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THERMAL MECHANICAL STRESS ANALYSIS OF LADLE LINING WITH INTEGRAL BRICK JOINT

Based on the theory of heat transfer, the influence of expansion joints on the temperature and stress distribution of ladle lining is discussed. In view of the current expansion joint, the mathematical model of heat transfer and the three dimensional finite element model of ladle lining brick are established. By analyzing the temperature and stress distribution of ladle lining brick when the expansion joints are in different sizes, the thermal mechanical stress caused by the severe temperature difference can be reduced by the suitable expansion joint of the lining brick during the ladle baking and working process. The analysis results showed that the thermal mechanical stress which is caused by thermal expansion can be released through the 2 mm expansion joint, which is set in the building process. So we can effectively reduce the thermal mechanical stress of the ladle lining, and there is no risk of steel leakage, thus the service life of ladle can be effectively prolonged.

Keyword: Ladle; Heat transfer model; Lining; Expansion joint; Thermal mechanical stress

1. Introduction

The thermal mechanical stress is one of the important reasons for the failure of the ladle under high temperature and heavy load. Under the working of high temperature, when the ladle lining and ladle shell by thermal expansion deformation are generated from each other mutual restraint, they produce heat mechanical stress. Gongfa Li proposed a new type of Nano thermal insulation material for ladle lining structure based on heat transfer theory and finite element technology, a new three-dimensional finite element model of ladle is established. The research results show that the thermal insulation effect of Nano thermal insulation material is good and the maximum stress of the new shell is lower than that of the traditional ladle that is 114 MPa [1-2]. The thermal stress of ladle lining in the working state was analyzed by A.S. Nikiforov. It shows that the thermal stress of ladle lining and the tensile stress of the shell are very large in the course of working. Under the action of such a large thermal stress, the ladle lining is crushed and broken. Finally, the lining is broken and eroded by molten steel [3]. V.K. Orlov analyzed the reason of ladle lining damage. The ladle in the process of using has been eroded by molten steel. A new method for thermal repair is put forward which is paint the spray coating to the damaged parts [4]. Jin Congjin calculates the temperature distribution of ladle lining in the baking condition. The influence on the working layer, the permanent layer and the insulation layer of thickness on the temperature field of the ladle was studied [5]. Jiang Guozhang has established the finite element model of the expansion joint of the ladle bottom liner in the ladle composite structure by using ANSYS based on the finite element method [6]. In view of the above problems, the method is to set expansion joint. Expansion joints are too large to cause leakage of steel and major accidents. Expansion joints are too small to increase thermal stress and reduce the use of shell and refractory bricks. The calculation of thermal expansion stress is of great practical value [7]. The size of the expansion joint of the lining is determined in the process of building the ladle. The standard thickness of the board is placed on the side of the expansion joint of the ladle lining. At the end of the ladle baking package into the steel of conditions, the board is set aside the expansion joint due to high temperature combustion. In order to reduce the thermal stress of ladle lining and to avoid the occurrence of steel leakage, the size of expansion joint of ladle lining is considered. Therefore, when the ladle is finished into the steel working condition, expansion gap for lining working layer will be filled with the expansion of the lining brick to ensure the safety of production. In this paper, the mathematical model of heat transfer and finite element model of ladle lining are established. The influence of expansion joint size from 0 mm to 4 mm on the thermal mechanical stress is analyzed by the ANSYS finite element method. It provides guarantee for the safe production of steel making process in the future [8-9].

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2. Finite element modeling

Since actual ladle loads heavily and requires frequent lifting, it's similar to the bucket in shape, but it's oval, there isn't much difference between its' long axis and short axis. In order to facilitate the finite element modeling and subsequent analysis, it assumes that the long axis and short axis are equal. That is to say both the inner and outer side of ladle is round [10]. After reducible process, it can be concluded that temperature loads of molten steel on the circumferential wall are equal. On the same horizontal line, the lateral pressure that exerted by gravity of molten steel is equal, as the depth increases; it increases accordingly [11-13]. The heat of molten steel has been reduced to a very small part by the thermal resistance of the working and permanent layers, the heat loss have been reduced to a very small part, the shell mainly plays the role of load-bearing. Shell is easy to deform under the action of high temperature, it is also steel products and cannot withstand the higher temperature. The working layer is made of materials with low thermal conductivity, corrosion resistance and impact resistance, the thermal conductivity of the permanent layer cannot be high, the shell is made of steel, which is generally made of high strength steel. In the process of simulation calculation, the ladle can be taken to reach a stable state in the process of working. At this time, the ladle can be regarded as a steady-state temperature distribution. The following figure is a model of working layer, permanent layer and shell of ladle. Ladle heat transfer model is illustrated in Figure 1. r_0 and r_1 is the inner diameter and outer diameter of ladle working layer respectively. r_2 and r_3 is the outer diameter of the permanent layer and outer diameter of the outer shell respectively. the corresponding temperature of T_0, T_1, T_2, T_3 in Figure 1 is of r_0, r_1, r_2, r_3 respectively. The thermal conductivity of the working layer, the permanent layer and the shell of the ladle is K_1, K_2, K_3 respectively. In thermal equilibrium, heat flow of the circular section can be expressed as:

