Thermal stress analysis and structural optimization of ladle nozzle based on finite element simulation

Zichao Rong, Jianhong Yi, Fengxian Li, Yichun Liu and Jürgen Eckert

1 School of Materials Science and Engineering, Kunming University of Science and Technology, Kunming 650093, People’s Republic of China
2 Key Laboratory of New Material Preparation and Processing of Yunnan Province, Kunming University of Science and Technology, Kunming 650093, People’s Republic of China
3 Key Laboratory of Rare and Non-ferrous Advanced Materials of Ministry of Education, Kunming University of Science and Technology, Kunming 650093, People’s Republic of China
4 Erich Schmid Institute of Materials Science, Austrian Academy of Sciences, Jahnstraße 12, A-8700 Leoben, Austria

* Author to whom any correspondence should be addressed.
E-mail: 175182344@qq.com

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Abstract
The ladle nozzle is one of the most important components in metal smelting. The cracking phenomenon occurs due to excessive thermal stress, which seriously affects the performance and life of the ladle nozzle. In this paper, a new composite structure of ladle nozzle is proposed, which consists of two materials with different properties and costs. The thermal physical parameters of the material are measured by high temperature dynamic Young’s modulus test method, thermal expansion test and flashing method. Based on the new structural model of the composite ladle nozzle, finite element simulation is used to combine the material ontology model, contact mechanics model and heat transfer model to study the temperature and thermal stress distribution inside the composite structure of the ladle nozzle during the casting process by taking representative key points inside the ladle nozzle. There is a large temperature gradient in the area near the casting hole, and the farther away from the casting hole, the smaller the temperature change. The ladle nozzle structure was optimized and compared with the existing ladle nozzle structure. The results show that the optimized composite structure of the ladle nozzle has significantly lowered thermal stress extremes under thermal shock, while the thermal stress distribution tends to be more uniform, which can largely reduce the chance of crack generation. This study is of great significance for improving the reliability and service life of the ladle nozzle and reducing its production cost.

1. Introduction
The ladle nozzle is an indispensable key component to control the steel flow and casting speed in the steel smelting process. If the ladle nozzle fails in the process of use, it will lead to vicious production accidents such as broken pull of the casting machine and burned equipment of the continuous casting machine, which will seriously threaten the safety of people and equipment [1]. It is of great importance to reduce or eliminate ladle nozzle accidents due to damage and improve the quality and life of ladle nozzle for the steel making plant where the production pace is getting faster and faster. The ladle nozzle in the service process repeatedly by the metal liquid flushing, chemical erosion and thermal shock, the ladle nozzle itself temperature changes sharply, which makes the ladle nozzle unevenly heated and the formation of a certain temperature gradient, the ladle nozzle everywhere expansion deformation and shrinkage deformation is not consistent, mutually constrained, and finally produces thermal stress. When the thermal stress exceeds the limit strength of the ladle nozzle, it will form a crack centered on the casting hole, resulting in thermomechanical erosion. Steel and slag will penetrate through the cracks to the ladle nozzle, and react with the ladle nozzle material, causing thermochemical erosion of the ladle nozzle [2]. In order to improve the service life of the ladle nozzle, it must have good overall
performance, such as high temperature resistance, excellent high temperature strength, thermal shock resistance and corrosion resistance. It is important to study the law of thermal stress change in the service process of the ladle nozzle to improve and enhance its design quality and service life.

Currently, the ladle nozzle materials include Al$_2$O$_3$-C, Al$_2$O$_3$-ZrO$_2$-C, MgO-C and ZrO$_2$ embedded ring types [3–5]. According to the manufacturing process, the ladle nozzle can be divided into three categories: high temperature firing, low or medium temperature firing and no firing. There are disadvantages such as high energy consumption, complex asphalt impregnation process, long production cycle, low efficiency and serious pollution in fired ladle nozzle. Compared with the burned ladle nozzle, the unfired ladle nozzle without impregnated asphalt has many advantages such as environmental protection, simple process, energy saving and high efficiency. Therefore, more and more ladles are using unfired ladle nozzle. As a result, more and more ladles are using non-burning ladle nozzle. Compared with other materials, Al$_2$O$_3$-C refractories are widely used in ladle nozzle due to their excellent thermal shock resistance, corrosion resistance, low wettability to steel and slag melt, and unique oxidation resistance and mechanical strength [6–9].

