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Effects of riser temperature field on shrinkage defects in investment-cast centrifugal wheels

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Abstract: In investment casting process, the temperature of the riser plays a critical role in solidification behavior and shrinkage feeding capacity. Riser temperature inevitably declines owing to multiple processes prior to pouring and heat exchange with the surrounding environment during casting. The centrifugal impeller, a key component of aerospace engines, was studied. A temperature field control method for the riser during casting was proposed, based on a quantitative analysis of pre-pouring temperature variations and their influence on shrinkage defects. By wrapping the riser with insulation cotton and applying riser insulation agent, the pre-pouring temperature loss of the riser is reduced by 76 °C and the solidification time is significantly extended. As a result, the number of shrinkage defects in the casting is reduced from 12 to 2, representing an 83.33% reduction, while the defect volume decreases from 2.55 cm^3 to 0.31 cm^3, an 87.84% reduction. This method effectively enhances casting quality by minimizing shrinkage defects caused by disturbances in the riser temperature field. It provides a practical solution for temperature field control in investment casting, offering significant technical support for improving production efficiency and product quality.

Keywords: investment casting; riser temperature; temperature field control methods

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1 Introduction

Controlling the temperature field during the casting process is essential for optimizing process parameters and enhancing casting quality[1-6]. By precisely controlling the pouring temperature, shell preheating temperature, and the heat exchange between the mold and the casting, the molten metal can flow uniformly within the mold. This prevents defects such as porosity, cold shut, and shrinkage, which are often caused by excessively high or low temperatures. Effective control of the temperature field promotes balanced solidification, optimizes the metal crystallization process, and improves the mechanical properties of the casting[7-12].

In investment casting, the riser primarily serves to compensate for the shrinkage voids created by volume contraction during metal solidification, thereby preventing shrinkage defects in the casting[13]. Concurrently, the riser contributes to optimizing the solidification sequence, thermal management, and regulation of the solidification process of the casting. Consequently, the riser should solidify last in the casting process, ensuring a continuous supply of molten metal to the shrinkage areas, effectively filling any internal defects. Furthermore, preventing premature solidification of the riser is critical for

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maintaining sufficient molten metal feeding, thereby avoiding insufficient flow, gas entrapment, and impurity inclusions, and ultimately improving casting quality. The temperature of the riser is influenced by the shell temperature, while the preheating temperature and cooling rate of the shell directly determine the solidification sequence of the riser[14-18]. A higher shell temperature helps sustain the elevated temperature of the riser, effectively delaying its solidification rate. In investment casting, the shell typically requires preheating to ensure that the temperature differential between the casting surface and the shell remains minimal, facilitating effective control of the cooling rate and ensuring uniform solidification of the casting. However, in practical production, the shell temperature fluctuates during pre-treatment operations, such as shell transfer and vacuum extraction prior to pouring. This fluctuation leads to a discrepancy between the actual shell temperature at the time of pouring and the intended preheated temperature, which consequently affects the temperature distribution of the riser[19-21]. Such variations in the temperature field have a direct impact on the capacity of the riser to compensate for shrinkage during the solidification of the casting.

In the context of investment casting, extending the solidification time can enhance the efficiency of shrinkage feeding of the riser[22]. Solidification time is defined as the duration of cooling that occurs between the pouring temperature and the solidification temperature[23]. Insulated risers constructed from high-temperature-resistant materials, such as ceramics, exhibit exceptional thermal insulation properties, thereby effectively decelerating heat loss and enabling the metal within the riser to maintain a higher temperature for an extended period. However, the implementation of insulated risers typically necessitates specialized design and manufacturing processes, which can elevate costs. In investment casting production, it is more prevalent to utilize thermal insulation cotton in specific areas of the shell, given its economic viability and widespread availability. Particularly in large-scale production scenarios, the adoption of insulation cotton can substantially diminish overall production costs[24, 25]. Moreover, the application of insulation cotton around the riser offers greater flexibility compared to the direct use of an insulated riser. The thickness and wrapping technique of insulation cotton can be modified according to specific requirements, whereas the design of insulated risers tends to be more rigid and challenging to adapt to varying casting needs and production conditions. However, it is important to note that the thermal insulation material significantly reduces heat loss from the sides of the riser but is less effective in compensating for heat loss at the top of the riser, where heat loss is comparable to that at the sides[26]. The riser insulation agent is used to reduce heat loss from the exposed molten-metal surface at the top of the riser during casting. It typically comprises aluminum-silicon-iron powder as a heating agent and contains minor amounts of catalysts and oxidizers to expedite the ignition time. After pouring, the riser insulation agent is applied onto the exposed molten-metal surface at the top of the riser[24]. As the casting solidifies, the molten metal in the riser continues to compensate for shrinkage, and the riser insulation agent gradually sinks, ensuring the formation of a stable layered structure on the molten metal surface within the riser, thereby providing excellent thermal insulation. Additionally, the riser insulation agent optimizes the casting solidification sequence by delaying the solidification of molten metal inside the riser, thereby improving thermal regulation and molten metal feeding performance.

