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Research Paper

A shrinkage cavity model based on pressure distribution for Ti-6Al–4V vertical centrifugal castings

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ABSTRACT

Vertical centrifugal castings from Ti-6Al–4V alloy are investigated, with detailed analysis of evolution of isolated liquid volumes and shrinkage location in each isolated liquid volume, in order to predict the shrinkage cavities. Based on the minimum potential energy principle, the shrinkage distribution rule and boundary criterion used in the search algorithm for isolated liquid areas were formulated. The applied boundary criterion estimates the critical pressure, at which an isolated liquid volume can be fed by another one. In each isolated liquid volume, the shrinkage cavities would be distributed at the zero isostatic surface. Pressure values are critical for the proposed shrinkage cavities prediction model, the flowchart and solutions for which are discussed in detail. The proposed model feasibility was verified by a series of the U-type vertical centrifugal casting experiments and simulations on Ti-6Al–4V alloy.

1. Introduction

The vertical centrifugal casting, as a variant of mold filling method (Zhou et al., 2012), is commonly used for casting melts with poor liquidity, which is mainly attributed to the centrifugal force-induced enhancement of filling ability of melts. It is widely applied to casting of aerospace components (Ling et al., 2015) from titanium alloys, in particular, Ti-6Al–4 V, whose lack of liquidity is compensated by the advantages of low density, high-temperature resistance, high specific strength and corrosion resistance (Wang et al., 2015). However, in view of more complicated force and motion conditions of melts in the centrifugal machine, the shrinkage cavity distribution prediction for vertical centrifugal casting is much more complicated than that for the gravity casting case and necessitates the application of intricate numerical simulations (Vijayaram et al., 2006).

During the casting solidification process, some areas of molten metal surrounded by solidified metal, which are referred to as "isolated liquid volumes", usually appear. The latter being isolated from each other cannot feed each other, while their annihilation results in generation of shrinkage cavities. Numerous criteria and models of shrinkage cavities have been proposed, in order to predict the isolated liquid volume locations and describe the shrinkage cavity formation and evolution. The shrinkage porosity distribution criterion of Niyama et al. (1982) was considered to be quite feasible, until Gao et al. (2011) revealed that it fails to predict the macroporosity of complex casting. Li and Cui (2002) advanced a new method for searching the isolated liquid volumes based on the constant threshold of metal feeding ratio. Zhou (2003) put forward the so-called "top liquid-level highest temperature method" (TLHTM), which assumed that all shrinkage cavities are formed at the "top isostatic liquid surface". Suzuki and Yao (2004) reported that the melt flow into mold cavities occurred without breaking the contact with the vertical inner walls of the cavity from the anti-rotation side, while the directional solidification took place by accumulating and shifting a solidified layer from the far end of the cavity to the gate, according to the centrifugal force gradient. Li et al. (2006a,b) subdivided the total filling process of vertical centrifugal castings into forward filling and back one, wherein the former is an accelerated process and the latter has a uniform velocity. Reis et al. (2008) proposed a pressure-based criterion, satisfaction of which implies creation of a free surface of the shrinkage area. Carlson and Beckermann (2009) have modified the Niyama criterion to the dimensionless form, using the Darcy equation for porous fluid flow and the metal feeding capacity assumptions. Zhang (2011) derived the equations for direct assessment of forces acting on the molten metal in the mold cavity in the vertical centrifugal machine. Jakumeit et al. (2012) proposed the Böttger-Laqua-Jakumeit (BLJ) criterion, which combined pressure estimation with a geometrical factor and provided the porosity prediction. Jia et al. (2012) reported that the share of macro- and microscopic casting defects decreases with the centrifugal force. Ravi (2012) and Sutaria et al. (2012) revealed that shrinkage

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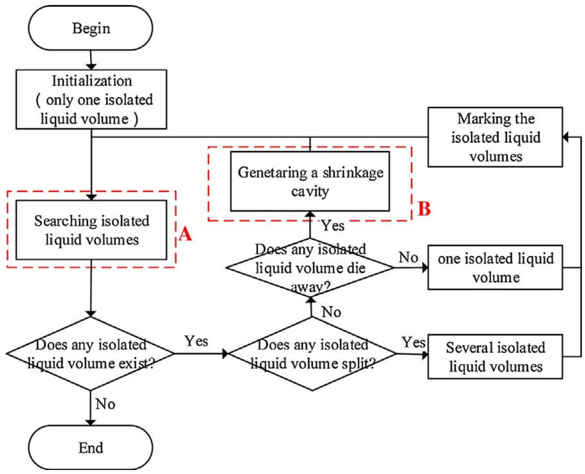

Fig. 1. Evolution of isolated liquid volumes in vertical centrifugal casting process.

cavities tend to appear at the intersection of feeding paths cross. Tavakoli (2014) summarized several thermal criteria functions, such as temperature gradient method and critical solid fraction ratio method that ignored the centrifugal force effect.

Researchers usually study the formation of the isolated liquid volume separately from shrinkage cavity distribution, although they are coupled and affected by the centrifugal force. This study presents a method for predicting the evolution of shrinkage cavities in vertical centrifugal casting with account of pressure effect on the formation of isolated liquid areas and shrinkage cavity distribution in each area.

2. Casting shrinkages prediction model

The evolution of isolated liquid areas in the vertical centrifugal casting process implies that the initial isolated liquid area is split into several smaller ones or disappear, generating a shrinkage cavity (Fig. 1).

