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Intensive riser cooling of castings after solidification

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ABSTRACT

A new method – post solidification intensive riser cooling (PSIRC) was proposed. Risers are cooled by forced air or water mist from its top surface as the solidification of a casting finishes, then 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 can realize inside-out, fast and even cooling of castings, which may improve the production efficiency and reduce residual stress and deformation. A forced air cooling system with close-loop control for PSIRC was designed and developed. The temperature difference between the typical thick and thin locations of a casting was fed back to control the cooling intensity. The PSIRC method was applied to the casting process of a stress frame specimen and a hydro turbine blade. The effect of PSIRC on the cooling of the castings was investigated. The cooling speed of these castings increased apparently with improved temperature distribution uniformity. One day was saved for the blade casting before shakeout. The PSIRC method improved the strength and hardness of the blade casting, and significantly reduced its residual stress 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 (Kang et al., 2008). 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 (Yu et al., 2010). Therefore, it is necessary to improve the cooling after the solidification of heavy castings.

Speeding up the cooling of castings has been often adopted in their solidification process. For example, chills are popularly used at the bottom of castings or the thick area where feeding is difficult. Vassilevsky and Shiriajev (1962) further increased the cooling of a casting by blowing compressed air to chills. Singh et al. (2011) used a movable water-cooled chill to improve the cooling by reducing the air gap forming between the casting and mold during the casting process. Cooling pipes were buried in sand mold and or core, compressed air (Zhao et al., 1997) or water (Zhao et al., 2000) or even liquid nitrogen (Ning et al., 2007) was then used as cooling media in the pipes to enhance the cooling of castings. For a unidirectional solidified or single crystal blade, a water cooled copper plate is used at its bottom or the grain selector. To further increase the cooling of blades, special liquid metal could be applied (Kermanpur et al., 2000). These methods increased the cooling rate of the casting at the end far away from feeding risers, on the other hand, the solidification of the top and the thick areas of the casting were postponed so as to realize sequential solidification and then good feeding to avoid shrinkage. Therefore, these methods only result into more faster cooling of special areas, but more uneven cooling of the whole casting.

Embedding cooling channels in the mold or core has been employed to speed up the post-solidification cooling of heavy castings as well. In production shaking the casting in the sand mold can facilitate the convection with the atmosphere. Water spray can be used on the mold surface to extract more heat. Shakeout at high temperature was also applied. These methods can improve the cooling of the whole casting, but uneven cooling still exists. Rapid but uneven cooling of castings makes them susceptible to cracking, deformation and high residual stress (Lee and Lee, 2005), especially for some kind of materials such as martensitic stainless steel undergoing martensitic phase transformation at relatively low temperature. Grassi et al. (2009) proposed ablation casting for aluminum alloys, in which the water soluble binder bonded mold was ablated (i.e., eroded) away by water after a shell formed. Thus, the solidification rate could be raised to levels normally unattainable and significantly enhanced properties can be achieved. However, the casting was cooled from one side to another side step by step, the residual stress may be significant. ASK company proposed the

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Ecoform method for blade castings, in which the sand mold contour was shaped according to the blade profile to realize uniform thickness of sand everywhere. Thus, the cooling of a blade was improved 75% (Müller, 2009). But this method is just suitable for castings with special shape like blade. 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, a new method to realize rapid and uniform cooling of heavy steel castings was proposed by the intensive cooling of the riser top after solidification of castings. This method was applied into a stress frame specimen and a hydro turbine blade casting and the effect was investigated.

2. Post solidification intensive riser cooling

Risers are necessary for castings to compensate the volume contraction of the melt during solidification, especially for steel castings. They behave as hot spots bring heat to the casting as shown in Fig. 1(a). For a steel casting, risers usually take around 30% or more of the total poured melt, and their moduli are higher than the hot spots in the casting, which means they own the thickest sections. While after the solidification of a casting, risers cool slowest, which greatly affects the production efficiency. If risers are fast cooled by water spray or forced air after solidification of the casting, inverse thermal gradient can be achieved $T_1 < T_2 < T_3$ and the heat transfer can be reversed, as shown in Fig. 1(b). The feeding channel may be converted to a heat extraction channel, the heat from the core of the casting or even the heat from the surface of the casting or some heat from sand can be extracted through this channel. It is a kind of inside out cooling of the casting. Therefore, the cooling time of the whole casting can be saved, meanwhile, more even cooling can be realized, which is helpful for the reduction of residual stress and deformation. This method is abbreviated as PSIRC.

