Steel Ingot Mold's Tapper Designing and Validation Based on Solidification Simulation

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Abstract: A 15t steel ingot, in which shrinkage cavity and porosity were often found during production, was analyzed by solidification simulation using casting simulation software. Position and size of the shrinkage porosity were predicted, agreed with dissection result very well. On the basis of solidification simulation, a series of new steel ingot molds were designed and the molds with preferable simulation results were selected for manufacture, which performed well in production.

1. Introduction

Advanced equipment manufacturing such as military industry, nuclear power, heavy machinery and wind power has put forward higher requirements for the quality of steel ingot. Shrinkage cavity and porosity is still the major internal defect of specific ingots. With the construction of 360MN die forging press, computer-aided analysis is being integrated into traditional ingot mold structure design. In order to avoid shrinkage cavity and porosity, technological parameters such as shape and size of steel ingot mold and riser, and auxiliary processes like heating material have to be optimally designed [1-6].

Involving high temperature solidification, the ingot solidification process is a complex process which can hardly be directly observed and controlled in the manufacture of ingots. Based on the analysis of defect formation and distribution during ingot solidification, optimizing the ingot mold dimension and productive technology proves an important guarantee of ingot quality. The formation of ingot shrinkage cavity and porosity depends on the solidification sequence of molten steel in ingot mold, which is largely determined by taper and height-diameter ratio of ingot mold. In this paper, taking commonly used 15t ingot mold as research object, numerical simulation was employed to study the solidification of high alloy steel ingots (Cr-Ni-Mo system) in which shrinkage cavity and porosity was liable to from.

2. Mathematical Model

Ingot solidification was a complicated heat transfer process and following methods were adopted to establish the mathematical model of solidification process.

(1) The latent heat release in solidification process was treated with enthalpy method;

(2) The effect of fluid flow on heat transfer was treated with equivalent thermal conductivity method.

The three-dimensional transient mathematical model of steel ingot solidification and heat transfer was established as follows:
\[
\frac{\partial (\rho H)}{\partial t} = \lambda \nabla^2 T + q
\]  

Where, \( \rho \) was the density (kg·m\(^{-3}\)), \( \lambda \) was the thermal conductivity (W·m\(^{-1}\)·K\(^{-1}\)), \( t \) was the time (s), \( H \) was the enthalpy (J·kg\(^{-1}\)), \( T \) was the temperature (K), and \( q \) was the source term (including the heat lost by exothermic compound, W·kg\(^{-1}\)).

For ingot solidification with liquid-solid phase transition, the enthalpy in equation (1) could be expressed as:

\[
H = \int \tilde{c}_p C_p dT + (1 - f_s) L
\]  

Where, \( C_p \) was the specific heat capacity (J·kg\(^{-1}\)·K\(^{-1}\)), \( L \) was the latent heat of solidification (J·kg\(^{-1}\)), \( f_s \) was the solid fraction.

The initial temperature of molten steel was uniform, which was the casting temperature. The heat transfer on the symmetry axis and symmetry plane of the steel ingot was under adiabatic condition, and heat transfer on other boundaries was treated as follows:

\[
-\lambda \frac{\partial T}{\partial x} = h(T - T_\infty)
\]  

Where, \( h \) was the heat transfer coefficient on the boundaries (W·m\(^{-2}\)·K\(^{-1}\)). \( T \) and \( T_\infty \) were respectively the temperature of boundary element and environment. In consideration of the influence of air gap between ingot and ingot mold caused by solidification contraction on solidification heat transfer, the interface thermal resistance (1/\( h_\text{in} \)) between ingot and ingot mold was introduced into the heat transfer model. The heat flow calculating formula in the interface of ingot and ingot model was as follows:

\[
q = h_\text{in} (T_{\text{steel}} - T_{\text{mold}})
\]  

Physical property parameters of the material included density, thermal conductivity, specific heat capacity or enthalpy of ingot and ingot mold, temperature range of solidification solid-liquid phase transition, solidification latent heat and thermal expansion coefficient of steel, etc. Physical property parameters of the material varied with the temperature and effected the results of heat transfer analysis.

In this paper, taking the grade of steel H13 as an example, the liquidus and solidus temperature were respectively 1477°C and 1405°C obtained by the built-in material database of AnyCasting software. The ingot mold material was HT200 and the initial temperature was 70°C. In the procedure of casting, it was assumed that the mold was instantaneously filled with molten steel with the initial temperature of 1535°C. The risers were thermally insulated by hanging insulation board. The grid was divided into 200,000 units. The thermal conductivity of the riser insulation material was 0.15 W·m\(^{-1}\)·K\(^{-1}\) and the interfacial heat transfer coefficient between the riser insulation material and the steel ingot was 20 W·m\(^{-2}\)·K\(^{-1}\). The interfacial heat transfer coefficient between the ingot mold and ingot varied with the temperature, with the average value set as 1250 W·m\(^{-2}\)·K\(^{-1}\). The convective heat transfer coefficient between the outer surface of the ingot mold and air was 10 W·m\(^{-2}\)·K\(^{-1}\). With the heating efficiency of 8000kJ/kg and heating duration of 40min, 15g of exothermic compound was put in.

