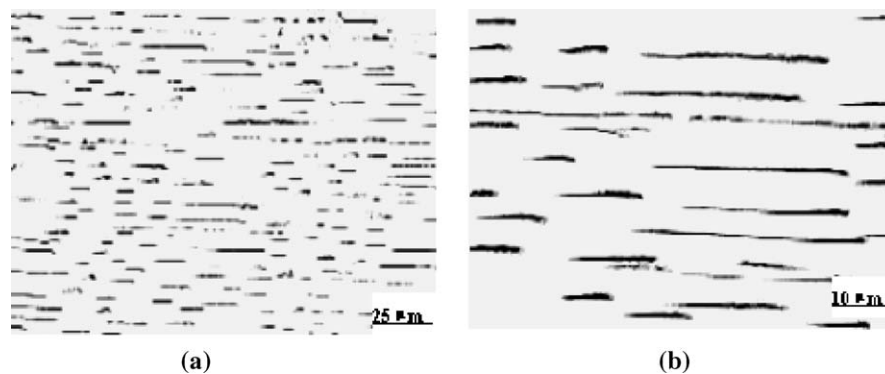


Figure 3 Divorced eutectic of the directionally solidified Cu-0.74%Cr alloys.

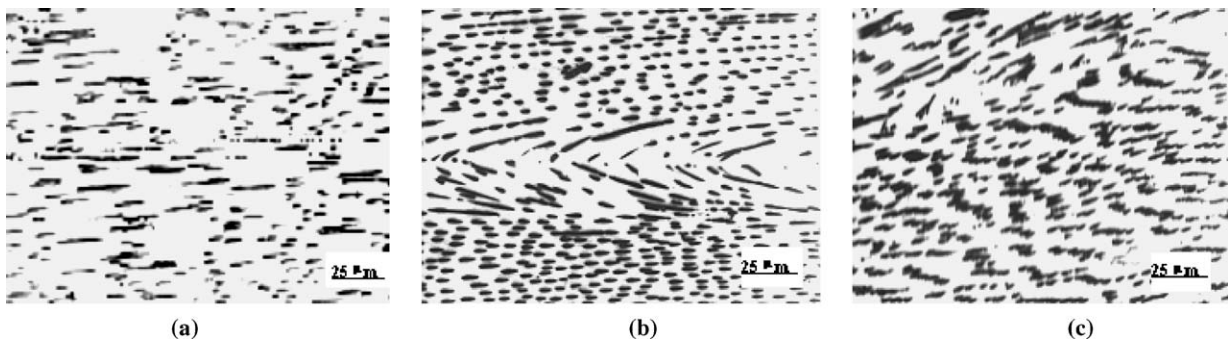


Figure 4 Divorced eutectic morphology for different solidification rates: (a) $R = 20 \mu\text{m/s}$, (b) $R = 60 \mu\text{m/s}$ and (c) $R = 100 \mu\text{m/s}$.

is regular at 20 $\mu\text{m/s}$ (see Fig. 4a); cellular eutectic appears at 60 $\mu\text{m/s}$ (see Fig. 4b); and when solidification rate is 100 $\mu\text{m/s}$, eutectic changes to an aggregative structure (see Fig. 4c). This can be known that, based on the Equation 1. S/L interface is planar at the solidification rate of 20 $\mu\text{m/s}$ so that eutectic grows regularly as rod-like and ranges directionally on a higher degree (see Fig. 4a). With the increase of solidification rates, a partial β phase ranges irregularly at 60 $\mu\text{m/s}$ and cellular eutectic comes forth (see Fig. 4b). When the solidification rate is 100 $\mu\text{m/s}$, S/L interface becomes unstable, and in the definite distance, interface develops a group of onward protuberant points instead of planar or cellular, so that eutectic of aggregative structure forms. As a result, the whole structure loses regularization and becomes disheveled (see Fig. 4c).

In our research, it was found that the rod-like divorced eutectic ($\alpha + \beta$) appears in the microstructures of the directionally solidified Cu–0.74wt%Cr *in situ* composites. With the increase of solidification rates, the morphology of S/L interface undergoes change from planar to cellular to dendritic in turn, and the morphology of the divorced eutectic undergoes the change from regular to cellular to aggregative structure in turn.

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