



Effect of Dy on the microstructures of directionally solidified NiAl–Cr(Mo) hypereutectic alloy at different withdrawal rates



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ABSTRACT

The effect of various Dy content on the microstructure of Ni–31Al–32Cr–6Mo hypereutectic alloy was studied at the withdrawal rates of 6, 30 and 90 $\mu\text{m/s}$. The results show that the solid–liquid interface morphology has an evolutionary process of planar \rightarrow cellular \rightarrow dendritic interface with the increasing withdrawal rate. The primary Cr(Mo) dendrites are gradually weeded out through competitive growth between the primary phase and the eutectic phase. The volume fraction of primary Cr(Mo) dendrites decreases with the modest addition of Dy (0.05 wt.%) at 6 $\mu\text{m/s}$. When the withdrawal rate increases to 30 $\mu\text{m/s}$, the appropriate addition of Dy (0.1 wt.%) refines the microstructure, such as the width of intercellular zone and the lamellar thickness in the intercellular zone. With the increase of withdrawal rate to 90 $\mu\text{m/s}$, the addition of Dy has no significant effect on the microstructure. In addition, the white Dy-containing phase can occur in the boundary of eutectic cells when the Dy content is no less than 0.1 wt.%.

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1. Introduction

Intermetallic compound NiAl has some excellent properties, including a high melting temperature, good thermal conductivity, excellent oxidation resistance and relatively low density, which make it an attractive candidate to replace nickel-based superalloys in the turbine blade applications. However, NiAl alloy possesses a few inherent defects, such as the low ductility and fracture toughness at room temperature and the inadequate strength and creep resistance at elevated temperature [1–3].

The second-phase strengthening or alloying is considered to be an efficient way to improve the fracture toughness and the elevated temperature strength. For the second-phase strengthening, researchers paid more attention to NiAl-based eutectic systems, such as NiAl–Cr [4,5], NiAl–Mo [6–8], NiAl–Cr(Mo) [9–14], NiAl–V [15,16], NiAl–Ta [17], NiAl–Nb [18] and NiAl–W [19]. Among the eutectic systems, NiAl–(34 – x)Cr–xMo eutectic systems take on better room temperature fracture toughness and elevated temperature strength. However, higher elevated temperature strength is still necessary for advanced aircraft engine applications. Alloying

appears to be beneficial to further increase the strength. Previous studies demonstrated that the element Hf can obviously improve the elevated temperature strength of NiAl–Cr(Mo) eutectic systems by the solid solution strengthening and precipitation strengthening [20–24]. Unfortunately, the distribution of Heusler phase Ni₂AlHf along the NiAl/Cr(Mo) interface reduces the interface bonding strength, thus it results in the decrease of the ductility and fracture toughness at room temperature. Considering that the rare earth (RE) elements can increase the interface bonding strength by purifying the interface, researchers added the RE elements to the NiAl/Cr(Mo)–Hf eutectic alloy and the results showed that the appropriate addition of RE elements is beneficial to the improvement of room temperature properties (Ho [25–28], Dy [29–33], Ce [34], Y [34], Nd [34], Gd [35] and Sc [36]). Nevertheless, the fracture toughness is still unimproved.

Johnson et al. [37] and Misra et al. [38] thought that the refractory Cr(Mo) phase can increase the fracture toughness and elevated temperature strength. Previous studies mostly focused on NiAl–(34 – x)Cr–xMo eutectic system. However, little work is carried out in the NiAl–Cr(Mo) hypereutectic system. If the fully eutectic structure can be obtained in the hypereutectic system, the volume fraction of strengthening phase (Cr(Mo) phase) will be greatly increased. Only Shang et al. [39,40] investigated the microstructural evolution of directionally solidified NiAl–Cr(Mo) hypereutectic alloy and found that the volume fraction of lamellar

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Cr(Mo) phase increases obviously compared to the eutectic alloy. Moreover, the surface active RE elements may significantly influence the microstructure and properties of NiAl–Cr(Mo) hypereutectic alloy. Gao et al. [29] and Sheng et al. [30–32] found that the appropriate addition of RE element Dy refines the solidification structure and enhance the compressive strength and ductility by the arc melting or rapid solidification. Nevertheless, the effect of RE element Dy on the microstructure of NiAl–Cr(Mo) alloy by the other solidification way (e.g. direction solidification) is rarely studied. For the arc melting or rapid solidification, solidification structures are equiaxed eutectic cells, and the directions of eutectic lamellas are chaotic. However, for the standard Bridgeman method, the growth of eutectic lamellas is unidirectional, which may improve the properties of the alloy further. The aim of this paper is to experimentally investigate the effect of Dy on the microstructure of directionally solidified NiAl–Cr(Mo) hypereutectic alloy by the standard Bridgeman method.