$$Q = \frac{2\pi KL(T_x - T_y)}{\ln\left(\frac{r_y}{r_x}\right)} \tag{1}$$

Among: Q is the heat flux in the thermal equilibrium state, the unit is W; T_x and T_y are the temperature of the point corresponding to x and y, the unit is K. K is heat conductivity of cylindrical section, the unit is $W/(m \cdot K)$; r_x and r_y are the radius of the point corresponding to x and y, the unit is m. Thermal resistance of cylindrical section is as below:

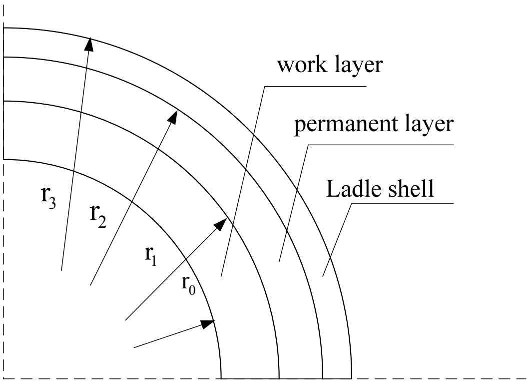

Fig. 1. Heat transfer model of ladle

$$R = \frac{\ln\left(\frac{r_y}{r_x}\right)}{2\pi KL} \tag{2}$$

Combine the thermal resistance of the lining brick and the permanent layer with the shell of the ladle, it can be expressed that the total thermal resistance is

$$R = \frac{1}{2\pi L}\left[\frac{\ln\left(\frac{r_0}{r_1}\right)}{K_1} + \frac{\ln\left(\frac{r_1}{r_2}\right)}{K_2} + \frac{\ln\left(\frac{r_2}{r_3}\right)}{K_3} + \frac{1}{\alpha}\right] \tag{3}$$

Among: K_1 is the thermal conductivity of ladle shell, the unit is $W/(m \cdot K)$; K_2 is the thermal conductivity of refractory materials of the permanent layer, the unit is $W/(m \cdot K)$; K_3 is the thermal conductivity of refractory materials of the lining bricks, the unit is $W/(m \cdot K)$; α is an integrated heat transfer coefficient considering thermal radiation and convection heat transfer in ladle shell [14-15]. The temperature on the surface of the ladle shell can be expressed by the heat flux on the surface layer. The temperature on the surface of the ladle shell can be obtained by the heat flux and the relative temperature of different parts in different sections. The temperature (T_0) of ladle shell surface can be obtained. The formula below can be used for calculating the temperature of ladle shell [16-17].

$$T_0 = T_3 - Q\left[\frac{\ln\left(\frac{r_0}{r_1}\right)}{K_1} + \frac{\ln\left(\frac{r_1}{r_2}\right)}{K_2} + \frac{\ln\left(\frac{r_2}{r_3}\right)}{K_3}\right] \tag{4}$$

Among: Q is the heat flux through the side wall section of the ladle, the unit is W, r_x and r_y are radius on the position of x and y, the unit is m; K_1 is thermal conductivity of ladle shell, the unit is $W/(m \cdot K)$; K_2 is thermal conductivity of refractory materials of the permanent layer, the unit is $W/(m \cdot K)$; K_3 is the thermal conductivity of refractory materials of the lining bricks, the unit is $W/(m \cdot K)$ [18].

It is very important to set the parameters of the material when the finite element method was used to simulate the temperature field and stress field of ladle lining brick. Due to the material parameters are generally changed with the change of the temperature of the material, it is difficult to find the parameters of the material under various temperature conditions from the existing information. Therefore, the parameters of the material in other temperature can be calculated by interpolation method based on the existing temperature conditions. In the process of thermal stress analysis, the parameters of material are mainly concluding:the thermal conductivity, specific heat capacity, density, expansion coefficient, elastic modulus, Poisson's ratio etc. The material property parameter of ladle lining is shown in Table 1 [19].

TABLE 1

Material property parameters of ladle lining

Physical parameters / Refractory	Expansion coefficient (K^{-1})	Density Kg/mm^{-3}	Modulus (MPa)	Poisson ratio
Working layer	8.5e–6	2.95e–6	6300	0.21
permanent layer	5.8e–6	2.8 e–6	5700	0.21
Ladle shell	13e–6	7.8 e–6	175000	0.3

According to the ferrous metallurgy industry standard YB/T4198-2009 “the shape and size of refractory bricks for ladle”, according to the use of the site, the ladle lining firebrick can be divided into refractory bricks for wall and bottom. The former can also be divided into wedge brick side thick wedge brick and a half million ladle brick [20]. The latter is also called ladle bottom brick. The type of ladle lining brick is shown in Fig. 2.

