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Effects of convection patterns on freckle formation of directionally solidified Nickel-based superalloy casting with abruptly varying cross-sections

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ABSTRACT

The effects of convection patterns on freckle formation of directionally solidified Nickel-based superalloy sample with abruptly varying cross-sections were investigated experimentally and numerically. The experimental results demonstrate that freckles were only observed at the bottom of larger cross-section. Numerical results indicate that this phenomenon should be attributed to the different convection patterns at front of solidification interface. As the withdrawal rate increased, the primary dendrites spacing has an obvious influence on freckle formation. A more in-depth investigation of the convection patterns can provide a better understanding of freckle formation and perhaps offer methods to minimize freckles in turbine blades.

1. Introduction

Directional solidification (DS) techniques enable the solidification structure of materials to be aligned in a specific direction. Specifically, directional or single crystal structures could be formed, which may improve the strength, thermal fatigue property and corrosion resistance of the materials [1–5]. With the development of directional solidification technology, more advanced techniques have been applied to manufacture the turbine blades, such as High Rate Solidification (HRS) method [6,7], Liquid Metal Cooling (LMC) method [8], Gas Cooling (GCC) method [9], etc. However, according to the studies of Copley et al. [10], Gu et al. [11] and Wang et al. [12], the DS technologies above mentioned could not completely eliminate the freckle defects caused by the thermosolutal convection. When the driving force for the fluid flow exceeds the viscous resistance force, that is, the density difference between the less dense solute in the mushy zone and the bulk liquid ahead of the dendritic tip can cause thermosolutal convection [13]. This convection can fragment and remelt the dendrite arms and finally leads to the freckle formation [14,15]. The freckles must be eliminated due to their severity negative influences on the high-temperature mechanical properties of the turbine blades [16]. Thus, a more in-depth investigation of the convection patterns can provide a better understanding of freckle formation, perhaps giving further methods to minimize freckle defects in directionally solidified blades of superalloys.

In recent decades, with the rapid development of numerical simulation method, it is possible to investigate the convection during alloy solidification. To date, a numbers of numerical studies have been conducted to understand the relationship between convection and solidification defect formation. Schneider et al. [17,18] investigated the thermosolutal convection and macrosegregation of Ti in the CMSX-2 superalloy during the process of solidification by Calphad software, the effects on the freckle formation of withdrawal rate and temperature gradient. Felicelli et al. [19,20] employed a full set of conservation equations to simulate the heat and mass transport during alloy solidification and found several qualitative features of freckle channels. Lee et al. [21,22] directly simulated the freckle formation in three dimensions with a microstructure level model by μMatIC software. While, the blade always has complex shapes in the industrial production, the prior studies did not consider the geometrical effect on freckle formation. Recently, Ma et al. [23,24] investigated some effects of geometry on freckle formation, such as the shadow effect, the edge effect and the step effect. However, the convection in the liquid was seldom concerned. Therefore, it is necessary to have an in-depth study on the effects of convection patterns in the liquid on the freckle formation in the directionally solidified Nickel-based

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superalloy sample with abruptly varying cross-sections. Besides, freckles often appear on the casting surface. Dong et al. [25–28] conducted an in-depth study on the formation mechanism of surface scale during directional solidification of Ni-Base superalloys. This work shows that oxide plays an important role in the formation of TiO_2, Cr_2O_3, and Al_2O_3 on the surface. The Al_2O_3 layer is stripped away from the metal surface and adhered to the mold. These findings can provide a better understanding of defect formation mechanism at the surface.

Due to the need for optimum aerodynamic performance and cooling efficiency, the turbine blades have complex shapes inevitably. In order to accurately explore the geometrical effect on the freckle formation in directionally solidified blades of superalloys. The geometric design of the sample units was based on the local feature of hollow blades. In this paper, a three-dimensional (3-D) numerical model that predicts thermal field, flow field and solidification interface is applied to investigate the evolution of convection patterns caused by abrupt cross-section change and to discuss the internal relevance between the convection pattern and the freckle formation. In addition, the effects of melt temperature and withdrawal rate on convection intensity are also presented.

2. Mathematical modeling and experimental procedure

2.1. Governing equations

In order to simplify the simulation, the following assumptions were made: (1) the temperature of cooling water keeps constant during the process of directional solidification; (2) the melt is incompressible Newton fluid; (3) the flow remains laminar in the liquid. Based on the above assumptions, the transport phenomena were governed by the continuity, Navier–Stokes, energy (Eqs. (1)–(3)).

$$\nabla \cdot \left(f_l \vec{u}\right) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(f_l \vec{u}\right) + \nabla \cdot (f_l \vec{u}\,\vec{u}) - \nabla \cdot \left[\frac{\mu}{\rho}\nabla\left(f_l \vec{u}\right)\right] = -\frac{f_l}{\rho}\nabla P + g(1 - \beta_T(T - T_{ref}) - \beta_C(C - C_{ref})) \tag{2}$$

$$\frac{\partial T}{\partial t} + \nabla \cdot (\vec{u}\,T) = \frac{\sigma}{\rho c_p}\nabla^2 T - \frac{L}{c_p}\frac{\partial f_l}{\partial t} + q_{rad} \tag{3}$$

where T is the temperature, $\vec{u}$ is the velocity in the liquid, c_p is the specific heat, P is the pressure, μ is the viscosity in the liquid, σ is the thermal conductivity, ρ is the density, L is the latent heat, f_l is the mass fraction of liquid phase, g is the acceleration due to gravity, β_T is the thermal expansion coefficient, β_C is the solute expansion coefficient.