The top of the nozzle is connected with the nozzle, the steel shell and the clamping mechanism are fastened around, and the inner channel is provided with casting holes. The inner wall of the casting hole is directly in contact with the high-temperature metal liquid, and the top is constrained by the downforce and expansion of the nozzle, while the outer surface is tightened and restrained by the steel shell, which makes the nozzle bear large thermal mechanical load and complicated thermal stress state in the working process. The optimization design process of the nozzle structure by using the experiment is complicated, expensive and the test cycle is too long, while the temperature and stress coupling simulation by using the finite element method can greatly save the optimization design cost and improve the efficiency to the greatest extent [10–12]. The damage and failure behavior of the nozzle can be predicted in advance by finite element simulation, which provides a theoretical basis for the structure and material design of the nozzle material. In recent years, finite element analysis technology has been gradually applied to ladle smelting and refractory design. Hyoung-jun Lee et al [13] used finite element simulation to simulate the temperature and thermal stress distribution of ladle slide during the working process, and proposed a method to suppress the crack generation according to the simulation results. Wu Songgen et al [14] used finite element method to analyze the thermal stress of the slide plate and pointed out that the tensile stress in the sliding direction was the main factor leading to the longitudinal crack and promoting the crack expansion in the use of the slide plate. The existing ladle nozzle structure mostly adopts the integral structure, which is not only high in price, poor in disintegration, but also high in cost of renewal after damage. At present, there are few studies on the design and structural optimization of composite structure nozzles. Research and design of the composite structure of the nozzle is very meaningful to improve its service life. In this study, the composite structure of inner and outer layers is used to replace the overall structure, which is conducive to the assembly and replacement of the nozzle, and the inner and outer layers are made of different materials, which reduces the cost of the product without reducing the performance of the product. The casting hole and the surrounding part of the nozzle are made of aluminum carbon material, while the outer ring of the casting hole and the part that does not contact the molten steel are made of recycled nozzle material after smelting, and the production method of feeding twice and forming once is adopted. Reasonable use of melted spout as the raw material of the outer ring material of the composite spout can optimize the matching of different material properties of the composite spout to a great extent, and conform to the policy of low-carbon circular economy now advocated.

In order to improve the performance and service life of the nozzle, based on the structural design idea of heterogeneous materials, a kind of combined structure of the nozzle is proposed in this paper. By analyzing the thermal stress change law of the nozzle during the working process, the durability and reliability of the new nozzle structure are explored. Based on the finite element simulation of the nozzle, from the perspective of calorics and mechanics, the three-dimensional models of the nozzle as the research object, using the finite element analysis software ABAQUS simulation calculation, comprehensive consideration of the temperature field and stress field of the nozzle is skateboard under pressure and steel shell fastening force under the influence of many factors, such as nozzle thermal stress analysis. The optimization and evaluation of the nozzle structure, combined with orthogonal test method, multi-parameter structure optimization design, determine the optimal nozzle structure.

2. Modelling methodology

The heat transfer between the nozzle and metal liquid is a comprehensive heat transfer process composed of convection and radiation heat transfer. Ladle nozzle in the practical work of unsteady complex heat transfer process of the design and calculation of heat transfer model for the nozzle caused a lot of trouble and inconvenience, reasonable assumption that the heat transfer process of nozzle, not only simplified the nozzle
heat transfer model, the convenience of calculation, smelting and the calculation results and the nozzle in the work of the real data won’t produce too much discrepancy. The hypothesis of the nozzle heat transfer model is simplified as follows:

1. Without considering the natural convection of melted steel inside the ladle, the internal heat transfer of molten steel is considered as heat conduction.

2. The temperature of the part of the ladle’s inner surface in contact with molten steel is equal to the temperature of molten steel, regardless of the contact thermal resistance between them.

3. During casting, the metal liquid is three-dimensional turbulent and meets the condition of wall non-slip. Turbulent boundary layer is formed when turbulent fluid flows through a solid wall. In the boundary layer, because there is no movement and mixing of fluid particles in the direction of heat transfer, its velocity relative to the inner wall of the nozzle casting hole is 0. In addition, because the fluid can’t cross the wall, the wall normal direction fluid velocity is zero, the speed of the liquid metal can be approximately as 0, then the gate in contact with high temperature liquid metal casting hole wall meet the first kind of thermal boundary conditions, so the temperature of the liquid metal as the thermal load can be applied to the nozzle casting hole wall. In this way, the fluid-structure coupling heat transfer problem between metal liquid and cast hole wall can be simplified to a solid heat transfer problem.

The function $T(x, y, z, t)$ is used to represent the temperature of the nozzle at the position $(x, y, z)$ and the time $t$. The heat transfer between the nozzle and the metal liquid is described by a three-dimensional heat conduction equation.

$$
\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right)
$$

Where $\varepsilon (J/kg \cdot K)$ is the specific heat capacity of the material, $\rho (kg/m^3)$ is the material density, $t(s)$ is the time, and $k (W/m \cdot k)$ is the thermal conductivity of the object at $(x, y, z)$.