Combined numerical simulation and experimental verification, this work investigated the impact of riser temperature control on shrinkage defects during the casting process. By analyzing the temperature variation in the riser shell prior to pouring, a method was proposed to control the riser temperature field during casting, which was validated through practical casting production. In this method, the solidification time of the riser was extended and the solidification sequence was optimized by wrapping the riser with thermal insulation and applying riser insulation agent.

2 Experimental procedures

2.1 Numerical simulation

This work focused on the centrifugal wheel, a key component of aerospace engines. The centrifugal wheel was investment cast from S-08 high-strength stainless steel. A numerical simulation of the vacuum investment casting process for the centrifugal wheel was developed using ProCAST, with surface and volume meshes generated using Visual-Mesh. As shown in Fig. 1, the mesh size for the gating system is set to 2 mm, while the mesh size for the casting area is set to 1 mm. This division is based on the significant differences in physical properties and computational requirements between the two areas. A larger mesh size in the gating system can reduce the computational burden and improve efficiency, while a finer mesh in the casting area can ensure the accuracy of the simulation results[22, 27, 28].

In accordance with the structural characteristics of the

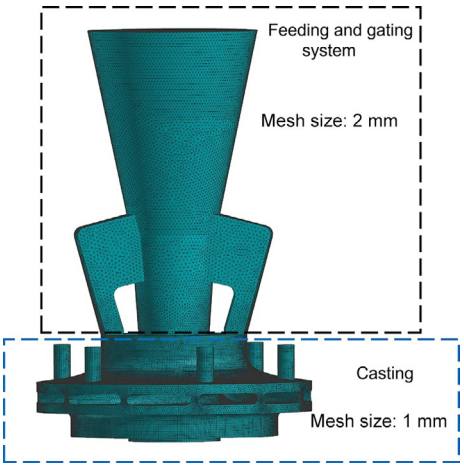


Fig. 1: Finite element model and mesh division

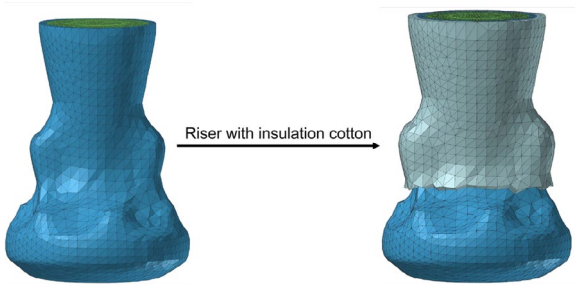


Fig. 2: Model of the riser wrapped with insulation cotton

casting gating system, 8 mm thick insulation cotton was applied to the riser area of the shell mold, as illustrated in Fig. 2.

The casting process was simulated using ProCAST (ESI Group), a casting simulation software, by numerically solving the Navier-Stokes equations for fluid flow and the Fourier equations for heat transfer. The radiation heat transfer between the external surface of the shell mold and the cavity wall was modeled using an effective heat transfer coefficient, as expressed in the following equation[26]:

$$h = \sigma\varepsilon(T_1^2 + T_2^2)(T_1 + T_2) \quad (1)$$

where ε represents the emissivity of both the molten metal and heated mold material, considering radiation heat transfer. σ denotes the Stefan-Boltzmann constant (σ=5.670×10^{-8} W·m^{-2}·K^{-4}), T_1 and T_2 are the temperatures of the two bodies involved in heat transfer.

Shrinkage defects were quantitatively predicted using the built-in "feeding criterion" function. Based on the obtained temperature field, the Niyama criterion[29], which is widely recognized as one of the most commonly used criteria in metal casting, was employed to predict shrinkage defects related to feeding. The Niyama criterion is defined as a local thermal parameter as follows:

$$N_y = \frac{G}{\sqrt{T}} \quad (2)$$

where G represents the temperature gradient, and T denotes the cooling rate. These parameters are assessed at a specified temperature near the end of solidification.

To ensure the parameters could be accurately used in the numerical simulation of the investment casting process, the thermal conductivity coefficient (35 W·m^{-2}·K^{-1}) and emissivity for the shell mold (0.7) were employed based on a comprehensive consideration of literature data[22, 26-28], experimental measurements, and numerical simulation validation.