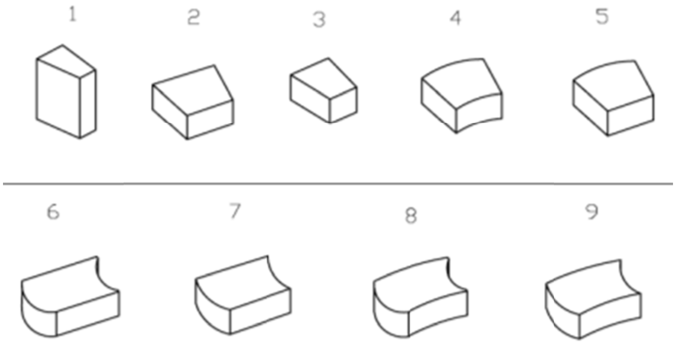

Fig. 2. Types of ladle lining brick

The single layer method is based on the principle that the refractory material is considered as a single ring, and the ladle shell is considered as another ring. At the same time, single method employs a experience parameters – the equivalent gap. The equivalent gaps are used to represent the radial and upward initial loose between refractory brick and the contractility of refractory clay. It is also used to correct the simple way in the process of modeling and adjust to the unstable properties of refractory bricks under the condition of high temperature.Single method of calculating diagram as shown in Fig. 3.

Equivalent interval parameter is seen as a function of the radius between brick lining and the ladle shell interface, the coefficients of function expression are chosen based on past experience and analysis of the research work. During ladle preheating, the stress of ladle shell is generated due to the expansion of the liner, and the maximum stress value of the ladle shell appears in this period.Calculation of the maximum stress value of the ladle shell origin :

$$\sigma_s = \frac{pr_2}{t_s} \tag{5}$$

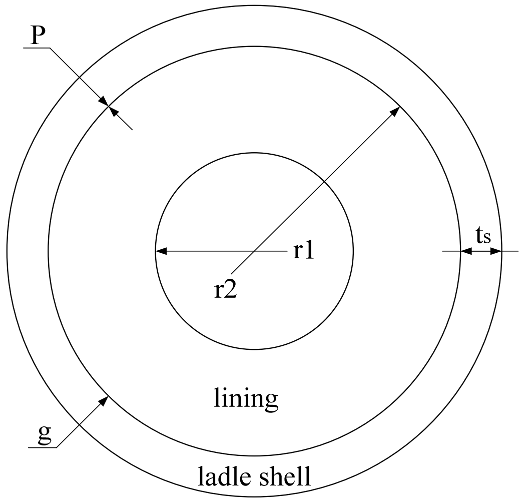

Fig. 3. Single method for the calculation of the diagram

Calculation of the stress of the refractory brick:

$$\sigma_b = \frac{-2pr_2^2}{r_2^2 - r_1^2} \tag{6}$$

Calculation of interaction pressure origin:

$$P = \frac{C}{A+B} \tag{7}$$

Among:

$$A = \frac{r_2}{E_b}\left(\frac{r_2^2 + r_1^2}{r_2^2 - r_1^2} - \upsilon_b\right)$$

$$B = \frac{r_2}{E_s}\left(\frac{r_2}{t_s} + \upsilon_s\right)$$

$$C = \frac{1}{2\alpha_b \Delta T_b (r_1 + r_2)} - \alpha_s \Delta T_s r_2 - g$$

P is the interaction between the lining brick and the ladle shell, σ_s and σ_b are respectively the stress which is caused by the expansion of ladle shell and lining brick. r_1 and r_2 are respectively the inner and external diameter of the lining, the thickness of the shell is t_s, α_s and α_b are respectively the thermal expansion system of ladle shell and lining brick. ΔT_s And ΔT_b are respectively the ladle shell and lining brick of temperature increment, E_s and E_b are respectively the elastic modulus for ladle shell and lining brick. υ_s and υ_b are respectively poison’s ratio for ladle shell and lining brick. G is experience equivalent gap on the ladle shell, taking 0.075% of interface radius.

In this paper,the structure size of the wedge is chosen as the $170 \times 155 \times 100$ mm as the analysis object for analyzing the thermal stress distribution of lining brick.The expansion gap will be set as 2 mm between the bricks in the model. In order to simplify the analysis, a layer of brick thickness along the height of the ladle is analyzed. The finite element model of lining brick for ladle is shown in Fig. 4.