The thermal radiation generated by the nozzle during its operation can be described by Stephan-Boltzmann equation:

$$
q = \varepsilon \sigma A T_1^4 - T_2^4
$$

Where $q (W/m^2)$ is heat flow rate, $\varepsilon$ is the emissivity of the actual object, called the blackness, and its value is between 0-1, $\sigma$ is Stefan-Boltzmann constant ($5.67 \times 10^{-8} W/(m^2 \cdot k)$), $A (m^2)$ is the area of radiating surface 1, and $T_1, T_2 (K)$ is the absolute temperature of radiating surface 1, T2 (K) is the absolute temperature of radiating surface 2.

During the working process of the nozzle, the high temperature metal liquid has a strong thermal impact on the casting hole of the nozzle, which causes a large temperature gradient in the nozzle, and thus produces a certain thermal stress. The stress and strain generated during the operation of the nozzle can be expressed by the constitutive equation of material thermal stress:

$$
\sigma = K (\varepsilon_{s} - \varepsilon_{s}^{t}) I + 2 Ge
$$

Where $\sigma$ is the stress tensor, $K$ is the volume modulus, $\varepsilon_{s}$ is the volume strain, $\varepsilon_{s}^{t}$ is the strain generated by thermal expansion, $I$ is the tensor, $G$ is the shear modulus and $e$ is the partial tensor in the global strain tensor.

The nonlinearity of nozzle deformation is caused by material nonuniformity. The constant stress concentration in the nozzle is the essence of the nonlinear deformation of the nozzle. Therefore, it is appropriate to describe the thermo-mechanical coupling deformation behavior of the nozzle with elastic-brittle constitutive relation. When the stress level of the element does not reach its failure strength, the element obeys the elastic constitutive relation. Once the stress level of the element reaches or exceeds its failure strength, the brittle failure occurs. When the nozzle model element is in the state of tensile stress, the tensile failure criterion is taken as the element damage criterion, and tensile damage occurs in the element, and damage variable $D$ can be expressed as:

$$
D = \begin{cases} 
0 & \varepsilon < \varepsilon_{t0} \\
1 - \frac{\sigma_{te}}{\varepsilon_{E0}} & \varepsilon_{t0} \leq \varepsilon \leq \varepsilon_{tu} \\
1 & \varepsilon > \varepsilon_{tu}
\end{cases}
$$

Where $\sigma_{te}$ is the residual strength of tensile damage, $\varepsilon_{t0}$ is the elastic ultimate strain, $\varepsilon_{tu}$ is the maximum tensile strain, when the tensile strain of the element reaches $\varepsilon_{tu}$, the element completely loses its load-bearing capacity, $E_0$ is the initial modulus of elasticity.
When the element is in compression state, Mohr-Coulomb criterion is taken as the criterion of shear damage of the element, and damage variable \( D \) can be expressed as:

\[
D = \begin{cases} 
0 & \varepsilon < \varepsilon_{c0} \\
1 - \frac{\sigma_{cr}}{\varepsilon E_0} & \varepsilon \geq \varepsilon_{c0}
\end{cases}
\]

(5)

Where \( \sigma_{cr} \) is the residual strength of shear damage, \( \varepsilon_{c0} \) is elastic limit of compressive strain.

2.1. Geometry and mesh

In this study, UG was used to establish a three-dimensional geometric model according to the actual size of the sliding nozzle mechanism. There is a steel shell outside the nozzle body, and the steel shell is in direct contact with the nozzle body. There is a casting hole in the center of the nozzle. The geometric model of the nozzle is shown in figure 1(a). The sliding nozzle mechanism is composed of upper slide plate, lower slide plate, base, fastening mechanism, and nozzle. The upper surface of the nozzle is in contact with the bottom surface of the lower slide plate. The geometric model of the sliding nozzle mechanism is shown in figure 1(b).

When the metal is cast, the metal liquid flows out of the ladle, the lower slide plate is driven by the hydraulic cylinder to move to the position in the casting hole of the upper slide plate, the drainage sand falls off, and the metal liquid flows through the nozzle through the slide plate. In the process of establishing the nozzle finite element model, the temperature field and stress field are analyzed by means of the coupled Temperature-Displacement model. The mesh is divided by three-dimensional solid elements. The mesh is mainly divided by the eight-node hexahedron element C3D8T. A small amount of cuneiform six-node hexahedron element C3D4T is used at the rounded corners. The composite nozzle is divided into 138,440 units and 159,090 nodes, Steel shell is divided into 596 units and 966 nodes as shown in table 1.

2.2. Materials and properties

The working conditions of different areas of the nozzle are very different. During casting, the casting hole of the nozzle and its surrounding areas are scoured and eroded by high-temperature molten metal, accompanied by thermal shock, and the service conditions are poor. Therefore, this area needs better performance. Material. The rest of the nozzle is less affected by the molten metal, so the performance requirements for the material are lower. In this study, two materials with different composition ratios were designed. The material codenamed H1 has good heat resistance, high heat transfer coefficient and low thermal expansion rate, but its cost price is high. The material code-named P2 has higher strength, but weaker scour resistance and lower cost. The composite structure nozzle designed in this study uses material H1 in the area around the casting hole, and material P2 for the rest, as shown in figure 2.