The initial conditions were established as follows: the pouring temperature of the molten metal was 1,500 °C, the preheating temperature of the shell mold was 900 °C, and the thickness of the shell was 8 mm. In this numerical simulation model, the time consumed by pre-casting procedures, including the transfer of the shell mold from the reheating furnace to the pouring cavity and subsequent vacuum extraction within the pouring cavity, is defined as the shell mold dwell time. Based on field timing measurements in actual production, the shell mold dwell time was determined to be 120 s. This parameter setting enables accurate simulation of riser temperature variations during practical casting production.

2.2 Experimental validation

To validate the numerical simulation, the optimized casting process detailed above was employed. The castings produced were compared with those prepared by the original casting process, as illustrated in Fig. 3.



Fig. 3: Riser wrapped with insulation cotton

The riser region of the shell mold was wrapped with insulation cotton. After pouring, a commercial FOX-508 riser insulation agent was applied to the exposed molten-metal surface at the top of the riser. The chemical composition of the adopted FOX-508 insulation agent is listed in Table 1.

Table 1: Chemical compositions of FOX-508 riser insulation agent (wt.%)

C	Al_2O_3	SiO_2	CaO	Na_2O	Others (trace oxides)
6.24	29.17	49.29	5.29	2.00	8.01

Under the high temperature of the molten steel in the riser, the riser insulation agent gradually forms four layers above the molten steel, consisting, from top to bottom, of a thermal insulation layer, an overlapping layer, a second thermal insulation layer, and a fusion layer, as depicted in Fig. 4. These layers effectively isolate the molten metal in the riser from the ambient air, preventing convection and radiation heat transfer while reducing heat conduction, which results in a slower solidification rate of the molten metal.

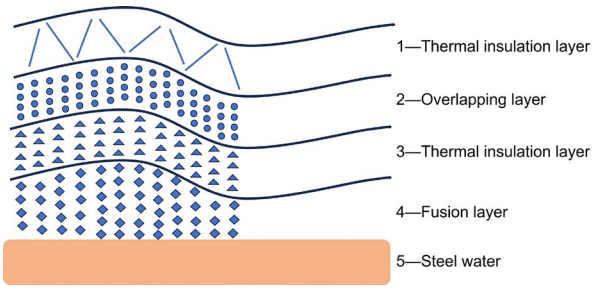


Fig. 4: Schematic of layered structure formed by riser insulation agent on molten steel

The usage method of the riser insulation agent is as follows:

(1) Timing of application: The riser insulation agent should be applied when the molten metal level rises to the mid-height of the riser. This operation must be completed before the riser fully solidifies. The pouring height should be strictly controlled not to exceed the top of the riser, ensuring proper application of the insulation agent.

(2) Application sequence: For castings with multiple risers, the riser insulation agent should be applied sequentially from the riser farthest from the gating system to the nearest one.

(3) Amount of application: The amount of riser insulation agent can be determined based on the diameter of the riser top, as well as the size and thickness of the casting. Typically, 1.2%–1.5% of the molten metal weight in the riser is appropriate (The thickness of the insulation layer should exceed one-eighth of the top diameter of the riser).

An X-ray inspection was conducted on the castings to assess their quality under the specified casting process. The manufacturer of the centrifugal wheel casting examined in this study adopts the defect acceptance criteria for aerospace-grade castings specified in ISO 16468:2015, Investment castings (steel, nickel alloys, and cobalt alloys) – General technical requirements, together with its internal enterprise standards. Quality inspection was performed in accordance with GJB 1187A. A 3.2 mm-thick reference film was adopted as the benchmark for comparison with the X-ray radiographic images of the centrifugal wheel casting. This comparison was used to evaluate whether the centrifugal wheel casting met the relevant acceptance criteria.

3 Results and discussion

3.1 Temperature variation of riser during shell mold dwell time

Figure 5 illustrates the temperature variation at the riser during the shell mold dwell time from 0 to 120 s. The shell mold temperature at the riser decreases from 900 °C during preheating to 814 °C before pouring. During the preparatory process, particularly when transferring the shell mold from the preheating furnace to the pouring position, the shell mold, due to its large heat capacity, loses heat through conduction and convection as it moves from a hotter to a relatively cooler environment, with its surface exposed to the air[26, 29]. Because the riser is typically located at a higher position on the shell mold, it loses heat more readily to the air, resulting in a greater temperature drop.

At shell mold dwell times of 30, 60, and 90 s, the corresponding riser temperatures are 890, 868, and 841 °C. This trend indicates that riser temperature declines with extended dwell time, demonstrating that pre-pouring preparatory processes directly affect the riser temperature.