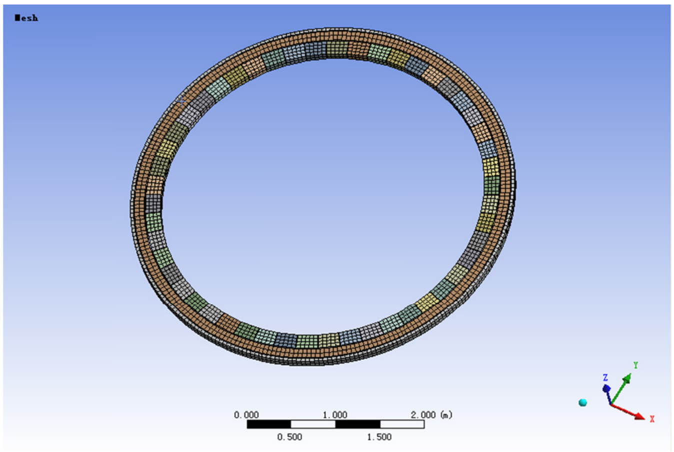

Fig. 4. Finite element model of inner lining of ladle lining

3. The relationship between the size and the stress of the expansion joint of the ladle lining

The high temperature molten steel in the ladle is directly contacted with the inner lining of the working layer. Under the action of molten steel, the temperature of the inner lining is gradually reduced from the inside of the ladle. Due to high temperature, the lining brick expands, while the expansion clearance can be exactly filled by the expansion rate. The method can greatly reduce the thermal stress between the lining brick and also the working layer and the permanent layer, which lays the foundation for the safety production of the steel making plant. Expansion clearance can reduce a part of compressive stress. If the expansion clearance is too small, stress will increase, if it is too large, it may cause the leakage of steel, so it is meaningful to set the suitable expansion clearance for service life of ladle lining [21-23].

Ladle lining brick work under high temperature and heavy load. Lining material damage is mainly because of the lining brick between the thermal stress of extrusion and cracking, peeling off. The thermal stress of the lining of the working layer is part of the extrusion from each other, and a part of the expansion of the lining brick from the upper and lower layers. Appropriate expansion joint have great effect on the reduction of thermal stress. It is not obvious that the expansion joint is set up too small to reduce the thermal stress. The service life of lining brick is reduced. Expansion joint setting is too large may lead to infiltration of molten steel production safety problems and cause major accidents. The size calculation of expansion joint is of great practical value [24-25]. Contact is one of the most common physical phenomena in nature, and the objects in contact with each other can transmit power, heat and so on. Contact is a simple and complex problem. the two objects in contact with each other can be determined whether contact by determining the contact surface of the distance its contact surface elastic deformation occurs elastic deformation will also very small when objects of the normal contact stiffness coefficient is small [26].Contact problem is a complex nonlinear problem, which belongs to the nonlinear problem of boundary conditions. Its complexity mainly comes from the change of system state which is the separation and contact between objects. In the contact problem, the contact surface between the two contact bodies is usually unknown, and the boundary conditions depends on the calculation results rather than giving before the calculation. The contact area and pressure distribution of the two contact surfaces are changed with the change of the external load and the initial clearance, and are related to the rigidity of the contact body. Deal with contact problems mainly include the penalty function method and penalty function method and Lagrange multiplier method. When the gap between the contact surface and target surface is more than zero, it is the open access; When it is less than zero, it belongs to the close contact. The contact permeability is represented by the gap value, and the contact occurs when the contact point penetrates the target surface. The relationship between the normal force of Contact part F_n with the clearance value is expressed as:

For the penalty function method, the normal contact force is expressed as:

$$F_n = \begin{cases} K_n \times g & g \le 0 \\ 0 & g \ge 0 \end{cases} \tag{8}$$

Among them, K_n is the contact stiffness; g is the contact gap.

For penalty function and Lagrange multiplier method, the force of Lagrange polynomial is repeated iterated in each unit, and the normal contact force is expressed as:

$$F_n = \min(0,\ \ F_n \times g + \lambda_{i+1}) \tag{9}$$

Among them, λ_{i+1} is the $i+1$ in the iteration step for Lagrange multiplier, it is expressed as:

$$\lambda_{i+1} = \begin{cases} \lambda_i + a \times K_n \times g & |g| \ge FTOLN \\ \lambda_i & |g| \le FTOLN \end{cases} \tag{10}$$

FTOLN is the compatibility of user defined clearance limit, a is internal calculation factor ($a < 1$).

The frictional force of the contact surface is the tangential force of the contact surface, which is caused by the contact node encountering and moving along the target node.

The process of thermal structure analysis is divided into direct and indirect coupling. Direct coupling uses thermal structural units directly and the temperature field and the stress field can be obtained by applying the structural load to the thermal structural unit. Indirect coupling is the temperature field analysis of the lining brick of ladle lining. In the process of structural analysis, the temperature unit is converted to the structural unit, and the result of the temperature analysis is applied to the structural analysis as the temperature load. The common results of temperature and structural loads are obtained by two calculation steps. The lining brick of ladle lining is the expansion thermal stress caused by high temperature in the actual working process. In the process of finite element simulates load and constraint, the degree of freedom coupling is very convenient, so the indirect coupling method is used in this paper.

