Intensive riser cooling of a turbine blade steel casting after solidification

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Abstract. To improve the production efficiency and reduce residual stress and deformation, a new method-Post Solidification Intensive Riser Cooling (PSIRC) was proposed for heavy steel castings. Risers are cooled by forced air from its top surface as the solidification of a casting finishes, so, the risers are turned into cooling passages during the cooling process of a casting with contrast to their function of feeding passages during the solidification process. This method was applied to a hydro turbine blade with 0.9 ton melt. Its cooling speed increased apparently meanwhile with improved temperature distribution uniformity and the hot spot was pushed almost to the casting bottom. The cooling efficiency was improved 40% before shakeout and its residual stress was reduced meanwhile.

1. Introduction

The cooling process of heavy steel castings in sand mold after solidification is usually very slow, maybe over a month or longer for some extra large castings weighing hundreds of tons, which undermines the production efficiency[1]. Furthermore, great thermal gradient appears across their thick sections and between the thick and thin areas, that may cause significant residual stress or deformation or even cracks[2]. In recent years there are more and more heavy castings and they get bigger and bigger, the heaviest one in China consumed 863.5 tons of liquid steel. Therefore, it is necessary to improve the cooling after the solidification of heavy castings. However, the research focus has been the solidification process for long time. For example, to realize sequential solidification of casting, the bottom or isolated hot spots are usually specially cooled by chills, water cooled copper plate or chills, cooling pipes buried in sand mold or core with compressed air [3] or water [4] or even liquid nitrogen [5] though the pipes. These methods only result into more faster cooling of special areas, but more uneven cooling of the whole casting. In production castings are shook by crane to break the wrapping of sand mold so as to facilitate the convection of castings with the atmosphere.
Sometimes water spray or forced wind is blown on the mold surface to extract more heat. Shakeout at high temperature is also a measure. These methods can fasten the cooling of the whole casting, but result into nonuniform temperature field. Rapid but uneven cooling of castings makes them susceptible to cracking, deformation and high residual stress [6], especially for some kind of materials such as martensitic stainless steel undergoing martensitic phase transformation at relatively low temperature. All of the above mentioned methods manage to promote the cooling of a casting from surface to center or from one end to the other end, which falls into a dilemma - high cooling speed, high thermal gradient and high residual stress or deformation. Inner chills can realize the cooling from inside, however; they are too small, which limits their cooling capability. Risers, the biggest hot spots, are conventionally considered as feeders during solidification of castings, no special attention has been paid to their slowest cooling feature after solidification which mainly leads to low production efficiency and uneven cooling. So as to solve this dilemma, the authors proposed a method post-solidification intensive cooling of risers (PSIRC) to realize rapid and uniform cooling of heavy steel castings. The application of this method into a hydro turbine blade casting was investigated in this paper.

2. Application of PSIRC into a hydro turbine blade casting

Hydro turbine blades are used for hydraulic turbines. A turbine blade with size 1460mm×1210mm×48mm, as shown in figure 1, was selected for the investigation of the effect of PSIRC. One riser was designed for its feeding. Two castings were cast in Harbin Electric Machinery Co., LTD, one was under normal cooling after solidification, the other was under PSIRC. The material is martensitic stainless steel ZG0Cr13Ni4Mo (Chinese standard, its composition is listed in Table 1). Resin bonded sand mold was adopted. Each casting required 0.9 ton melt. Pouring temperature was 1560°C.

| Table 1. The composition of ZG0Cr13Ni4Mo martensitic stainless steel (%) |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| C   | Si   | Mn   | P   | S   | Ni   | Cr   | Mo   | Cu   |
| 0.03 | 0.46 | 0.52-0.55 | 0.011 | 0.012-0.025 | 4.25 | 13.46-13.61 | 0.60-0.65 | 0.08-0.09 |

Figure 1. Hydro turbine blade
The functions of riser during solidification and PSIRC are compared in figure 2. During the solidification process, the riser serves as a feeding source with a feeding channel, the heat flows from the riser to the bottom of the blade. As its solidification finished, PSIRC is taken into application. Firstly, clean the riser top and then blow forced air onto the riser top surface to speed its cooling. As PSIRC is adopted, the riser serves as a cooling source, it draws heat out from the riser first, and then from the center of the casting. So the blade can realize fast and uniform cooling. In PSIRC, the cooling of riser reverses the feeding channel during solidification into a cooling channel.

![Figure 2. Schematic diagrams of functions of riser during solidification (a) and afterwards with PSIRC (b) for a turbine blade casting](image)

A close-loop PSIRC system was developed, as shown in figure 3. The measured temperature difference between the thinnest B2 and the thickest section B1 (the root of the riser) was sent back to control the operation of an electromagnetic valve to regulate the flow of cooling air on the riser top of the casting. Algorithm was programmed into the control board for the control of forced cooling.

![Figure 3. Close-loop PSIRC control system](image)
The onsite experiment is shown in figure 4. As the temperature of B1 dropped to 550°C, 18.3 hours after pouring, the insulation layer of the riser top was cleaned and PSIRC systems began to work with forced air speed 27.9m/s. The cooling speed of B1 was controlled 20°C/h by switching on and off air flow from the nozzle. The nozzle was tilted 100mm atop the riser, as shown in figure 5a. The air speed was measured by a wind gauge and the temperature of the riser top was measured by an infrared camera Flir T250. It can be seen from figure 5b that the forced air flow covered half of the riser top.