Figure 6 illustrates the solidification time of the riser at each temperature. The results indicate that as the riser temperature decreases, the solidification time also decreases from 249 s at 900 °C to 210 s at 814 °C. When the temperature surrounding

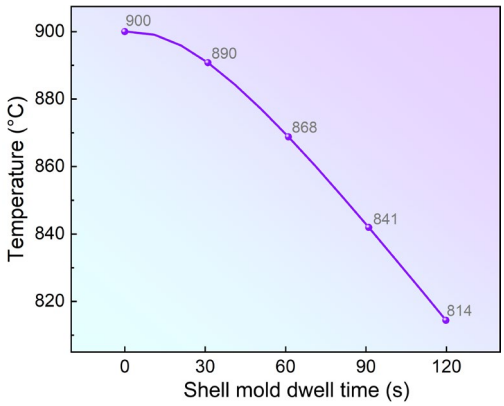


Fig. 5: Temperature of riser during shell mold dwell process

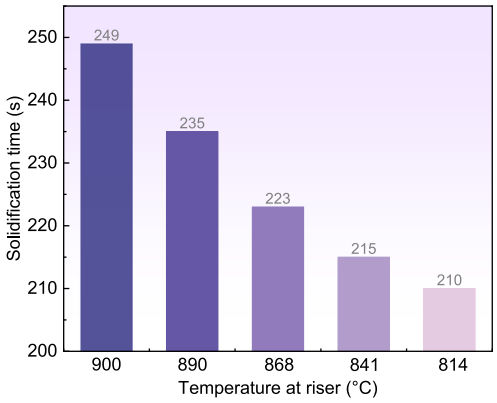


Fig. 6: Solidification time of the riser at different temperatures

the riser decreases, the temperature difference between the shell mold and the casting increases. A greater temperature difference leads to a faster heat transfer rate, causing the heat in the riser to be absorbed more quickly by the surrounding environment and the shell mold. This accelerates the solidification process.

The primary function of a riser is to compensate for casting solidification shrinkage defects. A shorter riser solidification time causes premature riser solidification while the casting is still shrinking. As a result, the riser cannot supply sufficient molten metal to feed shrinkage regions, losing its feeding capability and leading to more internal casting defects.

As shown in Figs. 7 and 8, when the riser-region shell mold temperature drops from the preheating temperature of 900 °C to 814 °C, the number of shrinkage defects rises from 4 to 12, equivalent to a 200% increase. Meanwhile, the total defect volume increases from 1.87 cm^3 to 2.55 cm^3, representing a 36.36% growth.

3.2 Riser temperature field control methods

Numerical simulations were conducted on the constructed model, and the results are presented in Fig. 9. In this numerical model, all casting process parameters including shell mold dwell time, shell mold preheating temperature, and pouring temperature were kept identical, with the addition or removal of insulation cotton as the only variable for single-factor comparison. The findings indicate that after insulating the riser with the insulation cotton, the temperature of the riser remains

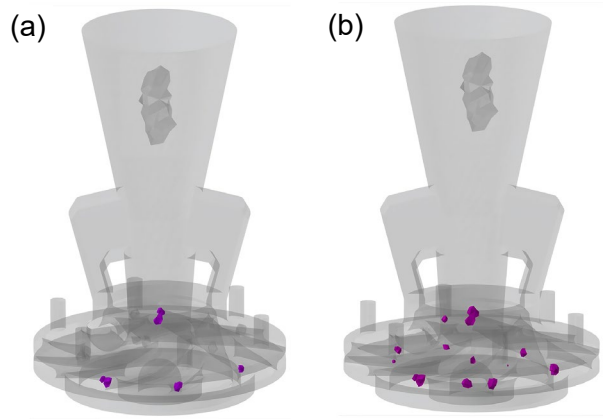


Fig. 7: Distribution of shrinkage defects within the riser at different temperatures: (a) 900 °C; (b) 814 °C

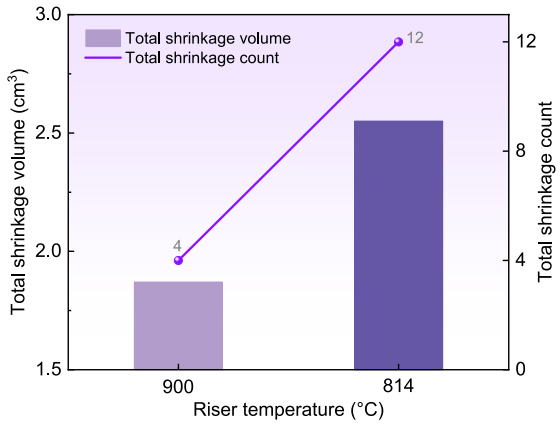


Fig. 8: Number and volume of shrinkage defects within riser at different temperatures