Lagrange multiplier method is used to calculate and analysis through the understanding of nonlinear contact. the specific calculation formula of Lagrange multipliers are practical and simple, as long as the balance equation and the internal force function are given, it can be directly eliminated by the formula Lagrange multiplier. Finally, the reaction force and the internal force are obtained [27]. The ladle is analyzed for finite element through a piece of brick lining thickness selected from the direction of the height, so geometric model is shaped and the work layer lining bricks, integral casting permanent layer and steel ladle shell concluded. The adjacent two bricks in the working layer lining brick will be in contact with each other and each lining brick will be in contact with the permanent layer [28]. In the establishment of the model, the surface should be set face-to-face contact due to the thermal expansion of the contact surface.

The expansion joints and the size of the stress were studied by selecting several typical inner liner expansion in different sizes and the expansion joints were studied by 0 mm, 1 mm, 2 mm, 3 mm and 4 mm, respectively. In the analysis of the stress of ladle lining of integral brick, it is required to analyze the temperature of ladle firstly, then impose the result of temperature analysis on the structure analysis and apply the thermal structure coupling principle on the basis of temperature analysis. In structural analysis, it is needed to define the properties of the material, such as specific heat, elastic modulus, Poisson's ratio, density and so on. Because of the temperature of the ladle is varied, the various properties of the material should also be applied to simulate the temperature and stress of the ladle with the change of temperature realistically. We can learn about the stress distribution of ladle integral and working lining brick from figure 5÷15 with expansion joint of ladle lining set to 0 mm÷4 mm.

From Figure 5 and figure 6, we can be seen the ladle shell stress is184 MPa when expansion joints is not set, its force is very strong, the main reason is that allowance for expansion of lining bricks cannot be used to offset part of ladle shell stress due to expansion gap is not set.

Compared from figure 5 to 8, we can see stress of ladle shell have been reduced to 158 Mpa from the original 184 MPa when expansion joints of ladle lining brick is from 0mm to 1mm. During expansion joints increased along the thickness direction of lining brick, the stress have reduced from 55 MPa to 44 MPa when the 0mm was reduced to 1 mm.

Compared from figure 5 to figure 10 shows that stress of ladle shell have been reduced to 121 Mpa from the original 184 MPa when expansion joints of ladle lining brick is from 0 mm to 2 mm, the effect of stress reduction is still very obvious.

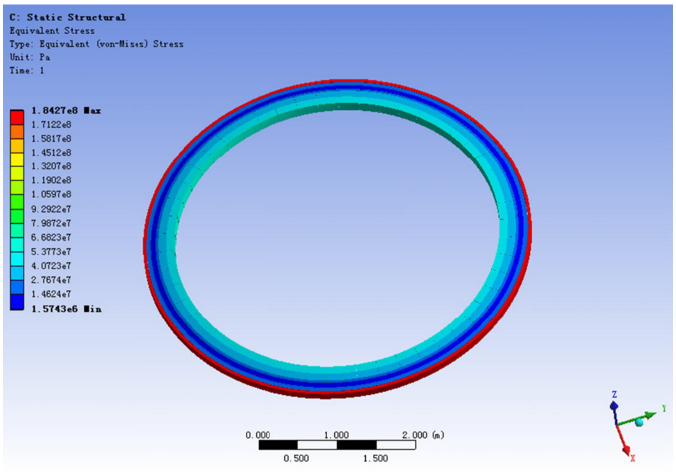

Fig. 5. The overall stress distribution of ladle in the expansion joint with 0 mm

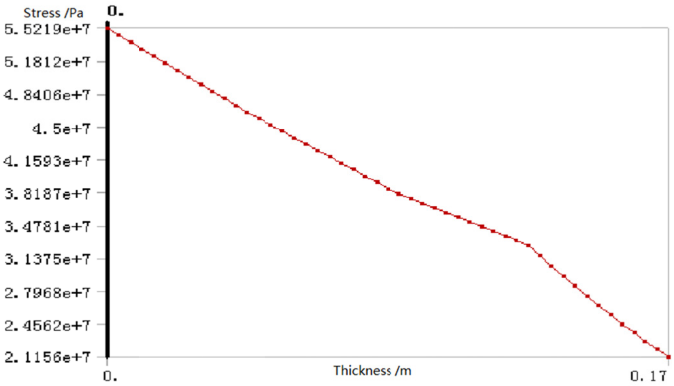

Fig. 6. The distribution of the stress along the thickness of the lining of the working layer when the expansion joint is set up 0 mm

