Simulation Analysis of Exothermic Powder in Riser Area on Inner Quality of Steel Ingot

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Abstract. 15t steel ingots of different amount of exothermic powder were under computer simulation analysis by casting simulation software with the distribution of shrinkage cavity predicted. The results showed that, with increasing adding of exothermic powder, the final solidification high temperature area moves from the main body of the ingot onto the riser area, so that the riser can feed the shrinkage cavity very well. The simulation result agrees with validation experiments very well. It indicates that the optimized adding suitable amount of exothermic powder in riser area can effectively eliminate the shrinkage cavity, and enhance the steel ingots' quality and the ration of utilization.

1. Introduction

Advanced equipment manufacturing such as military industry, electricity power, heavy machinery and marine engineering has put higher requirements on the quality of steel ingot. Numerous production practice indicates that defects such as shrinkage cavity and porosity are still the main internal defects of specific steel ingot. 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 exthermic powders have to be optimized. Computer numerical simulation has provided essential technical means for the traditional ingot production optimization [1-5].

Shrinkage cavity and porosity defects are formed during the solidification process. The quality of steel ingots and subsequent products are severely affected by these defects. To reduce or avoid defects, insulating riser and exothermic powder are adopted in production to keep the molten steel liquid in riser for a longer time and form favorable feeding channels, so that the ingot body was adequately fed by molten steel during solidification. On the other hand, molten steel remaining liquid for longer time can contribute to the low-melting and low-density inclusions accumulation onto the riser with enough time and to be removed before solidification. In addition, liquid steel in ingot mold is maintained overheated by adding exothermic powder in the riser area, which can suppress the formation of "crystalline rain" on the upper surface of steel ingot at the initial stage of solidification. Thereby, the probability of inclusions being captured by 'crystalline rain' become less and then the volume of "deposit cone" on the bottom of ingot are reduced. And the internal quality of steel ingot being improved. In actual production, the shrinkage cavity frequently emerged in the ingot body due to improper addition of exothermic powder, resulting in quality degradation or even to be scrapped [6]. The riser has always been a concern for technologists in the ingot production and various methods have been proposed to increase the feeding rate of the riser, such as electrically heating riser, exothermic riser, insulating riser, etc. All these technical methods aiming at prolonging the solidification time of molten steel in riser area to ensure favorable feeding channel and sufficient feeding liquid for the ingot body during solidification. At
present, a trinitarian method of hanging insulating plates, adding exothermic powder and covering flux are generally employed to postpone the solidification time of molten steel in risers and obtain ingots of high quality, which is simple, convenient, low-costing and effective. In this paper, computer simulation analysis of solidification process of 12t steel ingots under three different heating conditions were performed to study the effect resulting from different amount of exothermic powder. Actually cast ingots were dissected to observe the distribution of shrinkage cavity and the accuracy of simulation results was verified by comparing with computer simulation results, and then accurate boundary conditions were determined, providing reliable scientific basis for further optimization of riser heating process and study on solidification characteristics.

2. Heating Mechanism of Exothermic Powder
The heating mechanism goes that, exothermic reaction of reactant and oxidant in exothermic powder keeps the molten steel in riser at a high temperature for a long time to achieve the purpose of riser insulation and final solidification. All kinds of exothermic powder are composed of oxidant, incendiary agent, aggregate additive, bonding substance, etc. Aluminum, ferrosilicon and organic matter with high colorific value are usually utilized as incendiary agent, while iron sheet and ore are adopted as oxidant in most cases. When the exothermic powder add into the riser, the effect of exothermic powder can be divided into three phases: ignition phase, exothermic phase and heat preservation phase. The exothermic phase is an exothermic chemical reaction with intense self-acceleration. According to the chemical composition of exothermic powder, the main exothermic reaction can be described as chemical equation (1), ie

$$2\text{Al} + \text{Fe}_2\text{O}_3 = 2\text{Fe} + \text{Al}_2\text{O}_3 + \Delta Q$$  (1)

Where, $\Delta Q$ is the heat generated by reaction. The physical process of exothermic powder in ignition phase and heat preservation phase is relatively simple, preventing heat loss mainly relying on the thermophysical properties of exothermic powder itself.