In this study, the materials used in the composite structure nozzle are divided into H1 and P2. The steel shell material is Q235. The composition of the material code-named H1 and the material code-named P2 is shown in table 1.

| Table 1. The units numbers and nodes of three-dimensional mesh. |
|-----------------|-----------------|-----------------|
| Units | Steel shell |
| Nozzles | 138440 | 596 |
| Nodes | 159090 | 966 |

Figure 1. Schematic diagram of ladle nozzle mechanism.

(a) Nozzle model  (b) Sliding nozzle mechanism model
Both materials consist of 6 kinds of raw materials, which are tabular alumina aggregate ($\text{Al}_2\text{O}_3 \geq 99.16\% \text{ wt%})$, $0-2\text{ mm}$, alumina fine powder ($\text{Al}_2\text{O}_3 \geq 99.16\% \text{ wt%})$, $\leq 50\ \mu\text{m}$, Yunnan Aluminium Industry Co., LTD), aluminum powder ($\text{Al} \geq 99\% \text{ wt%})$, $66\ \mu\text{m}$, Luoyang Refractory Materials Co., LTD), Si powder ($\text{Si} \geq 99\% \text{ wt%})$, $\leq 50\ \mu\text{m}$, Advanced Chemical Co., LTD), phenolic resin ($\text{C} = 62.3\% \text{ wt%})$, $\leq 80\ \mu\text{m}$, and flake graphite ($<0.20\ \text{mm}$, 96.6 wt% Fixed carbon). The difference between H1 and P2 is the weight percentage of the raw materials contained.

Mix the two raw materials evenly according to the formula in table 2, and then use a hydraulic press to make samples with specifications of $15\ \text{mm} \times 15\ \text{mm} \times 6\text{mm}$ under a pressure of 150 MPa. Then, the samples were put into a drying oven, and the physical properties and thermo-mechanical properties of the samples of the two materials were tested successively after being heated and cured at 473K for 24 h. According to Chinese standards GB/T 2997-2015 (Test method for bulk density, apparent porosity and true porosity of dense shaped refractory products), the 3H-2000TD densimeter manufactured by Best Instrument Technology coMPany was used to measure the density of the material. According to Chinese standards GB/T34186-2017, to obtain the Young’s modulus, High temperature dynamic Young’s modulus test was conducted at ambient temperature with a elastic modulus tester (HEMT-1601, Luoyang Refractory Research Institute), the test temperature range is $300K \sim 1473K$, Young’s modulus was measured at 373K intervals, the obtained partial Young’s modulus values are shown in table 3. According to Chinese standards GB/T7320-2018 (Test method for thermal expansion of refractories), High temperature thermal dilatometer (RPZ-04P, Luoyang Refractory Research Institute) was used to measure the thermal expansion rate of the sample, the test temperature ranges from $300K$ to $1473K$, the thermal expansion rate was measured at 298K intervals, and the obtained partial thermal expansion rate was shown in table 3. According to standard YBT4130-2005 (Test method for thermal conductivity of refractories - water flow plate method), the thermal conductivity of the sample is determined by using a water flow plate thermal conductivity meter. According to the standard CSN725031-1973, the specific heat capacity of the sample was determined by using the Netch DSC214 differential scanning calorimeter. The physical and thermo-mechanical properties of the nozzle and the steel shell (performance parameters of Q235 material can be obtained by consulting the data) are shown in table 4.

### Table 2. Compositions of specimens.

| Raw materials          | Content of main ingredients | Particle size | Specimens |
|------------------------|----------------------------|---------------|-----------|
| Tabular alumina        | $\geq 99.16\% \text{ wt%}$ | 2-1 mm/0 mm   | H1 (wt%)  |
| $\text{Al}_2\text{O}_3$ powder | $\geq 99.16\% \text{ wt%}$ | $\leq 50\ \mu\text{m}$ | P2 (wt%)  |
| Al powder              | $\geq 99\% \text{ wt%}$    | $\leq 66\ \mu\text{m}$ | 10        |
| Si powder              | $\geq 99\% \text{ wt%}$    | $\leq 50\ \mu\text{m}$ | 7         |
| Phenolic resin         | $C = 62.3\% \text{ wt%}$   | $\leq 80\ \mu\text{m}$ | 2         |
| Flake graphite         | $96.6\% \text{ wt% Fixed carbon}$ | $<0.20\ \text{mm}$ | 3         |

Figure 2. Materials in different areas of composite structure nozzle.
2.3. Initial and boundary conditions

The temperature of liquid metal is as high as 1803K, and the density is about 7000 kg m\(^{-3}\). According to the actual situation of the casting workshop, the time of one casting operation is about 30 min. According to the casting port area, the average flow rate of molten steel is about 1.2 m s\(^{-1}\). Thus, it can be calculated that the time for molten steel to fill the casting hole of the sliding nozzle mechanism is about 0.046 s, which is quite short. Therefore, you can directly start from the time when molten steel is filled with casting holes and set the total casting time as 30 min (1800 s).

