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Research Paper

Numerical simulation of multilayered multiple metal cast rolls in compound casting process

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HIGHLIGHTS

- The model for a compound casting is established using ProCAST.
- The mold filling, solidification of melt and evolution of temperature field in each stage were investigated.
- The simulated temperature history of the Cr4 layer was compared with the measured CCT diagram of Cr4 material.
- The position of poor merging with the intermediate layer was ascertained to guide the improvement of the actual process.

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ABSTRACT

Compound casting consists of two techniques: horizontal centrifugal casting and gravity filling casting. In this study, a numerical model was developed for compound casting of multilayered multiple-metal cast rolls, and a 500-mm CR4 casting roll was simulated. In the simulation, the process of compound casting was divided into three stages and the development of filling flow, solidification of melt and evolution of temperature field in each stage was computed with the model. The model was then verified by comparison of (1) the simulation result with the measured temperature history on the surface of a 500-mm CR4 casting roll produced in a test process and (2) the simulated temperature history of the CR4 layer with the measured CCT (continuous cooling transformation) diagram of CR4 material. The simulation results in different stages of compound casting are also discussed for improving casting process design and defect preventing. The lower temperature at the location 15 mm away from both ends on the inner surface of the CR4 layer could cause poor merging with the intermediate layer.

1. Introduction

Multilayered multiple-metal cast rolls consist of outer layer, intermediate layer and core. The outer layer is required to have high wear ability and red hardness because these qualities have significant influence on the surface properties, dimensional precision and rolling productivity of the rolled steel products [1,2]. Compound casting (which combines horizontal centrifugal casting and gravity filling casting) is one of the most efficient techniques for producing multilayered multiple-metal cast rolls [3,4].

The process parameters in compound casting are very difficult to control, especially the time interval between each step and the temperature of the molten metal. Improper selection of parameters would lead to poor metallurgical melting and very high and inhomogeneous tensile residual stress field, causing cracking or fracture of the roll and mold [5–7]. In order to better understand this process, numerical methods were used to study the process of compound casting, since it is difficult to study with conventional methods [8]. Numerical simulation has been widely utilized to investigate the evolution of temperature field, solidification, segregation, and microstructure during casting [9–12]. The behaviors of fluid flow, thermal solidification and microstructure variation in centrifugal casting and gravity casting have been sufficiently investigated [13–17]. The behaviors of fluid flow, thermal solidification in centrifugal casting of rolls (which is one stage of the compound casting in this paper) have been sufficiently investigated by Song et al. [3,4,16], and Field and Ludwig [18] have discussed core filling process of rolls (which is one stage of the compound casting in this paper), but compound casting of cast rolls has not been simulated because there exists great difficulty when two kinds of completely different processes need to be considered in one simulation model. So

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the research of this paper takes a very important role in process parameter selection of compound casting.

CR4 cast rolls are also known as multilayered multiple-metal cast roll because they use CR4 steel (alloy structural steel with a nominal chromium content about 4.0 percent) as the outer layer and ductile cast iron as the intermediate layer and core. In this paper, a numerical model based on previous research [19] was developed for compound casting of CR4 cast roll using the ProCAST software, and verification experiments were also conducted. In the simulation, the process of compound casting was divided into three stages and the simulation results in each stage are discussed for improving casting process design and defect preventing.

2. Model description

The compound casting process of a 500 mm CR4 cast roll is illustrated in Fig. 1. Fig. 1a shows the technique of horizontal centrifugal casting, which is used to produce the outer layer and intermediate layer. Driven by the centrifugal force generated in a rotating cylindrical mold (rotating-mold) with the desired shape, molten metal is successively (CR4 for the outer layer and ductile cast iron for the intermediate layer) pressed on the wall of the rotating-mold. After the molten metal has been solidified, the rotating-mold is turned to the vertical position and assembled with the upper mold and lower mold, and then the core of the roll is formed using the technique of gravity filling casting, as shown in Fig. 1b. A multilayered multiple-metal cast roll is thus produced.

A numerical model was developed to simulate the actual compound casting process in three stages: (1) centrifugal casting of the outer layer, which includes outer layer filling and the 1st cooling and lasts for approximately 360 s; (2) centrifugal casting of the intermediate layer, which includes intermediate layer filling, the 2nd cooling and adjustment, and lasts approximately 920 s. In the adjustment step, the rotating mold is adjusted from the horizontal to the vertical position; (3) gravity filling casting of the core, which includes core filling and the 3rd cooling and lasts for about 38 hours.