3. Structural Design and Simulation Results of Ingot Mold

For the original problem of serious secondary shrinkage in the solidification process of 15t steel ingot mold, two ingot molds with different parameters were newly designed to improve solidification quality and eliminate ingot defects.

Three design schemes, among which scheme1 was the original process, were demonstrated in Fig1 and Table1. The positions of design parameters in Table1 referred to Fig1.
The parts of the steel ingot mold were built with 3D drawing software Pro/E and then assembled. Files of the STL format, generated by each component of the assembly, were imported into the preprocessing module of the casting simulation software of AnyCasting to set up the initial conditions, boundary conditions and physical property parameters. Numerical simulations of filling process and solidification process were performed for three design schemes respectively with the temperature distribution obtained during solidification process demonstrated in Fig2. It could be seen in Fig2 that the solidification process trend of the molten steel was basically consistent in three design schemes, axially solidifying gradually from the bottom to the top of the ingot and radially solidifying gradually from the inner wall to the center of the ingot. Comparing the heat dissipation on axial direction and radial direction, it could be drawn that the heat dissipation of ingot solidification was mainly by the sidewall while dissipation by undersurface was weak, specifically expressed in the U-shaped distribution of temperature field isotherm at different time. According to the temperature field distribution at the very ending, it was apparent that the temperature distribution of scheme2 was reasonable, with the characteristics of bigger U-shaped opening, basically satisfying the principle of sequential solidification and final solidification site concentrated near the riser. Nevertheless, the solidification sequence of scheme1 (original mold) and scheme3 was not reasonable, embodied in smaller U-shaped opening, overlong high-temperature area and difficulty for liquid steel in the riser to feed the ingot effectively, causing the result that the final solidification area was involved in the ingot ontology and defects such as secondary shrinkage cavity and porosity were consequently apt to form in the ingot during solidification.

Meanwhile, it could be seen from Fig2 that the complete solidification time in three design schemes (especially the complete solidification time of the risers) varied largely. The complete solidification time of scheme1 and newly designed scheme3 were respectively 30181.2s and 26621.4s, while complete solidification time of newly designed scheme2 was significantly increased to 43555.7s. Therefore, the temperature field distribution of molten steel during solidification in ingot mold could be changed by optimizing the design of ingot mold (mainly taper design) to move the final solidification point to the ingot riser. Besides, the complete solidification time of the riser could be delayed by changing the taper design of ingot mold, largely increasing the riser feeding time during solidification, which was helpful in eliminating the ingot solidification defects.
The predictions of internal shrinkage cavity and porosity of the steel ingot under conditions of different design schemes were demonstrated in Fig3. Analyzing the temperature field and defect prediction of three design schemes, it could be discovered that: Shrinkage cavity in scheme2 was concentrated at the riser instead of distributing in the ingot ontology. While in scheme1 and scheme3, an isolated liquid region with relatively long high-temperature zone developed, where the liquid steel could not get fed effectively and large shrinkage cavity was prone to forming.

With analysis conducted by the analytical procedure of AnyCasting, prediction manifested that the defect was distributed in the central area of 220-900mm under the riser with a diameter of 180-200 roughly. In order to verify the reliability of simulation results, lateral dissection analysis was performed respectively on sites of 500mm and 700mm under the riser of the ingot manufactured in scheme1. At the same time, lateral dissection analysis was carried out on the riser line of the ingot manufactured in scheme2. Dissection surfaces were demonstrated in Fig4 and the actual dissection results were consistent with the simulation predictions.

In conclusion, scheme2 was the optimal design. Comparing the three schemes above, it was determined that the mold would be manufactured according to scheme2 and the steel ingot molded out with the newly designed mold eliminated shrinkage cavity and porosity defects in practical production (Fig4c).
4. Conclusion
(1) Taking advantage of numerical simulation of 15t ingot, important information in the ingot solidification process such as solidification time, location of shrinkage cavity and porosity, etc. are obtained. In addition, the rationality of ingot mold design is verified and period from mold design to optimization is shortened.

(2) Dissection analysis and shrinkage cavity and porosity observation are performed on both 15t steel ingots manufactured respectively according to original and new mold taper design schemes, finding high level of consistency between simulation results and actual test sections.

(3) Mold optimum design for ingots of specific steel grade and tonnage can be carried out with numerical simulation to ensure the quality of ingots.

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