In order to reduce the temperature difference inside the nozzle and prevent stress concentration cracking caused by temperature drastic change, the nozzle was preheated to 573K before casting. The convective heat transfer coefficient between the nozzle and the steel shell is 25 W m\(^{-2}\) K\(^{-1}\). The convective heat transfer coefficient between the nozzle and the lower slide plate is 10 W m\(^{-2}\) K\(^{-1}\).

The surface of the outlet in contact with the outside air meets the third type of boundary conditions. The temperature of the outside air is 340 K, and the radiation of the environment is processed by converting the radiation heat transfer formula into convective heat transfer, that is, converting the radiation heat transfer formula into the comprehensive convective heat transfer coefficient. Determination of comprehensive heat transfer coefficient on the outer surface of the nozzle:

\[
T_m = \frac{T_W + T_b}{2}
\]

Where \(T_W\) is the outer surface temperature of the nozzle, \(T_b\) is the ambient temperature.

\[
h_r = \varepsilon \cdot C_0 \cdot \left( \frac{T_m}{100} \right)^4 - \left( \frac{T_b}{100} \right)^4
\]

Where \(C_0 = 0.8\), \(\varepsilon = 5.67 \text{ W/m}^2 \cdot \text{K}^4\).

In this study, considering the actual work of the spout, the spout is fixed at the bottom of the slide plate, so 0 displacement constraint in the direction of Z axis is applied to the upper surface where the spout and the slide plate contact. Full constraints in X, Y and Z directions are applied to the outer surface of the nozzle.

2.4. Numerical parameters

Casting steel is a transient process, so we choose the transient for calculation. In order to accurately simulate the variation of the transient temperature field and stress field of the nozzle during the casting process, the casting process is divided into two analysis steps:

1. The first analysis step simulates the 10 seconds before casting. The molten metal began to flow into the nozzle from the ladle, and the temperature of the inner wall of the nozzle casting hole increased sharply. In order to reflect this change, the simulation took 10 seconds before the beginning of casting and divided it into 10 analytical steps, each step of which was 1.

2. The second analysis step simulates the casting process from 10 seconds to 1800 seconds, with a total length of 1790 seconds. It is divided into 5 sub-steps and each analysis step is 10 seconds. The initial incremental step is 1, the minimum incremental step is 10–5, and the maximum incremental step is 1800.

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| Table 3. Young’s modulus of materials at different temperatures. |
|---------------------------------------------------------------|
| Young’s modulus (MPa) | 300(K) | 600(K) | 900(K) | 1200(K) |
|-----------------------|--------|--------|--------|---------|
| H1                    | 51868.5| 44277.7| 57632.6| 62583.5 |
| P2                    | 44688.6| 36057.7| 38560.2| 30859.6 |

| Table 4. Thermal expansion coefficient of material at different temperatures. |
|------------------------------------------------------------------------------|
| Thermal expansion coefficient (K\(^{-1}\)) | 300(K) | 600(K) | 900(K) | 1200(K) |
|---------------------------------------------|--------|--------|--------|---------|
| H1                                          | 6.52E-06| 6.56E-06| 7.02E-06| 7.12E-06|
| P2                                          | 7.49E-06| 7.28E-06| 7.16E-06| 7.19E-06|
3. Results and discussion

3.1. The temperature field and stress field of the nozzle in the casting process

In this study, three structural parameters A, B and C were selected as indicators to optimize the nozzle structure, A distance from the top of the nozzle for P2 material, B is the P2 material at the top of the radius, C for the vertical height of P2 material, as shown in Figure 3(a).

The ladle nozzle works under the periodic scouring of metal liquid, and the Ladle nozzle and its adjacent areas are affected by the thermal shock of high-temperature metal liquid. Therefore, the working conditions of different areas of the ladle nozzle are very different. As shown in Figure 4, the temperature field clouds from the inlet at 300 s, 600 s, 1000 s and 1800 s show obvious stratification in temperature from the radial direction of the inlet. Due to direct contact with high-temperature metal liquid, the temperature rises faster in the area near the casting hole, and due to the high thermal conductivity of H1 material, the temperature rises faster at the top and bottom of the nozzle. P2 material area is far from the casting hole, resulting in low thermal conductivity, slow heat transfer and small temperature change.