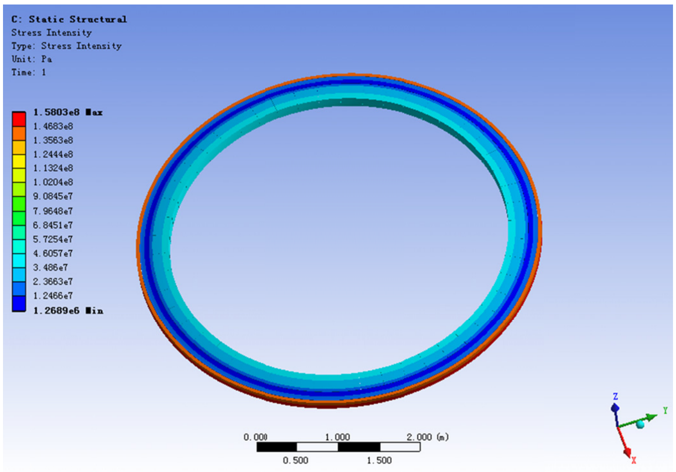

Fig. 7. The overall stress distribution of ladle in the expansion joint with 1 mm

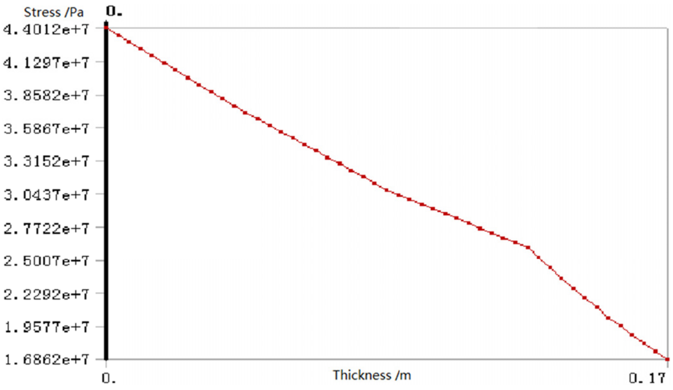

Fig. 8. The distribution of the stress along the thickness of the lining of the working layer when the expansion joint is set up 1 mm

During expansion joints increased along the thickness direction of lining brick, the stress has reduced from 55 MPa to 36.5 MPa when the 0 mm was reduced to 2 mm.

From figure 5 to figure 12 shows that stress of ladle shell have been reduced to 96 Mpa from the original 184 MPa when expansion joints of ladle lining brick is from 0 mm to 3 mm,

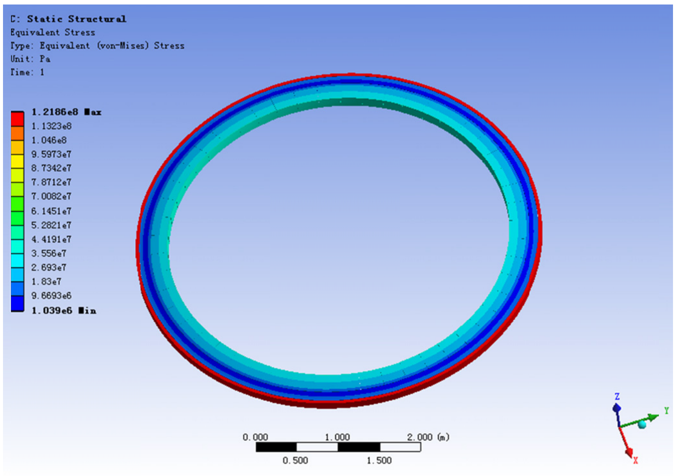

Fig. 9. The overall stress distribution of ladle in the expansion joint with 2 mm

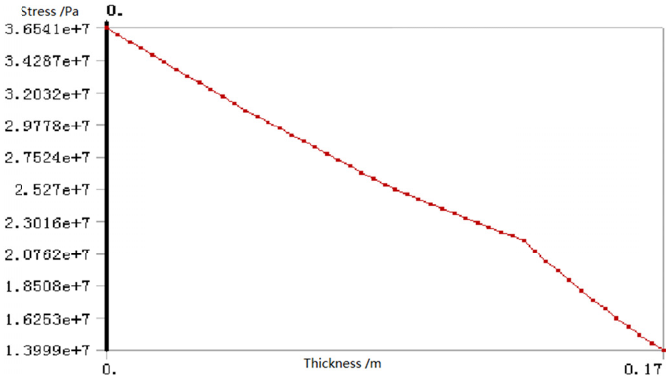

Fig. 10. The distribution of the stress along the thickness of the lining of the working layer when the expansion joint is set up 2 mm