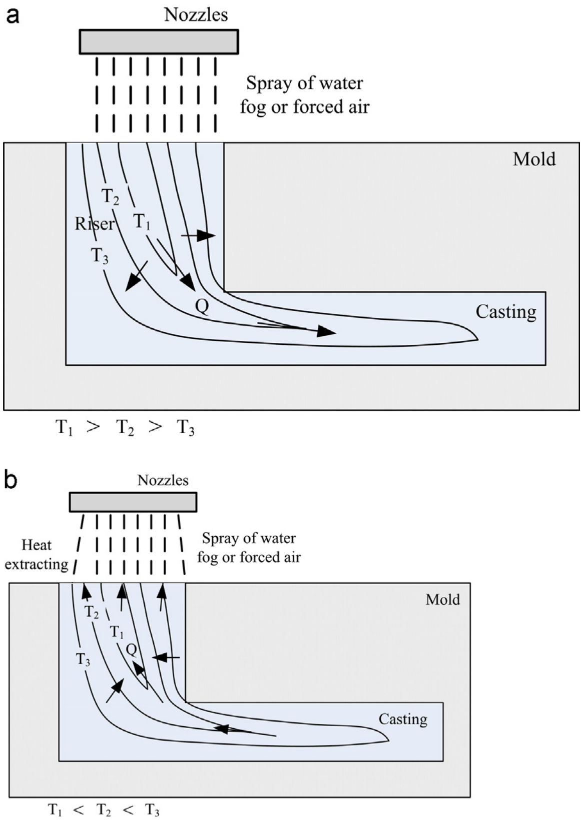

Fig. 1. Comparison of heat transfer during solidification and post solidification intensive riser cooling. (a) Hear transfers from the riser to surface and thin areas as riser feeds during solidification. (b) Hear transfers from thin areas and surface to the riser with post solidification intensive riser cooling.

The heat transfer coefficient between the riser top and atmosphere in PSIRC method is

$$h = h_c + \varepsilon\sigma(T_r + T_0)(T_r^2 + T_0^2) \tag{1}$$

where h is the combined heat transfer of forced convection and radiation of the riser top to the atmosphere, h_c is the forced air or water spray cooling heat transfer coefficient, ε is the emissivity, σ is the Boltzmann coefficient. T_r is the surface temperature of the riser, T_0 is room temperature.

The Biot number is a simple index of the ratio of the heat transfer capability inside and at the surface of a body. As the Biot number is less than 1, the heat transfer is mainly controlled by the surface heat transfer coefficient, i.e., it is possible to increase the cooling of a riser by increasing its top surface heat removal. Let the Biot number along the longitudinal direction of the riser be equal to 1:

$$Bi = \frac{hl}{\lambda} = 1 \tag{2}$$

where λ is the thermal conductivity, l is the effective length from the riser surface to the hot spot core.

Then the effective length is obtained as

$$l = \frac{\lambda}{h} \tag{3}$$

For typical steels as the Biot number = 1 the relationship between the effective cooling length and the riser top heat transfer coefficient is plotted in Fig. 2. It can be seen from Fig. 2 that the intensive cooling of the riser top is significant for carbon steel. Although it is less effective for high alloy steels, such as stainless steels, the effective length can still reach 1.1 m and 0.2 m as the interface heat transfer coefficient reaches 15 W/m^2 K and 80 W/m^2 K, respectively. Therefore, the intensive cooling method can be used for heavy carbon steel castings with feeding path of several meters long and stainless steel castings with that of 1 m

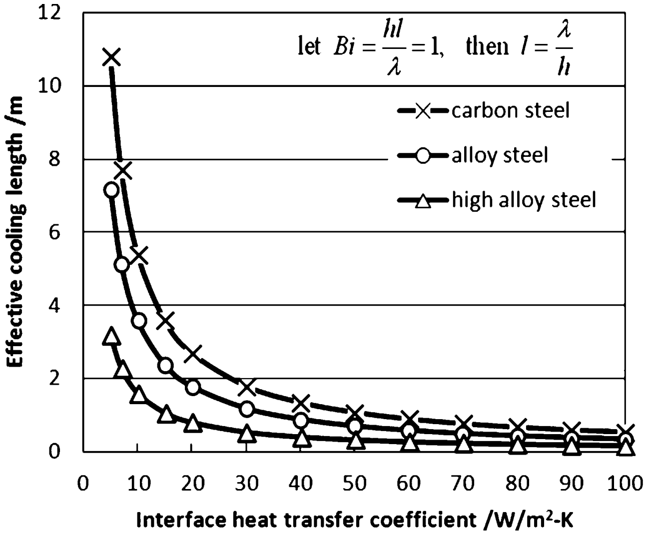

Fig. 2. Relationship between the effective cooling length and the riser top heat transfer coefficient with Biot number = 1.