2. Experiments

The materials used for this investigation were Ni–31Al–32Cr–6Mo (at.%)– x Dy ($x = 0, 0.05, 0.1, 0.2, 0.4$ wt.%) alloys. Button ingots for directional solidification were prepared by the vacuum non-consumable arc melting furnace. Each alloy button was turned over and remelted 5 times to ensure the homogeneity. The $\varnothing 4$ mm rods were cut from the homogenized buttons by electro-discharge machining (EDM). The rod was put in a high purity alumina crucible which was 4 mm in inner diameter and 100 mm in length for directional solidification in Bridgeman apparatus with induction heating. The temperature gradient at the solid–liquid interface was about 250 K/cm. The samples were pulled down at the withdrawal rates of 6, 30 and 90 $\mu\text{m/s}$. The pulling length of directional solidification sample was 40 mm. At the end of the experiment, the crucible was quickly dropped into the liquid Ga–In–Sn alloy to quench the solid–liquid interface.

The directionally solidified samples were cut along the longitudinal and transverse directions, and the location of the cross sections was 5 mm below the solid–liquid interface. The sections were mechanically polished and then etched with a solution of 80% HCl + 20% HNO₃ by volume. The microstructures were observed by optical microscope (OM) and scanning electron microscopy (SEM). The compositions of the constituent phases were identified by electrical probe microanalyzer (EPMA-1720, accelerate voltage = 15.0 kV). The eutectic interlamellar spacing and the width of intercellular zone were measured by SISCIAVS8.0 metallurgical analysis software.

3. Results and discussion

3.1. The evolution of directional solidification structure of Ni–31Al–32Cr–6Mo hypereutectic alloy at different withdrawal rates

Fig. 1(a–c) shows the solid–liquid interface morphology at the withdrawal rates of 6, 30 and 90 $\mu\text{m/s}$, respectively. The result shows that the interface morphology has an evolutionary process of planar \rightarrow cellular \rightarrow dendritic interface with the increasing withdrawal rates. This should be attributed to different constitutional undercooling. According to the constitutional undercooling theory, the interface is unstable when $G/V < \Delta T/D$, where G , V , ΔT and D are the temperature gradient in the liquid, the growth rate, the interval of the crystallization temperature and the diffusion coefficient of solute in the liquid, respectively. The value of G/V decreases with the increasing growth rate, thus the interface becomes unstable and the interface morphology can change from planar to cellular, even dendritic.

Fig. 2(a–d) illustrates the microstructures of as-cast zone, initial zone, transition zone and steady-state zone of directionally solidified Ni–31Al–32Cr–6Mo hypereutectic alloy at 6 $\mu\text{m/s}$, respectively. The microstructure of as-cast alloy is the primary dendrite + equiaxed eutectic cells, as shown in Fig. 2(a). The

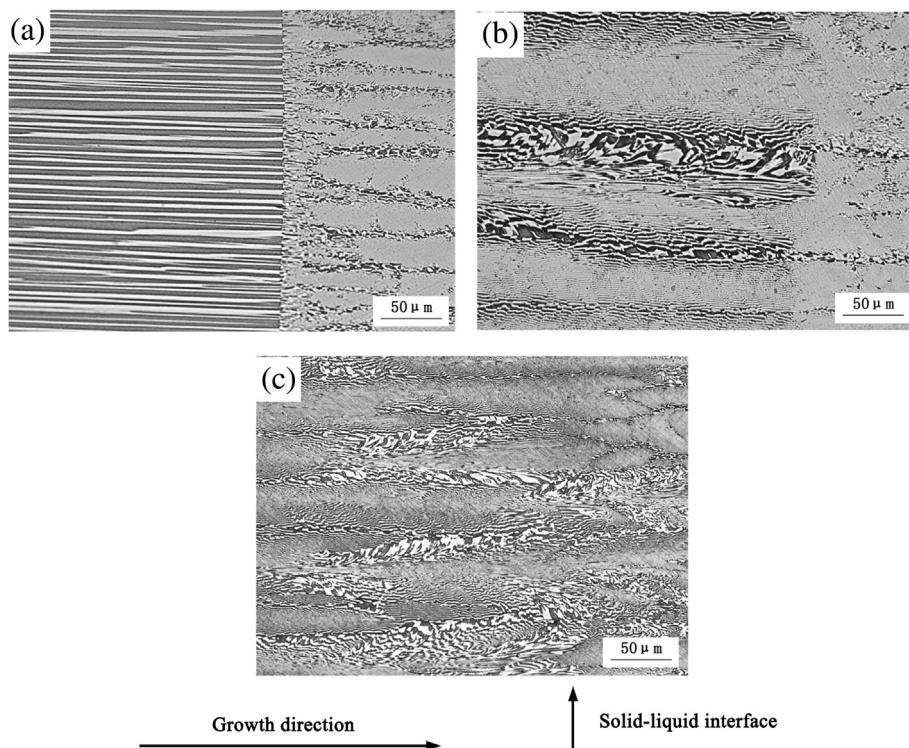


Fig. 1. Solid–liquid interface of directionally solidified NiAl–32Cr–6Mo hypereutectic alloy at 6 (a), 30 (b) and 90 $\mu\text{m/s}$ (c).

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