2.1. Mathematical models

The development mold filling, solidification of melt and temperature field in each stage was simulated using the commercial FEM casting simulation software package ProCAST. Previous research showed that the melt flow in horizontal centrifugal casting can be factitiously divided into two parts, channel flow and centrifugal flow, but in this paper, channel flow was neglected. The following assumptions were made: (1) the incoming liquid metal is evenly distributed only at the inlet of the centrifugal flow stages; (2) the inlet is on the inside surface of outer layer and intermediate layer, with one component of inlet velocity parallel to the rotation axis and the other component vertical to the rotation axis; (3) the liquid metal is incompressible Newtonian fluid; (4) the solutal convection is ignored and (5) heat transfer is coupled with the melt flow during mold filling.

The natural convection of the liquid metal is described by the mass conservation equation and the Navier–Stokes equations as follows:

The mass conservation equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

Navier–Stokes equation:

$$\frac{\partial(\rho\Phi)}{\partial t}+\nabla\cdot\left(\rho\underline{\vec{V}}\Phi\right)=\nabla\cdot(\mu\nabla\underline{\Phi})+\underline{S_u}-\nabla P \tag{2}$$

where ρ is the density, Φ is the velocity component, t is the time, $\underline{\vec{V}}$ is the velocity vector, μ is the dynamic viscosity, $\underline{S_u}$ is the sources into the momentum, and P is the pressure.

For heat transfer behavior during steel solidification, the energy conservation equation is employed.

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\frac{\lambda}{\rho c}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+\dot{Q} \tag{3}$$

where u, v and w are velocity components; T is the temperature; λ is the thermal conductivity; ρ is the density; c is the specific heat; and $\dot{Q}$ is the internal power source. Details of the numerical model can be found in the user manual of ProCAST [20].

2.2. Boundary and initial conditions

2.2.1. Interface parameters

Fig. 2 shows the finite element mesh of the mold and casting roll. Since the mold filling of centrifugal casting is spiral, a quarter model cannot be used to reduce the operation time. The complete geometries of all parts were adopted, and the mesh was generated according to several mesh sizes. The mesh size of cooling mold is 80 mm, the others are 40 mm, but coating region was refined as 10 mm because of its relatively small thickness. The finite element mesh of the mold and casting roll consists of 290,549 nodes and 1,385,373 tetrahedral elements. Fig. 3 shows the geometry of the model and the position of two important interfaces. Combining Figs. 2 and 3, there are 13 geometry in the model, which are divided into four parts: the upper mold (including upper sand box and casting sand), rotating mold (including upper cup, upper cup sand, cooling mold, coating, lower cup sand and lower cup), lower mold

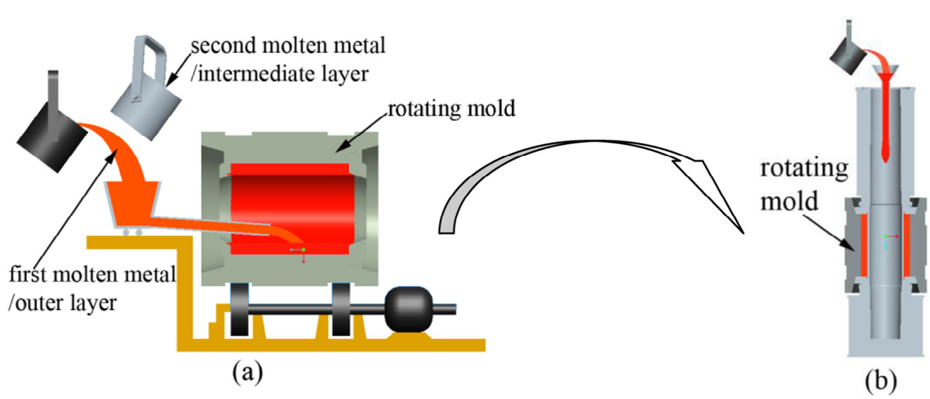

Fig. 1. Schematic diagram of compound casting. (a) Schematic diagram of horizontal centrifugal casting. (b) Schematic diagram of gravity casting.