A transport equation for Ni, Cr, Co, Mo, W, Al, Ta, Ti, etc is required. When a multicomponent liquid solidifies, solutes diffuse from the solid phase into the liquid phase. This effect is quantified by the segregation coefficient of solute k_i. In the present study Lever's rule for species segregation at the micro-scale is used. The Lever rule assumes infinite diffusion of the solute species in the solid. In the Lever rule, species transport Eq. (5) is solved for the mass fraction of species

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho \vec{u}\, Y_{i,liq}) = -\nabla \cdot \vec{J}_i \tag{4}$$

$$\vec{J}_i = -\rho\left[f_l D_{i,liq}\nabla Y_{i,liq} + (1 - f_l)D_{i,sol}\nabla Y_{i,sol}\right] \tag{5}$$

where $Y_{i,liq}$ is the species i mass fraction in the liquid phase and $Y_{i,sol}$ is the species i mass fraction in the solid phase. $D_{i,liq}$ is the diffusion coefficients of the liquid. $D_{i,sol}$ is the diffusion coefficients of the solid. The solid/liquid interface is not resolved explicitly. In the present approach the liquid–solid mushy zone is treated as a porous zone, where the solid and liquid species mass fractions are coupled with the segregation coefficients

$$Y_{i,sol} = k_i Y_{i,liq} \tag{6}$$

The temperature T' at the solid–liquid interface is calculated by

$$T' = \frac{T_{liquidus} - T_{melt}(1 - f_l)(1 - R)}{1 - T_{melt}(1 - f_l)(1 - R)} \tag{7}$$

With

$$R = \frac{T_{melt} - T_{liquidus}}{T_{melt} - T_{solidus}} \tag{8}$$

Density inversion can be given by:

$$\left(\frac{\Delta\rho}{\rho_0}\right) = \beta_T(T - T_{liquidus}) + \beta_C(C_l - C_0) \tag{9}$$

where C_0 is the initial concentration, $T_{liquidus}$ is the liquidus temperature, $T_{solidus}$ is the solidus temperature, ρ_0 is the initial density in the liquid.

Radiation in the Bridgman furnace was described by the discrete ordinates (DO) radiation method. The global model has shown notable advantages that the effect on radiative transfer was taken into account, since the direction and distance was changed between the heater and sample due to its downward movement, and this model for the whole Bridgman furnace was performed to obtain the real temperature distribution. The process of radiative heat transfer can be given by:

$$\nabla \cdot (I(\vec{r}, \vec{s})\,\vec{s}) + aI(\vec{r}, \vec{s}) = an^2 I_b \tag{10}$$

where I is the radiation intensity, a is the wall absorptivity, $\vec{r}$ is the position vector, $\vec{s}$ is the direction vector, I_b is the black body intensity, the radiant heat flux $\vec{q}_{rad}$ can be given by:

$$\vec{q}_{rad} = \sum_m \omega_m \cdot (\vec{\Omega}_m \cdot \vec{n}) I_m \tag{11}$$

The radiation intensity I can be solved by Eq. (10), in which the temperature and emissivity of different parts of the enclosure are shown in Table 1:

$$I = \frac{1 - \varepsilon}{\pi}\int_{s^{\rightarrow}\cdot j \cdot n^{\rightarrow}} I(\vec{r}, \vec{s})_j \vec{s}_j \cdot \vec{n}\,\pi d\Omega + \frac{\varepsilon\zeta T_w^4}{\pi} \tag{12}$$

where T_w is the ambient temperature, ε is the surface emissivity, ζ is the Stefan-Boltzmann constant, ω_m is the angular quadrature weight, $\vec{\Omega}_m$ is the discrete direction, $\vec{n}$ is the normal unit vector, I_m is the radiation intensity for the discrete direction.

Table 1
Temperature and emissivity used in the radiative heat transfer [10–12,14].

Parameters	Values
Temperature of heating zone	1773 K
Temperature of baffle zone	1603 K
Temperature of cooling zone	973 K
Temperature of cover zone	1603 K
Emissivity of heating zone	0.8
Emissivity of baffle zone	0.95
Emissivity of cooling zone	0.7
Emissivity of cover zone	0.95