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Temperature distribution in bottomless electromagnetic cold crucible applied to directional solidification

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ABSTRACT

The novel technique of cold crucible directional solidification (CCDS) has been applied to prepare reactive and refractory metals and alloys with low or even no contamination. Microstructure formation is significantly influenced by heat transfer and temperature distribution in CCDS. The heating process and temperature distribution in two square cold crucibles designed for directional solidification were studied in this paper. A temperature-measuring device with anti-electromagnetic interference was devised to measure the temperature of Ti–46Al–6Nb (at.%), steel and aluminium (Al) ingots. A finite element (FE) model validated by experiment was used to calculate the temperature field in different materials. The results showed that the heating efficiency of cold crucible can be obviously improved by optimizing configuration. The temperature rise in heating process of all materials presents a slow tendency due to the heat loss. Compared with steel and Al, Ti–46Al–6Nb alloy exhibits the highest steady temperature even when the lowest power is applied, which is mainly attributed to the low heat conductivity. A Ti–46Al–6Nb ingot with the section of 30 mm × 30 mm was successfully directionally solidified under the power of 45 kW.

1. Introduction

Cold crucible directional solidification (CCDS) is a novel technique for melting and continuous casting of reactive or refractory materials with the advantages of low contamination and controlled microstructure [1,2]. TiAl base intermetallics have been successfully directionally solidified by CCDS, which exhibits promising application prospect in the next generation gas turbine engine [3,4].

Results reveal that in directional solidification (DS) the heat transfer significantly influences microstructure formation [5,6]. Therefore, heat transfer in CCDS plays an important role on the ingot formation, that is, high temperature gradient along vertical direction and efficient induction heating are preferred. Ti–6Al–4V and Ti–50Al alloys were prepared using a bottomless cylindrical crucible and the temperature distribution was investigated [1,7,8]. A square cold crucible was used to directionally solidify Ti–47Al–2Cr–2Nb alloy and Ti–46Al–0.5 W–0.5Si alloy [9,10]. Studies revealed that the heat transfer is a key parameter which influences the solidification interface and microstructure. Afterwards, Yang established physical models to investigate the heat transfer behavior in a mathematical way, indicating that the axial-to-radial heat flux density ratio (K) can be used to characterize the heat flux direction and temperature gradient (G_L) [11].

The heat transfer in cold crucible directional solidification is complex due to the influence of multi-physical fields. Also, the direct temperature measurement of Ti containing melt by thermocouples is really difficult because that molten Ti is high-chemically reactive. Up to now, there are two unsolved problems that related to heat transfer in CCDS: (1) The influence of material attribution on the heat transfer in CCDS; (2) The continuous improvement of heating efficiency of cold crucible used for directional solidification. In the current paper three different materials (Ti–46Al–6Nb, steel and aluminium) were induction-heated in two square cold crucibles. Meanwhile, a finite element (FE) model was established to calculate temperature fields for different materials. Based on that, the heating process and temperature distribution in CCDS process were studied and Ti–46Al–6Nb alloy was directionally solidified.

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2. Experimental procedure and numerical model

2.1. Principle of CCDS

The principle of CCDS is presented in Fig. 1, which was described in detail in [1]. An electromagnetic (EM) field is generated by an induction coil and the charge is induction-heated in a bottomless cold crucible. The upper raw material is continuously fed and the fresh solidified ingot is pulled into the Ga–In liquid alloy. Ga–In liquid metal is used to chill the ingot and get axial temperature gradient that is necessary for directional solidification.

2.2. Temperature measurement

Compared with cylindrical type, the cold crucible with square section possesses improved material utilization for a solidified ingot. As shown in Fig. 2(a), the dimension of crucible A is 26 mm × 26 mm × 100 mm ($S_{\text{in}} \times S_{\text{in}} \times H$), and it was employed to directionally solidify Ti–47Al–2Cr–2Nb alloy [9]. The columnar grain growth were studied and revealed that the microstructure formation is highly related to G_L. It was found that the EM field would enhance with the increase of power and the decrease of frequency [12]. The uniformity of magnetic field in cold crucible was investigated, which is helpful to the optimization design of cold crucible [13]. Based on that, an optimized crucible (crucible B) with the section of 30 mm × 30 mm was designed and fabricated for directionally solidifying high Nb-containing TiAl alloys, as shown in Fig. 2(b).