The most attention is given to the two computation steps of the procedure, which are highlighted in Fig. 1 by boxes A and B, respectively. For the step corresponding to box A, the computer algorithms of Breadth First Search (BFS) and Depth First Search (DFS) are used for searching the isolated liquid volumes, which require an interpretable condition to determine whether the analyzed microcell belongs to a current isolated liquid volume or not. For box B, which is related to the process of a single isolated liquid volume disappearing and generating a shrinkage cavity, the core problem is to assess the location, size and shape of the shrinkage cavity at each time step. The proposed prediction model of shrinkage cavity evolution takes into account the two coupled key factors.

2.1. Force status

Vertical centrifugal casting process including pouring, filling, solidification, shrinkage formation was a very complex physical process. Zhang (2011) described the force status of Ti-6Al–4 V molten metal in the vertical centrifugal machine as a sum of three kinds of force, $\vec{f} = \vec{f}_{\text{Centrifugal}} + \vec{f}_{\text{Coriolis}} + \vec{f}_{Gravity}$, in the Descartes coordinate system with z axis coinciding with the rotation axis, as follows:

$$\begin{cases} \vec{f}_{\text{Centrifugal}} = \omega^2 \vec{r}_{\perp} \\ \vec{f}_{\text{Coriolis}} = 2\vec{v}_{Relative} \times \vec{\omega} \\ \vec{f}_{Gravity} = \vec{g} \end{cases} \tag{1}$$

where $\vec{r}_{\perp} = (x, y, 0)$ and $\vec{r}_{//} = (0, 0, z)$ are the components of rotation vector $\vec{r}$ that are normal and parallel to the rotation axis, respectively, $\vec{g} = (0,0, -g)$ is the vector of gravity acceleration that has a vertical downward direction and is parallel to the rotation axis direction, and $\vec{\omega} = (0,0, \omega)$ is the rotation angular velocity vector that is parallel to the rotation axis direction.

The fluid flow at the pouring, filling, and solidification stages can be described by the Navier-Stokes Eq. (2), which is complex enough when the pouring or filling process is unfinished.

$$\frac{D\vec{v}}{Dt} = \vec{f} - \frac{1}{\rho}\nabla P + \mu\nabla^2\vec{v} \tag{2}$$

The casting process can be subdivided into two stages: the mold-filling and melt-freezing ones. One can assume that no melts are frozen during a few seconds of the mold-filling stage, insofar as the pouring temperature of constantly replenishing melt is higher than that of the available melt. Moreover, metallurgists tend to apply somewhat higher pouring temperatures than those required by the casting technology, in order to avoid the incomplete mold-filling due to frozen alloy jamming the runner at the mold-filling stage.

When the mold-filling is completed, the fluid velocity drops down to a uniform value (Li et al., 2006b; Wen, 2006), so the melts would rotate along with the centrifugal machine.

In a uniform circular motion, $\vec{v}_{Relative} = 0$ as the molten metal is relatively static with coordinate system. Coriolis force could be ignored. It could see that only gravity and centrifugal forces act in the liquid area, when the pouring of metal in the mold is completed and the centrifugal machine has a uniform rotation angular velocity.

$$\vec{f} = \vec{f}_{\text{Centrifugal}} + \vec{f}_{Gravity} = \omega^2\vec{r}_{\perp} + \vec{g} \tag{3}$$

Applying the curl/rot operator to both parts of Eq. (3), we get

$$\text{rot}\left(\vec{f}\right) = \omega^2\nabla \times \vec{r}_{\perp} + \nabla \times \vec{g} = 0 \tag{4}$$

The force $\vec{F}$, defined everywhere in space (or within a simply-connected volume of space), is called a conservative force (Han, 1999) if the curl of $\vec{F}$ is a zero vector. According to formula (4), the unfrozen melts subjected to uniform circular motion in the centrifugal machine are considered to be located in the conservative force field. A conservative force must have a potential function U, where $\vec{f} = -\nabla U$.

Using the vector calculation formula (Xie, 2012) and $\vec{v} = \vec{\omega} \times \vec{r}_{\perp}$, some terms of Eq. (2) could be calculated.

$$\nabla\cdot\vec{v} = 0 \tag{5}$$

$$\nabla \times \vec{v} = 2\vec{\omega} \tag{6}$$

By taking the Euler material derivative $\frac{D\vec{V}}{Dt} = \frac{d}{dt}\vec{V} + (\vec{V}\cdot\nabla)\vec{V}$, we can get

$$\frac{d}{dt}\vec{v} = 0 \tag{7}$$

And

$$(\vec{v}\cdot\nabla)\vec{v} = \frac{1}{2}\nabla(\vec{v}\cdot\vec{v}) - \vec{v} \times (\nabla \times \vec{v}) = -\omega^2\vec{r}_{\perp} \tag{8}$$

So

$$\frac{D}{Dt}\vec{v} = -\omega^2\vec{r}_{\perp} = -\vec{f}_{\text{Centrifugal}} \tag{9}$$

Computation of the viscosity term in the Navier-Stokes equation yields

$$\nabla^2\vec{v} = \nabla(\nabla\cdot\vec{v}) - \nabla \times (\nabla \times \vec{v}) = 0 \tag{10}$$

Substitution of Eqs. (7) and (10) into Eq. (2) reduces it to the following form