3. Process Simulation and Experiment of Steel Ingot

3.1 Entity Modeling
Parts of the ingot casting system were 3D modelled with Pro/E and assembled as Figure 1. STL files generated by each component of assembly were imported into the pre-processing module of AnyCasting (Casting Simulation Software) to complete pre-processing, solidification calculation and post-processing.

![Figure 1. The assembly diagram of steel ingot system](image)
3.2 Initial Conditions and Boundary Conditions
As H13 is prone to shrinkage cavity, high-alloy steel H13 of Cr-Ni-Mo system was chosen as the casting steel, and the casting tonnage was 12t. The liquidus temperature and solidus temperature of the material were respectively 1477°C and 1405°C which obtained by the built-in material database of AnyCasting. The material of ingot mold was HT200 and the preheating temperature was 70°C. It was assumed that the mold was instantaneously filled with molten steel with the initial temperature of 1545°C. The riser was insulated by the trinitarian method of hanging insulating board, adding exothermic powder and covering flux. Mesh was divided into 200,000. The thermal conductivity of riser insulating board was 0.15 W·m⁻¹·K⁻¹ and the interfacial heat transfer coefficient between insulating board and steel ingot was 20 W·m⁻²·K⁻¹. The interfacial heat transfer coefficient between ingot mold and ingot varied with temperature and the average value was set to 1250 W·m⁻²·K⁻¹. The convective heat transfer coefficient between the outer surface of ingot mold and air was 10 W·m⁻²·K⁻¹. The heating efficiency of exothermic powder was 8000kJ/kg. The highest temperature after ignition was 1350°C. The time from ignition to maximum temperature was 9min. The heating duration of exothermic powder was 40min\textsuperscript{[7-8]}.

4. Simulation Result
Exothermic powder of different amount was added into risers of 12t steel ingots: (1) no exothermic powder; (2) 6 kg (0.5kg/t) exothermic powder added; (3) 21 kg (1.75kg/t) exothermic powder added. Simulation analysis was carried out for each situation and solidification sequence (temperature distribution) at the completing of solidification was given in Figure 2.

It was observed from the temperature field distribution at the end of solidification of 12t steel ingots with three different amount of exothermic powder added in Figure 2, for steel ingots with the same tonnage, the final solidification time would be extended with the increasing of the exothermic powder mass. The complete solidification time of 12t steel ingots with no exothermic powder, 6 kg (0.5kg/t) exothermic powder and 21 kg (1.75kg/t) exothermic powder were 20685s, 21901s and 24680s, respectively. It showed that with the increase of the amount of exothermic powder, the ingot complete solidification time elongated, and the longer the molten steel in riser being liquid, the more effective the ingot body shrinkage cavity being replenished, which was beneficial to improve ingot quality\textsuperscript{[9]}. Meanwhile, it could be obtained from Figure 2 that, compared to the situation with no exothermic powder, the high temperature area moved onto a distance up to the riser with 6 kg (0.5kg/t) exothermic powder added, but the movement range was small and the high temperature area of molten pool was still mainly distributed in ingot body, indicating the insufficient amount of exothermic powder. With the amount of exothermic powder increasing to 21 kg (1.75kg/t), the high temperature area at the end of solidification had completely moved onto the riser, which manifesting that adding 21 kg (1.75kg/t) exothermic powder could effectively increase the riser temperature and extend the riser solidification time and benefiting the shrinkage cavity feeding and improving the internal quality of steel ingot.