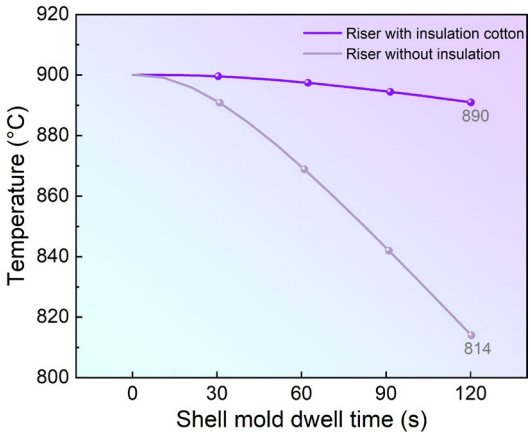


Fig. 9: Riser temperature during shell mold dwell process

at 890 °C during the 120 s dwell time of the shell mold. This treatment effectively prevents a temperature loss of 76 °C when compared to the riser without insulation cotton over the same duration.

This indicates that wrapping the riser with thermal insulation material allows the riser to stay at a temperature close to the preheating level even during prolonged waiting, preventing premature cooling, which is critical to the casting process. Furthermore, due to the capacity of the thermal insulation material to reduce heat loss, the temperature of the riser decreases more gradually during the pouring process, resulting in a slower cooling rate of the metal inside the riser. This extended solidification time allows the riser to provide liquid metal for a longer duration during the cooling of the casting, thereby mitigating shrinkage defects during the solidification process.

During casting, insulation cotton wrapped around the riser sidewalls effectively reduces heat loss and delays solidification to improve feeding performance. However, a lack of insulation on the riser top leads to rapid heat dissipation. This can cause premature solidification at the top, forming a “cold cap” and blocking the downward shrinkage feeding channel for the molten metal. This phenomenon causes shrinkage defects to concentrate below the riser top or in the transition area near the casting, impairing shrinkage feeding. It may even transfer defects into the interior of the casting, reducing its density and mechanical properties.

The riser insulation agent was incorporated into the model, and simulations were performed. Five monitoring points were established within the casting, as depicted in Fig. 10, to examine the variations in solidification time at each location under the influence of the insulation agent. The five monitoring points were evenly distributed across the riser region with consistent spacing. This arrangement ensures comprehensive monitoring of the solidification time across all regions of the riser, yielding detailed solidification time data.

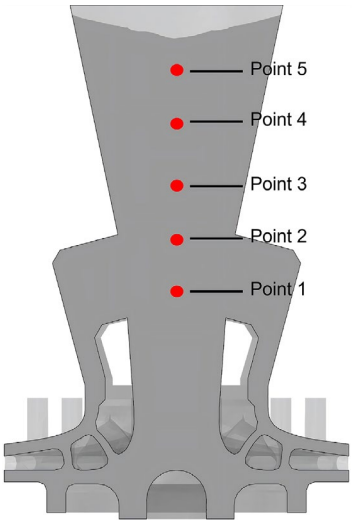


Fig. 10: Location of monitoring points within riser

Figure 11 shows that the riser insulation agent extends solidification time at all monitored positions within the riser, with solidification time increasing from the bottom to the top. This bottom-to-top solidification sequence ensures that the molten metal at the bottom of the riser solidifies at first, followed by gradual solidification in the upper regions, thereby preventing premature solidification of the molten metal. This ensures the riser can adequately feed casting shrinkage zones during solidification and improves its feeding capacity.

As illustrated in Fig. 12, the riser insulation agent can optimize the shrinkage feeding path within the riser, transforming it from a “V” shape to a “U” shape. The V-shaped

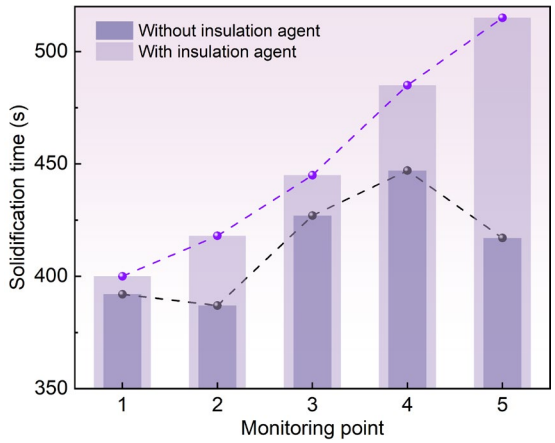


Fig. 11: Solidification time at each monitoring point

temperature distribution tends to be more concentrated, potentially causing localized overheating or undercooling and negatively impacting riser solidification time. In contrast, The U-shaped profile enables a wider temperature range and more uniform heat distribution. This configuration promotes even flow and distribution of molten metal inside the riser, supplying extra material for shrinkage feeding and improving feeding efficiency.

