International Journal of Heat and Mass Transfer 122 (2018) 1128–1137

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Numerical analysis for electromagnetic field influence on heat transfer behaviors in cold crucible used for directional solidification

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ARTICLE INFO

Article history:
Received 17 October 2017
Received in revised form 6 January 2018
Accepted 16 February 2018

Keywords:
Cold crucible
Induction heating
Electromagnetic pressure
Convective heat transfer
Directional solidification
Solid-liquid interface

ABSTRACT

Cold crucible directional solidification (CCDS) is the technique that the materials in the segmented water-cooled crucible are induction heated and heat transfer controlled by electromagnetic field for directional solidifying crystals without contamination. In order to control crystal growth by the CCDS efficiently, mathematical analysis of heat transfer during the CCDS process is presented by means of a combined electromagnetic, fluid and thermal model. A 3-D model is established and verified to investigate the characteristics of heat transfer in the melt, which considers the coupled effects of the shaped melt and the electromagnetically driven flow on the temperature field and the shape of solid–liquid (S/L) interface. The shaped melt by electromagnetic pressure along with the induction heat in the skin layer reduce and compensate the radial heat loss, which could decrease the radial temperature gradient in the melt with increasing input powers. A vigorous three-dimensional melt flow consisting of meridional flow and azimuthal flow is induced in the melt, which improves the uniformity of the temperature field and decreases the deflection of S/L interface in the center of melt. The solidification front changes from 'W' shape to planar when the power reaches 39 kW. Based on the above results and analysis, TiAl alloys are successfully directionally solidified by the CCDS method with planar S/L interface, and the growth direction of columnar crystals are nearly paralleled.

1. Introduction

Electromagnetic field is widely used for induction heating, melting and heat/mass transfer controlling during metallurgy and solidification process [1–3]. The electromagnetic cold crucible based on employing electromagnetic field is applied to melt refractory and reactive materials due to its advantages in getting uniform ingots without contamination [4–6]. The schematic sketch of the electromagnetic cold crucible with a water-cooled segmented crucible and the induction coils are shown in Fig. 1(a). The slits applied to the water-cooled crucible are important for electromagnetic field transparency of the crucible wall. Meanwhile, the induction coils surrounding the segmented crucible induce eddy current in each segment, which also can generate an electromagnetic field inside the crucible [7].

In order to directional solidify the refractory and reactive materials without contaminations and size limitations, the cold crucible directional solidification (CCDS) technique combining cold crucible melting technique and the Bridgman directional solidification method was first proposed by our research group [8], the schematic sketch of the CCDS process is presented in Fig. 1(b). In the process of directional solidification, the heat and mass transfer are two most important aspects. In order to control the crystal growth effectively, the investigation of heat transfer behaviors during traditional directional solidification has been studied both theoretically and numerically in many published papers [9–12]. Mooney et al. [10] used a transient Bridgman Furnace Front Tracking Model to investigate the heat transfer conditions in the Bridgman furnace, and the obtained heat transfer coefficients were applied for experiments. Battaglioli et al. [11,12] numerically studied the heat transfer behaviors during Bridgman furnace solidification and its influence on the final grain structure. Moreover, the convection in the melt significantly influence the heat transfer during directional solidification and influence the melting and solidification process. Volz et al. [13] have proved that the S/L interface shape tend to be flattened by enhanced convective heat transfer during Bridgman growth. Dadzis et al. [14] numerically and experimentally investigated the directional solidification process with a TMF. It was found that the electromagnetically driven flow enhances the heat transfer and changes the local melting rate and consequently a deformation of phase interface.

During the process of CCDS, a downward temperature gradient in the melt is formed due to intensive cooling of the Ga-In liquid

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.02.067
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Nomenclature

$\vec{B}$	magnetic flux density vector (T)
$\vec{F}_{EM}$	Lorenz force vector (N m^{-3})
$\vec{F}_p$	electromagnetic pressure gradient (N m^{-3})
$\vec{F}_d$	rotational Lorenz force vector (N m^{-3})
q_{in}	Joule heat (J m^{-3})
T	temperature (K)
t	time (s)
Re	Reynolds number of fluid
L	characteristic length scale of fluid flow (m)
$\vec{v}$	velocity vector of melt (m s^{-1})
p	pressure (N m^{-2})
g	gravitational acceleration (m s^{-2})
R_1, R_2	curvature radii of meniscus (m^{-1})
F	phase volume fraction
c_p	specific heat of melt (J (kg K)$^{-1}$)