Nozzle in the process of use, the most common damage is the damage of refractory materials, resulting in nozzle failure, metal leakage. The damage of refractories is mainly due to high thermal load and high thermal stress. Temperature field analysis is the premise of extracting thermal load from ladle thermal stress analysis, so it is necessary to analyze temperature field of ladle. In order to better optimize the structure of the nozzle of the composite mechanism and study the distribution and change of temperature and stress, EWQR was selected as four key points for temperature analysis. Point E is located at P2 material, 35 mm away from the casting hole wall and 66 mm away from the top of the nozzle. Point W is located at the H1 material, 16 mm away from the casting hole wall and 112 mm away from the top of the nozzle. Point Q is located at the H1 material, 32 mm away from the casting hole wall and 30 mm away from the top of the nozzle. Point R is located at H1 material, 39 mm away from the casting hole wall and 21 mm away from the bottom of the nozzle. The distribution diagram of key points is shown in Figure 3(b). The temperature of key points changes with time in the casting process, as shown in Figure 5(a). According to Figure 5(a), the temperature analysis of key points in the working process of the nozzle shows that the temperature of key point W rises rapidly in the process of casting because it is close to the center of the casting hole. At the end of casting, the temperature rises to 1733 K, with a large temperature gradient relative to the temperature at the beginning of casting. Although the key point R is a certain distance from the casting hole, H1 material has a high thermal conductivity, which makes its heating rate faster in the initial stage of casting. Key points Q and E are far from the center of casting hole, and point E is located in P2 material area with low thermal conductivity, so the temperature rises slowly. The temperature at the end of casting is 1096 K and 1184 K respectively, and the temperature gradient changes little. It can be seen from Figure 5(b) that between the thermal stress range of $-268.5$ MPa and $125.2$ MPa, the stress value fluctuates widely, the stress extreme value is also large, and the stress concentration area is obvious. Due to the extrusion of ladle sliding device, part of the upper part of the nozzle is subjected to tensile stress, while the rest of the nozzle is subjected to compressive stress due to
the thermal impact of high temperature metal liquid and the constraint of steel shell. On the whole, the thermal stress of the nozzle decreases with the increase of the distance from the pouring hole. There is a large stress concentration near the casting hole at the top of the nozzle and at the junction of H1 and P2 material at the bottom of the nozzle. The thermal stress in most other areas of the nozzle is relatively uniform. Therefore, in order to reduce the thermal stress borne by the nozzle and reduce the stress concentration, the bottom of the nozzle, the top of the nozzle and the area around the casting hole can be optimized and improved.
3.2. Design and optimization of nozzle structure

The optimal design of composite nozzle structure can effectively reduce stress concentration and improve the performance of the nozzle. Orthogonal experimental design is a design method that uses orthogonal table to study multi-factors and multi-levels, and calculates and analyzes the experimental results. It can achieve the equivalent results with a large number of comprehensive tests with the least number of tests. In this paper, the main structural parameters of the nozzle are optimized by orthogonal design method, and the best parameter combination scheme is obtained. For A, B, C three structure parameters, set three variables for each structure parameter. The three parameters affecting the nozzle structure and their corresponding three indicators are shown in Table 6.

According to the parameters and index number, an orthogonal table is made to design the finite element simulation scheme. The 9 simulation parameter combination schemes are shown in Table 7.

3.3. Simulation results and analysis

Nine parameter combinations in Table 7 were selected to create the nozzle model and conduct finite element simulation. Due to the extrusion of ladle sliding device, part of the upper part of the nozzle is subjected to tensile stress, while the rest of the nozzle is subjected to compressive stress due to the thermal impact of high temperature metal liquid and the constraint of steel shell. As can be seen from Figure 5, the compressive stress of the nozzle on the whole decreases with the increase of the distance from the pouring hole, and there is a certain stress concentration near the casting hole at the top of the nozzle and at the junction of H1 and P2 materials at the bottom of the nozzle. In the initial stage of casting, the nozzle compressive stress increases obviously, and the state tends to be stable with little change of compressive stress when the casting process reaches 750 s.

Because the key point Q is close to the top of the nozzle and is subjected to the pressure of ladle slide plate and the thermal impact of metal liquid, the key point R is located at the bottom of the nozzle and is subjected to the thermal impact of high-temperature metal liquid and the constraint of steel shell. Therefore, the stress of key points Q and E changes significantly and the stress is large. While point W is located in the middle of the nozzle and is close to the casting hole, heat transfer is fast and it is not easy to generate heat concentration. Point E is located in the interior of P2 material and is far away from the casting hole, and heat loss will occur when it passes.
through the junction between H1 material and P2 material. Therefore, the average stress of key points E and W is relatively small with a small variation range.