Numerical simulations were performed for risers treated with insulation cotton and insulation agent. Figure 13 compares the casting solidification processes with and without this riser insulation scheme. With the insulation cotton and the riser insulation agent, the riser exhibits enhanced feeding ability during the solidification process, with the molten metal at the

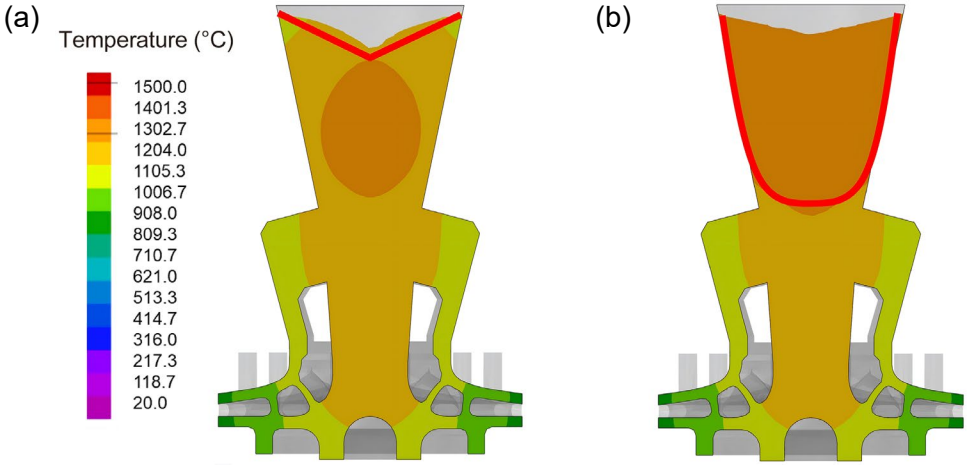


Fig. 12: Temperature distribution of the casting without (a) and with (b) riser insulation agent