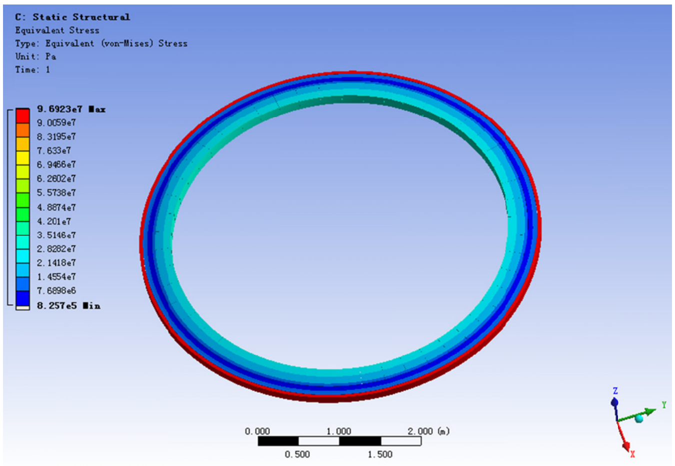

Fig. 11. The overall stress distribution of ladle in the expansion joint with 3 mm

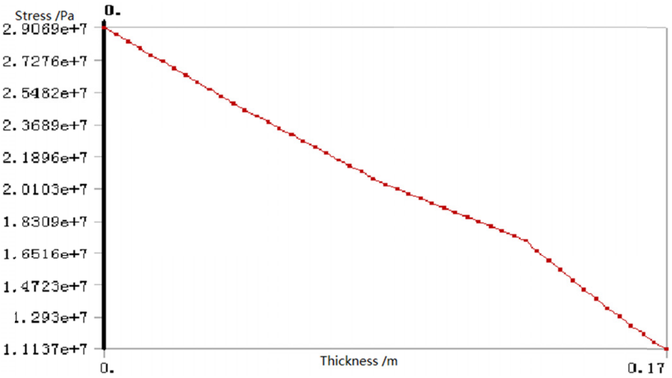

Fig. 12. The distribution of the stress along the thickness of the lining of the working layer when the expansion joint is set up 3 mm

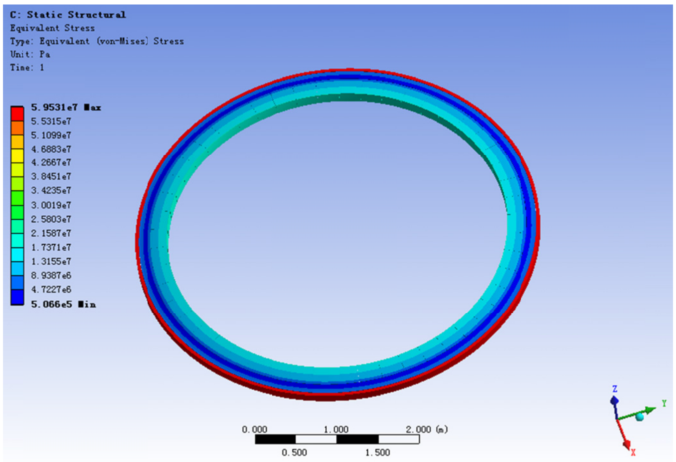

Fig. 13. The overall stress distribution of ladle in the expansion joint with 4 mm

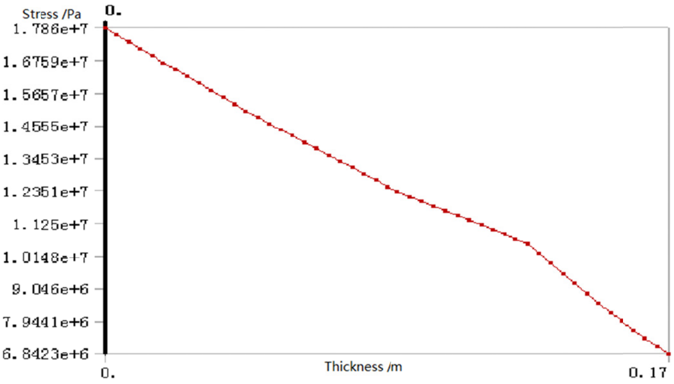

Fig. 14. The distribution of the stress along the thickness of the lining of the working layer when the expansion joint is set up 4 mm

When the expansion joint increased, the stress of the ladle shell can be reduced a lot. During expansion joints increased along the thickness direction of lining brick, the stress has reduced from 55 MPa to 29 MPa when the 0 mm was reduced to 3 mm.

From the above figure 5 to 14, the stress distribution of ladle lining expansion joint from 0÷4 mm lining structure can be seen that In the process of increasing the expansion joint of the lining brick in the baking bag stage from 0 mm to 4 mm, the ladle shell stress is maximum, and the maximum stress is 184 MPa when the expansion joint is not set. When the expansion joint increased, the stress of the ladle shell can be reduced a lot, the main reason is that expansion joint offset part of allowance of expansion of lining brick when it increased. The outward expansion force decreases and the permanent layer and cladding is reduced correspondingly [29]. The stress distribution of lining brick along the thickness direction can also be seen during expansion joints increased along the thickness direction of lining brick, the stress have reduced from 55 MPa to 17.8 MPa when the 0mm was reduced to 4 mm.