Greek symbols

υ	dynamical viscosity (kg m^{-1} s^{-1})
ρ	density of melt (kg m^{-3})
μ	permeability of melt (H m^{-1})
γ	surface tension coefficient (N m^{-1})
λ	thermal conductivity of melt (W m^{-1} K^{-1})

pool at bottom. Meanwhile, the contact of the melt and the crucible wall takes away lots of induction heat and results in radial temperature gradient, which will lead to a curved solid/liquid (S/L) interface and decreased temperature in the melt [15,16]. The lower melt temperature disturbs the continuous growth of columnar crystal, and the curved S/L interface leads to inclined columnar crystal and thermal stresses [17,18]. The CCDS technique for directionally solidifying reactive and refractory materials has been proposed but no investigations are reported on the heat transfer behaviors in the melt considering the shaped melt and the electromagnetically driven flow. Therefore, the main purpose of our investigation is to study the heat transfer behaviors during CCDS process, which considers the coupled effects of the shaped melt and the electromagnetically driven flow on the temperature field and the S/L interface shape. The temperature field of TiAl charge was calculated by means of a combined electromagnetic, fluid and thermal model, and the melting of TiAl alloys were conducted under different coil powers and the interface shapes were analyzed. Finally, TiAl alloys were successfully directionally solidified with optimized induction heating process by CCDS method.

2. Experimental procedure and numerical model

2.1. Experimental procedure

The as-cast ingots with the nominal composition of Ti-44Al and Ti-48Al were prepared by the cold crucible melting technology and remelted for three times for homogenization. Then the ingot was cut into many smaller bars (Φ20 mm) as the primer and feeding rod. A square electromagnetic cold crucible with section size of 30 mm × 30 mm was used, the induction coil can supply with the power of 0–100 kW and the frequency of 30 kHz. The Ti-48Al

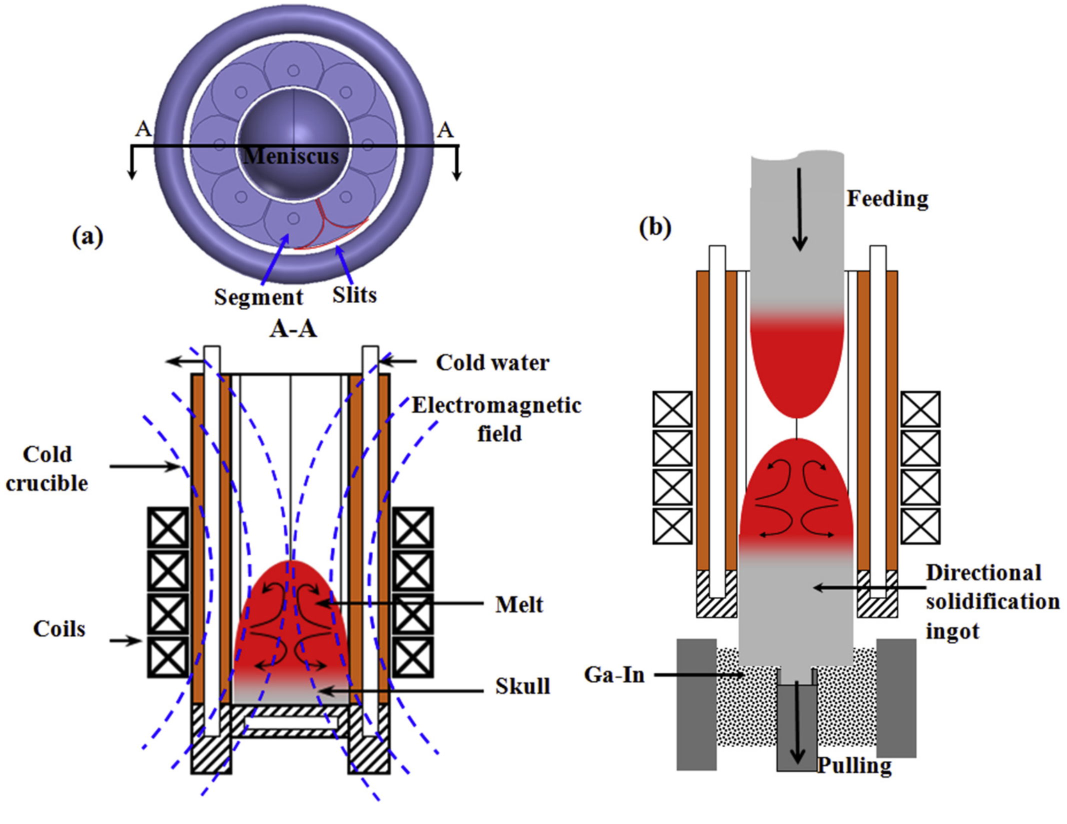

Fig. 1. The schematic sketch of two typical electromagnetic cold crucibles used for (a) melting and (b) directionally solidifying refractory and reactive materials.