As shown in Figure 6, in the simulation results of case1-9, the maximum compressive stress at the nozzle is 103.6 MPa, 118.1 MPa, 104.3 MPa, 105.2 MPa, 102.7 MPa, 102.5 MPa, 117.4 MPa, 106.1 MPa and 120.6 MPa, respectively. The stress concentration area of case1, case2, case3 and case5 is the edge of the casting hole on the upper surface of the nozzle and the junction of H1 material and P2 material at the bottom of the nozzle, with relatively large area. In addition to the above mentioned stress concentration areas in case4 and case6 simulation results, there is also a certain stress concentration on both sides of the casting hole wall. It can be seen from the cloud image that the composite nozzle stress concentration area of these two structures is the largest. However, the average stress of the nozzle of case7, case8 and case9 is relatively small, and the area of stress concentration is

Figure 6. The thermal stress nephogram of the nozzle of different composite structures based on the principle of maximum stress, (a) case 1, (b) case 2, (c) case 3 (d) case 4, (e) case 5, (f) case 6 (g) case 7, (h) case 8 and (i) case 9.
also small. With the change of A value, B value and C value, except for key point E, the locations of other key points are inside P2 material, the junction of P2 and H1 material and inside H1 material in sequence. When the key point is located inside H1 material, due to its good thermal conductivity, there will be no large temperature gradient and low thermal expansion coefficient, so the stress generated is relatively small. When the key point is located at the junction of H1 and P2 materials, due to the different thermal conductivity and thermal expansion coefficient of the two materials, there will be a certain thermal expansion coefficient mismatch at the interface, so the stress concentration will occur. This stress concentration changes with the difference of the distance between H1 material and the casting hole, that is, the difference of B value. When the key point is inside P2 material, the thermal conductivity of P2 material is small, the thermal expansion coefficient is large, and the heat is easy to concentrate, leading to the concentration of thermal stress. 

In this study, the average thermal stress value at the four key points E, W, Q, and R of the composite structure nozzle is selected as the structural optimization target. The smaller the stress value, the better the optimization result. Therefore, there are four optimization objectives in this study. Table 8 shows the average thermal stress values of 9 groups of nozzles with different structural parameter combinations at 4 key points. The orthogonal optimization results of the nozzle structure can be reflected by the stress values in these four places. Among the 9 groups of simulation results, the stress value of key point E in the second group is the lowest, which is $-71.9$ MPa, and the corresponding structural parameter combination is A1-B2-C3. The stress value of the fourth group of key points W is the smallest, which is $-73.9$ MPa, and the corresponding structural parameter combination is A2-B1-C3. The stress of the first group of key points Q and R is the minimum, which are $-80.2$ MPa and $-98.4$ MPa respectively. The corresponding structural parameter combination is A1-B1-C1.

The range analysis of the simulation results is carried out. Calculate the sum and average value of the corresponding index data of parameters A, B and C at each level, and perform range calculation. Table 9 is the range analysis table of orthogonal optimization test results. In this paper, the range analysis can scientifically and intuitively select the best combination of nozzle structure parameters. The four optimization indexes in table 9 correspond to the K values of three structural parameters respectively. K1, K2, and K3 in the table are the sum of
the stress values of the structural parameters A, B, and C at three levels respectively, that is, the sum of the stress data of the corresponding groups of simulation results in table 8. k1, k2, and k3 are the averages of K1, K2, and K3, respectively. The larger the average value k, the greater the influence of its corresponding level on the optimization of the nozzle structure. The R value is the difference between the maximum and minimum values of k-means. The range analysis evaluates the simulation results through the R value (factor range value). The larger the R value, the greater the influence of the corresponding structural parameters on the optimization of the nozzle structure.

The level changes of the main parameters have a great influence on the index, so the optimal level must be selected, while the secondary factors have a little influence on the index, so the appropriate level can be selected according to the actual situation. As shown in table 9, the primary and secondary order of the influence of the three structural parameters on the thermal stress of key points E, W, and Q are respectively C, A, B; C, B, A; B, C, A; A, C, B. According to the average value of four indexes, the optimal level combination of each structural parameter is determined. For the thermal stress of key point E, structural parameter C has the greatest influence, and the second level C2 is 120mm. Structural parameter A is the secondary influencing factor, and the third level A3 is 45mm. Structural parameter B has the least influence, and the second level B2 is 36mm, so the optimal combination C2-A3-B2 is obtained. Similarly, for the thermal stress of key points W, Q, and R, the optimal parameter combination is C1-B3-A1, B3-C3-A3 and A1-C2-B1, respectively.