![Onsite experiment of the turbine blade](image)

**Figure 4.** Onsite experiment of the turbine blade

![Forced cooling of riser of the hydro turbine blade](image)

**Figure 5.** Forced cooling of riser of the hydro turbine blade

### 3. Results and analysis

#### 3.1 Temperature results

The cooling curves of B1 with the PSIRC method were compared with the tradition one. With the new method, it just took 30 hours to drop to 300°C, while it takes 54 hours for the traditional method. So, 24 hours were saved. The cooling efficiency increased 40%, as shown in figure 6.

The temperature difference of the thickest and thinnest locations of the blade is shown in figure 7. As the PSIRC applied, their temperature difference dropped faster, that means more uniform distribution of temperature and finally less stress and deformation. And after 30 hours, the temperature of B2 was higher than that of B1, i.e., heat transferred from B2 to B1.
To study the heat transfer during the casting process, thermocouples were embedded in the sand mold with different distances to the casting, and their cooling curves are shown in figure 8. At the beginning, the temperature of the sand mold dropped with the distance from the casting surface. However, after cooling of 23 hours, the temperatures of P2, P3 and P4 came to be higher than that of P1, P4 higher than P3, P3 higher than P2, P2 higher than P1. That means the thermal gradient at the inner side of the sand mold reversed its direction, pointing to the casting. It indirectly proved that the temperature of casting surface was higher than the core, heat transferred from the casting surface to its center.

The casting process of the blade was simulated by using ProCAST. The heat transfer coefficient at the riser top during PSIRC was taken as 200 W/m²K. The heat transfer results are shown in figure 9. The simulated results also proved the effect of the intensive riser cooling. At the beginning of casting process, the casting was suddenly cooled by the sand mold, so the heat flux was pointing to the mold across the casting/mold surface, as shown in figure 9a. As the procession of the cooling, heat transfer from casting to mold came to be very slow, the heat inside of the casting mainly flew from the center of riser to the bottom of the casting, only little heat flew from the riser center to its top sidewall, as...
shown in figure 9b. As PSIRC was adopted, the hot spot shifted from the riser center to the middle of the casting, so the heat flew from the hot spot toward the top surface of the riser, and some heat still flew to the bottom of the casting, as shown in figure 9c. The total heat released by the casting, $6.18 \times 10^5 \text{KJ}$, was absorbed by the mold just before the adoption of PSIRC. Thirty hours later after pouring, more heat, $1.57 \times 10^5 \text{KJ}$, was released by the casting, it totally escaped to the atmosphere from the riser surface at an average rate of $1.29 \times 10^4 \text{KJ/h}$. Even some heat in mold, $5.6 \times 10^4 \text{KJ}$, was absorbed by the casting and then released from the riser top surface.

The temperature difference between the central line and surface under PSIRC is compared to that without PSIRC, as shown in figure 10. Without PSIRC the temperature at the center was always higher than the surface. However, as PSIRC was adopted, the center’s temperature got lower than that at the surface, so, the blade was cooled inside-out. With PSIRC, the hot spot was gradually pushed from the center of the riser to almost the bottom of the casting, as shown in figure 11. Thus, the significant effect of PSIRC is proved by simulated results.
3.2 Effect of PSIRC on residual stress

The residual stress at B1 at as-cast status was measured by X-ray method. The residual stress was greatly reduced with PSIRC from 151.4 MPa to 26.3 MPa, which is of significance for the control of residual stress. The reason is the even cooling as PSIRC was applied.

The casting was finally passed though ultrasonic test. Meanwhile, the surface quality, mechanical property and microstructure all met the requirement. Therefore, the PSIRC method is possible and valuable for heavy steel casting production.

3.3 Intermittent intensive cooling

During the intensive cooling of the riser of the blade, there still existed significant thermal gradient along the cooling channel. Therefore, intermittent intensive cooling was designed for the hydro turbine blade casting, 300 minute cooling and 300 minute suspension alternatively, as shown in figure 12. The simulated cooling curves of the points on the center line is shown in Figure 13. It can be seen that the temperature difference gets smaller during the suspension of PSIRC, such as from 237°C to 85°C for the first cycle. Thus, intermittent intensive cooling of the riser can achieve much more uniform cooling.
temperature distribution which is helpful for the reduction of residual stress and deformation. The step of the intermittent intensive cooling can be reduced to achieve smaller thermal gradient.

![Figure 12. Intermittent cooling schedule of PSIRC](image1)

Figure 12. Intermittent cooling schedule of PSIRC

![Figure 13. Cooling curves of the points on section A-A during intermittent PSIRC](image2)

Figure 13. Cooling curves of the points on section A-A during intermittent PSIRC

4. Conclusions
1) Post solidification intensive riser cooling method (PSIRC) was proposed for heavy steel castings to realize fast and uniform cooling, in which risers were cooled by forced air after the solidification of a casting, turning risers into cooling passages during the cooling process of castings in contrast to feeding passages during the solidification process. It may improve production efficiency and reduce residual stress and deformation.

2) One day was saved for a hydro turbine blade casting of 0.9 ton melt before shakeout under PSIRC, its residual stress was greatly reduced. The hot spot was pushed almost to the casting bottom and at the middle height, inside out cooling was achieved. To further improve the effect of PSIRC, intermittent cooling can make more uniform cooling.

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