According to figure 5 to figure 14, when ladle lining expansion joint is from 0 mm÷4 mm, the data describing its distribution of stress is shown in figure 15.

The analysis shows that the temperature of inner lining brick of ladle lining is linear decreasing from inside to outside. The gradual decrease of temperature leads to the change of thermal stress between the inner lining brick and the temperature. In baking stage pack wall temperature is 1000°C.When the expansion joints are not set, the maximum thermal stress of ladle lining brick is 55.2 MPa and the tensile stress of the ladle shell is 184 MPa. When the expansion joint is 1.mm, the maximum thermal stress of ladle lining brick is 44.0 Mpa, and the tensile stress is 158 MPa. When the expansion joint increases to 2 mm, the maximum thermal stress of ladle lining brick is 36.50 Mpa, and the tensile stress is 121 MPa. When the expansion joint increases to 3 mm, the maximum thermal stress of ladle lining brick is 29.0 Mpa, the tensile stress of cladding 96.9 MPa. When the expansion joint increases to 4mm, the maximum thermal stress of ladle lining brick is 17.8.0 Mpa, and the tensile stress is 59.5 MPa. When the expansion joint is larger, the stress of the lining brick will become smaller and smaller. The gap between lining brick is too large to produce leakage of steel accident. Therefore, the size of the expansion joint gap of lining brick should be set up properly [30-32].

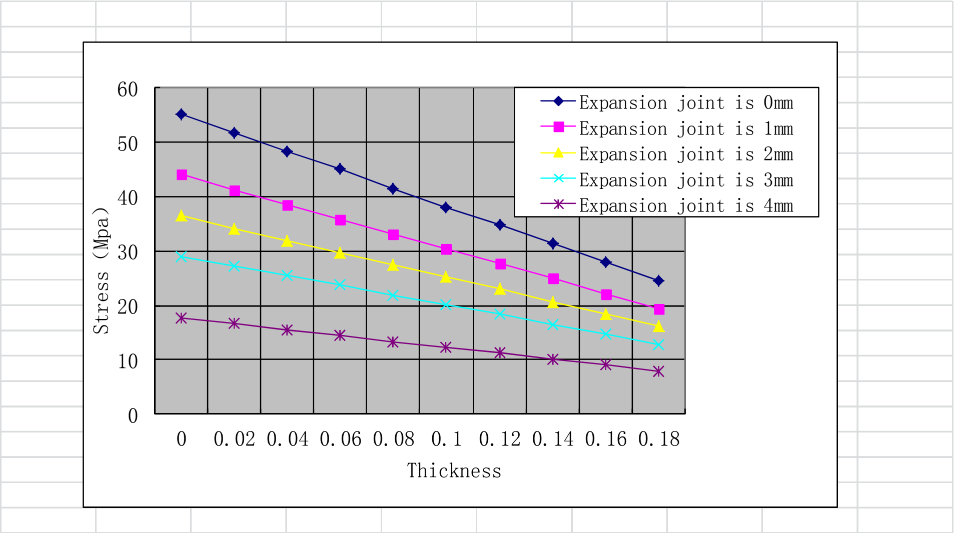

Fig. 15. Relation between expansion joints and stress

4. Conclusion

This paper establishes a mathematical heat transfer model and a finite element model of the lining structure based on heat transfer theory. The overall stress distribution and the stress distribution along the thickness direction of the inner lining of ladle lining with different expansion joint were analyzed by ANSYS software under the baking package. The maximum stress of ladle shell is 184 MPa when the expansion joint is not set. When the expansion joint is arranged, the stress of the ladle shell decreases as the expansion joint increases from 0 mm to 4 mm. When the expansion joint is set to 4 mm, the maximum stress of ladle shell is 59.5 MPa. It shows that the stress of ladle shell decreases obviously. When the expansion joints continue to be increased, the stress between the lining brick becomes smaller and smaller, even decrease to zero. But the expansion joint is set to 4 mm or more, it will produce leakage of steel accident, so the expansion joints of the liner brick should not be too large. Finally, the comparative analysis shows that the thermal mechanical stress of the lining of the ladle lining can be effectively released, when the expansion joint is set to 2 mm under avoiding leakage of steel. The thermal stress of the lining of the ladle lining is effectively reduced, which provides a guarantee for the safe production of the steel in making process. The conclusion also provides a theoretical basis for prolonging the service life of ladle.

Some follow-up studies that the ladle lining's lifetime under thermal mechanic stress was computed mathematically. Also, the analytical prediction of lining lifetime with various expansion joints was carried out. The computational results agree well with the experimental data. This study has offered a good way to prolong the lifetime of ladle lining, which can be a promising method in steel-making.

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