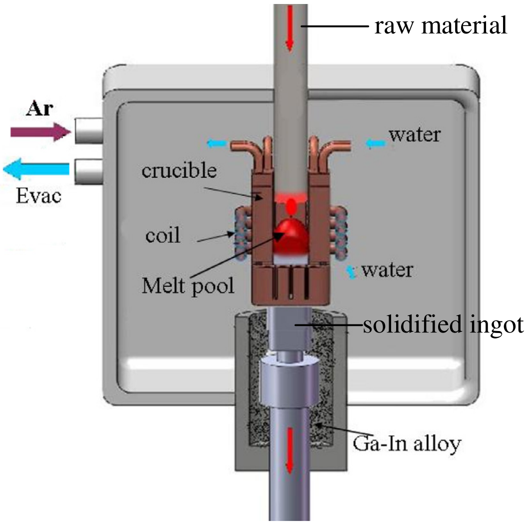

Fig. 1. The schematic of continuous melting and directional solidification in a cold crucible.

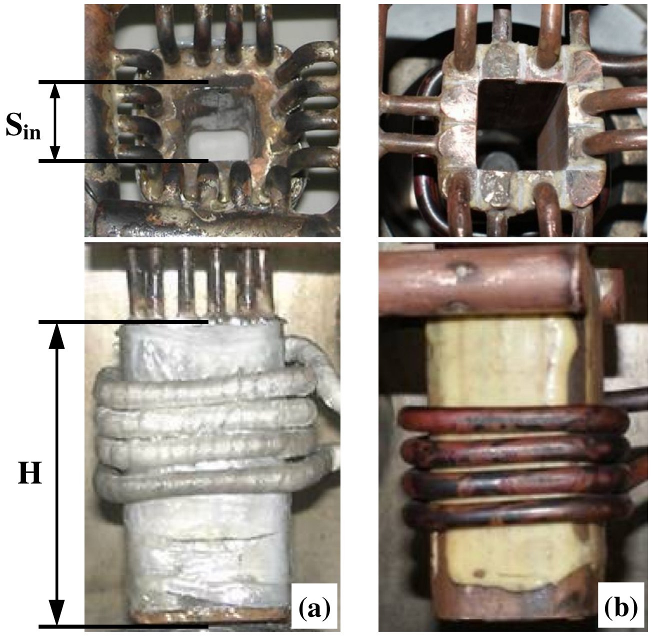

Fig. 2. Two square cold crucibles with different section sizes (S_{in}): (a) crucible A and (b) crucible B.

The CCDS system and the temperature measurement device are illustrated in Fig. 3. The induction coil can supply with the power of 0 ~ 100 kW and the frequency of 50 kHz. The liquid Ga–In alloy used to cool the ingot is within the bottom container. The K-type thermocouples (the red line in Fig. 3) were embedded into these holes in ingot with a vertical interval (d) of 8 mm. The K-type thermocouples were wrapped with a metal wire to shield EM interference. All the data signals were collected and converted by a temperature data-logging device with 16 channels. The power parameters performed in the experiments are listed in Table 1.

2.3. Heat transfer equations

The heat transfer in a three-dimension charge can be described by the Fourier equation:

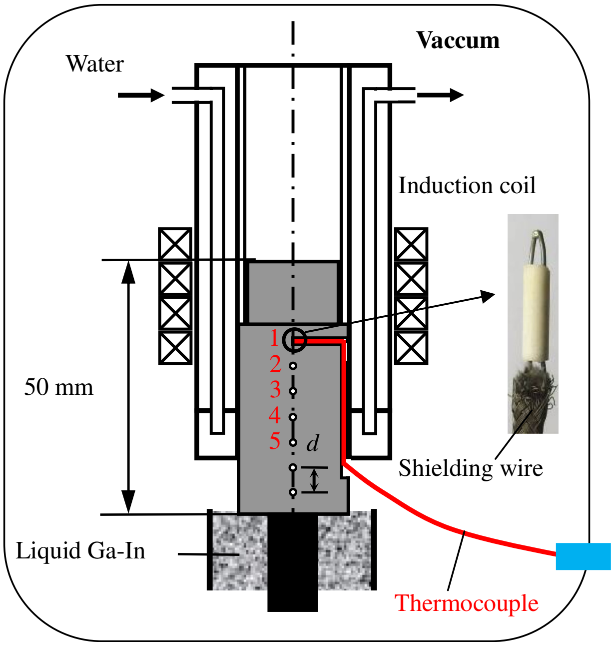

Fig. 3. Temperature measurement system for cold crucible directional solidification. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Input power for different materials in crucibles A and B.

Materials	Crucible	Input power (kW)		
Steel	A	4.40	6.24	8.40
	B	3.90	5.34	7.56
Aluminium	A	4.80	6.84	9.24
	B	4.60	6.48	8.68
TiAlNb	B	3.04	4.60	6.60