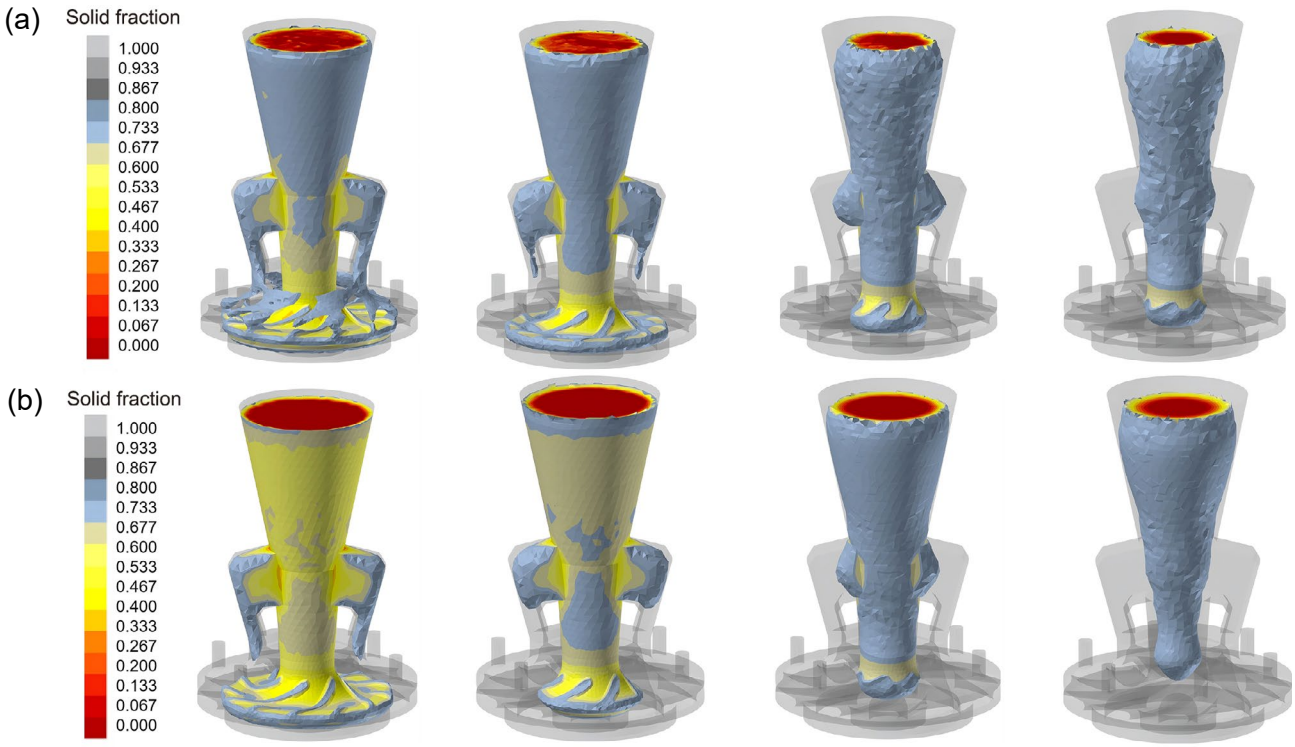


Fig. 13: Solidification process of castings under different riser insulation methods: (a) without insulation; (b) with insulation cotton and insulation agent

riser surface remaining in a high-temperature molten state.

As demonstrated in Figs. 14 and 15, compared with the process without riser insulation, the combined use of thermal insulation cotton and riser insulation agent reduces the number of shrinkage defects from 12 to 2, an 83.33% decrease. Meanwhile, the defect volume drops from 2.55 cm^3 to 0.31 cm^3, representing an approximately 87.84% reduction. These findings indicate that the combination of thermal insulation material and riser insulation agent optimizes the solidification time and sequence of the riser, effectively enhancing its feeding ability, ensuring that the molten metal can adequately compensate for the shrinkage zones in the casting, and thereby reducing the incidence of shrinkage defects.

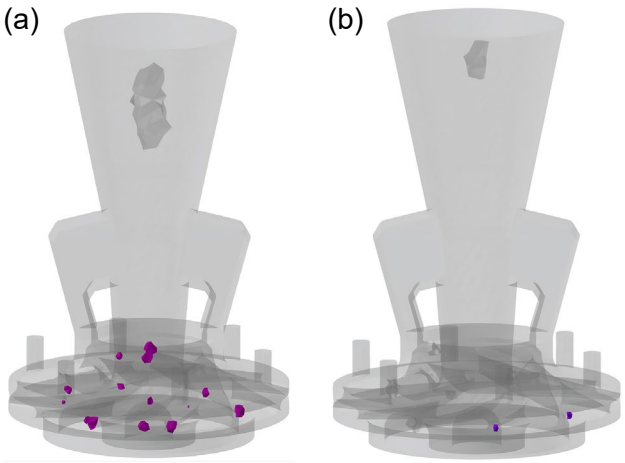


Fig. 14: Distribution of shrinkage defects in the riser without insulation (a) and with thermal cotton insulation and insulation agent (b)

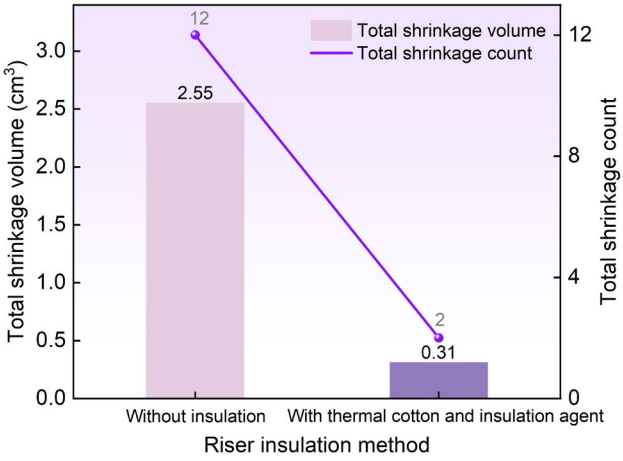


Fig. 15: Count and volume of shrinkage defects under different riser insulation methods

3.3 Experimental results

The X-ray inspection results are presented in Fig. 16. The optimized process markedly suppresses casting shrinkage defects, effectively improving the overall casting quality and satisfying industrial production requirements.