![Figure 2. Temperature distribution in ingot with three schemes](image)

(a) Scheme 1 (b) Scheme 2 (c) Scheme 3
It could also be seen from Figure 2 that, the solidification tendency during solidification process of molten steel in three exothermic powder addition schemes was basically the same: axially advancing from the bottom to the top of the ingot, while radially advancing from the inner wall of the ingot mold to the ingot center. Comparing the heat dissipation axially and radially, the sidewall of the ingot was the main way of heat dissipation during ingot solidification while the heat dissipation through the ingot bottom was relatively weak, specifically expressed in the U-shaped distribution of temperature isotherm at different time. According to the temperature field distribution at the very ending, it was apparent that the temperature distribution of Scheme 3 was reasonable, with the characteristics of bigger U-shaped opening, perfectly satisfying the principle of sequential solidification and final solidification site concentrated in the riser. Nevertheless, the solidification sequence of Scheme 1 and Scheme 2 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. The formation of ingot shrinkage cavity and microcrack was affected by the shape of the ingot solidification front edge. If the molten pool was deep and narrow, the columnar crystals formed during solidification would overlap each other, hindering the shrinkage cavity feeding channel supplying molten steel to the void formed by solidification, resulting in defects such as porosity and shrinkage cavity in the ingot body. On the contrary, if the molten pool was shallow and the opening was wide, the shrinkage cavity feeding channel would be smooth, the void formed by solidification being sufficiently replenished and the internal quality of ingot being improved.

In conclusion, Scheme 3 was the optimal design for exothermic powder adding.

The predictions of steel ingot internal shrinkage cavity of three different exothermic powder adding schemes demonstrated in Figure 3.

![Figure 3. Predicted porosity in ingot with three schemes](image)

Analysing the prediction results of temperature field and defect of three schemes, it could be discovered that: Shrinkage cavity in Scheme 3 was concentrated at the riser instead of distributing in the ingot ontology. While in Scheme 1 and Scheme 2, 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 built-in analytical procedure of AnyCasting, simulation prediction results manifested that the defect in Scheme1 was distributed in the central area of 150-820mm under the riser with a diameter of 180-220 roughly, while shrinkage cavity defect was eliminated in ingot body.

5. Experimental Verification

In order to verify the validity of shrinkage cavity prediction in simulation, cross-sectional analysis (lateral dissection analysis) at 300mm and 600mm below the riser line was carried out respectively on
the steel ingot prepared according to Scheme 2, while the steel ingot prepared on the basis of Scheme 3 was subjected to cross-sectional analysis (lateral dissection analysis) right on the riser line. The profile analysis results were demonstrated in Figure 4.

![Figure 4. Photograph of the ingot across section with three hot top designed 1 (a) and (b), and design 3 (c)](image)

It could be found by comparative analysis that the cross-sectional results and simulation results were well matched.

![Figure 5. The schematic diagram for sampling position](image)

![Figure 6. The cutting results of Scheme 2 and 3](image)

In order to verify the accuracy of the simulation results, ingots cast in Scheme 2 and Scheme 3 were sampled and analyzed in the riser, with the sampling experiment results demonstrated in Figure 5.
It could be seen from the anatomical results of ingot riser that, the insufficient quantity of exothermic powder in Scheme 2 brought out poor riser insulation effect and low riser feeding efficiency, resulting in V-shaped riser shrinkage and deep shrinkage cavity. Compared with the simulation result in Figure 3(a), it was found that the shape of riser shrinkage cavity was well agreed with the shape of simulation result. The depth of primary shrinkage cavity in simulation result was measured as 132mm while the actual anatomical result was 136mm. It was manifested that the simulation results were in good agreement with the experimental results, indicating that the boundary conditions and thermophysical parameters adopted in simulation were reasonable and qualified for further simulation and process optimization of steel ingot solidification.

6. Conclusion
Computer simulation of the solidification process performed on 12t steel ingots indicated that the riser solidification time could be effectively increased by adding an appropriate amount of exothermic powder, enhancing the effect of solidification feeding.

Cross-sectional analysis was carried out on ingot risers with different amount of exothermic powder addition and the shrinkage shape and depth of riser adopting different exothermic powder conditions were measured. Good agreement between simulation results and experimental results manifested that the boundary conditions and thermophysical parameters adopted in simulation calculation were reasonable and qualified for the simulation calculation and process optimization of the solidification of different series of steel ingot.

Adoption of the optimized exothermic powder process could significantly improve the riser insulation effect and solidification feeding efficiency, thereby eliminating the defects of ingot body and increasing material utilization.

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