Through the finite element simulation of 9 groups of compound nozzle structures with 4 kinds of structural parameters, 4 groups of optimal combinations are obtained. Now the optimal combination is selected from the 4 groups of structural combinations. As for the structural parameter A, it has the greatest influence on the thermal stress value of the key point R. In this case, it takes A1, and its influence on the thermal stress value of the key point E takes the second place, also taking A1. Therefore, the structural parameter A is A1. As for the structural parameter B, it has the greatest influence on the thermal stress value of key point Q. In this case, it takes B3, and its influence on the thermal stress value of key point W ranks second, also taking B3. So the structural parameter B is B3. For structural parameter C, it has the greatest influence on the thermal stress value of key points E and W. In this case, C2 and C1 are selected, respectively. The thermal stress value of key points Q and R is ranked second, and C3 and C1 are selected, respectively. So the structural parameter C is C1. To sum up, the optimal structural combination is A1-B3-C1. The composite nozzle structure is used for finite element simulation, and the simulation results are shown in figure 7.

It can be seen from figure 7 that the stress value of the nozzle after structural optimization ranges from −118.4 MPa to 45.1 MPa, and the thermal stress of the nozzle before structural optimization ranges from −268.5 MPa to 125.2 MPa. Compared with that before optimization, the stress extreme value decreases by 32.9%, and the average stress of the nozzle as a whole also decreases to a certain extent. Meanwhile, the stress concentration area is significantly reduced.

| Table 8. Analysis of extreme differences in simulation results. |
|-------------|-----|-----|-----|-----|
|     Case     |   E  |   W  |   Q  |   R  |
| ----------- |-----|-----|-----|-----|
|    1        | −72.3MPa | −74.3MPa | −80.2MPa | −98.6MPa |
|    2        | −71.9MPa | −75.1MPa | −83.6MPa | −111.7MPa |
|    3        | −73.1MPa | −74.6MPa | −82.8MPa | −99.8MPa |
|    4        | −72.1MPa | −73.9MPa | −81.9MPa | −108.3MPa |
|    5        | −74.9MPa | −74.8MPa | −86.9MPa | −99.1MPa |
|    6        | −75.1MPa | −75.6MPa | −81.3MPa | −109.2MPa |
|    7        | −74.3MPa | −75.9MPa | −84.2MPa | −107.5MPa |
|    8        | −74.4MPa | −75.5MPa | −83.7MPa | −112.2MPa |
|    9        | −73.5MPa | −73.8MPa | −75.6MPa | −120.5MPa |

| Table 9. Analysis of extreme differences in simulation results. |
|-------------|-----|-----|-----|-----|
|     E       |   W  |   Q  |   R  |
|  K1         | −217.5 | −224.1 | −222 | −224 | −224.1 | −225.4 | −246.6 | −246.3 | −245.2 | −309.9 | −314.2 | −319.8 |
|  K2         | −222.1 | −221.2 | −222.3 | −224.3 | −225.4 | −225.3 | 250.1 | −254.2 | −253.9 | −316.6 | −323 | −306.4 |
|  K3         | −222.2 | −221.7 | −217.5 | −225.2 | −224 | −222.8 | −243.5 | −239.7 | −241.1 | −340.2 | −329.5 | −340.5 |
|  k1         | −72.5 | −74.7 | −74 | −74.7 | −74.7 | −75.1 | −82.2 | −82.1 | −81.7 | −103.3 | −104.7 | −106.6 |
|  k2         | −74 | −73.7 | −74.1 | −74.8 | −75.1 | −75.1 | −83.4 | −84.7 | −84.6 | −105.5 | −107.7 | −102.1 |
|  k3         | −74 | −73.9 | −72.5 | −75.1 | −74.7 | −74.3 | −81.2 | −79.9 | −80.4 | −113.4 | −109.8 | −113.5 |
|    R        | 1.5 | 1 | 1.6 | 0.4 | 0.5 | 0.8 | 2.2 | 4.8 | 4.2 | 12.1 | 5.1 | 11.4 |
4. Conclusion

A new composite structure nozzle is optimized by using finite element simulation and orthogonal test method. It is composed of two different materials, the inner material has excellent thermal physical properties, and the outer material has low cost, which can improve the performance and service life of the nozzle and reduce the cost. The distribution and variation of nozzle temperature and thermal stress during casting were studied by selecting representative key points in nozzle. Simulation results show that the temperature gradient of the nozzle near the casting hole changes significantly, and the heating rate slows down with the increase of the distance from the casting hole. With the increase of temperature, the composite structure nozzle mainly produces compressive stress. Analyzing the simulation results are poor, it is concluded that the optimal structure of the composite nozzle, it compared with before optimization, the thermal stress of extremum peace stress were significantly decreased, soaking in the working process of the maximum stress value decreases by 32.9%, verify the reliability and rationality of new composite nozzle structure, for the new type of composite structure of nozzle provides a solid theoretical basis for practical production.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

ORCID iDs

Fengxian Li  @  https://orcid.org/0000-0001-6055-0408
Yichun Liu  @  https://orcid.org/0000-0002-8421-6348

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