From a cost-effectiveness perspective, insulated risers involve mold manufacturing and high-temperature sintering, leading to higher unit costs. Additionally, inventory management is more complex as various models must be provided to accommodate different sizes and structures. In contrast, both thermal cotton and riser insulation agent are low-cost common industrial consumables. Furthermore, this combined insulation method offers greater flexibility during assembly, allowing operators to adjust the insulation region based on the actual conditions

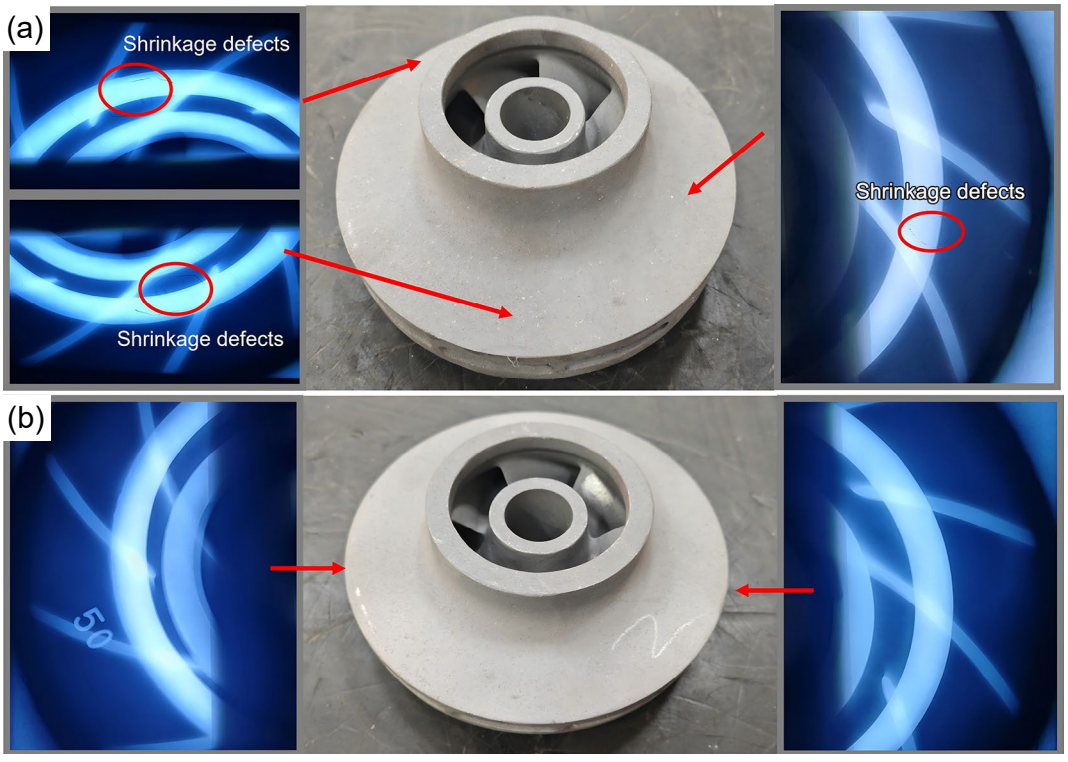


Fig. 16: X-ray inspection photos under different riser insulation methods: (a) without insulation; (b) with thermal cotton and insulation agent

before wax pattern assembly or pouring. Overall, the combined application of insulation cotton and riser insulation agent delivers superior temperature regulation and shrinkage feeding performance. It achieves higher material utilization and better process adaptability, making it highly applicable for large-scale, multi-variety, and complex investment castings. Therefore, compared to insulated risers, this combined insulation approach is not only more economical but also provides more reliable shrinkage control for complex castings, offering significant potential for broader application and engineering use.

4 Conclusions

This work employed numerical simulations to quantitatively analyze the thermal loss of the riser during the shell mold dewelling process before pouring. A temperature field control method for casting risers was proposed and validated via practical production data. The main conclusions are summarized as follows:

(1) During the 120 s pre-pouring shell mold dwell period, operations including mold transfer and vacuuming reduce the riser temperature by 86 °C. This temperature reduction shortens the riser solidification time during subsequent casting, resulting in a 200% increase in shrinkage defect count and a 36.36% increase in defect volume. Riser temperature is highly susceptible to process disturbances, causing deviations from the preset shell mold preheating temperature. Such temperature discrepancies directly weaken the riser feeding capacity and substantially degrade the overall casting quality.

(2) Insulation applied to the riser-section of the shell mold maintains the riser temperature at 890 °C during the entire 120 s dwell period. Furthermore, the insulation agent on the riser top after pouring further improves the thermal insulation effect. Compared with the non-insulated scheme, this composite insulation method prolongs the high-temperature molten duration and solidification time of the riser, and optimizes the solidification sequence. The combined insulation strategy effectively mitigates temperature disturbances during casting, ensuring robust control of the riser temperature field, and enhancing its feeding efficiency.

(3) The combined use of insulation cotton and insulation agent reduces the number of shrinkage defects by 83.33% and the defect volume by 87.84%. This verifies that the composite strategy optimizes the casting process and suppresses shrinkage defects. This technique is feasible for practical production and suitable for large-scale engineering promotion.

Acknowledgments

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Conflict of interest

The authors declare that they have no conflict of interest.

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