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Simulation Analysis of Stress Distribution and Its Influence Factors of the New Structure Ladle

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Abstract: With the increasing use of iron and steel enterprises, the demand for steel ladle is higher and higher. In this paper, a new type of ladle with heat insulation nano-material lining is put forward. Finite element method is used to analyze the stress distribution of the steel ladle with the new structure. And the stress distribution of the new structure ladle is compared with that of the traditional ladle under the steel holding condition. The results show that the stress distribution of the new structural ladle is better than that of the traditional ladle under the steel holding condition, and the maximum stress can be reduced by 22Mpa. The thermal conductivity, thermal expansion coefficient and elastic modulus of the thermal insulation material of the new structure are determined by the analysis. Stress simulation analysis of then. In a certain range, with the thermal conductivity of nano thermal insulation material is reduced, the stress of the new structure steel shell is reduced. The thermal expansion coefficient is reduced that the shell stress is reduced. However, the decrease of elastic modulus will increase the stress of cladding.

Keywords: ladle , stress distribution , stress simulation , heat insulation nano-material , influence factors

1 Introduction

In recent years, new structure ladle with heat insulation nano-material lining is studied to improve thermal insulation performance of ladle and prolong service life of ladle and some good results are obtained[1]-[7]. Two kinds of ladles temperature falling of liquid steel was studied[8]. One was traditional ladle and another was a new structure ladle with the nanometer adiabatic material. The result showed that temperature of new structure ladle was lower 1.9$^{\circ}C$/min than traditional one and could save 10.5% power. By optimizing adiabatic material, better energy saving and heat preservation was proposed. The heating time was shortened, the whole energy consumption was reduced and the productivity was improved. By using heat transfer theory, temperature distribution of five different drum wall was computed[9]. To further understand stress distribution of drum wall, simplified model of one and two layers was adopted. According to the mathematical derivation, calculation formula for thermal stress of adiabatic lining and shell of ladle was obtained. Ladle model of different working layers were built[10]. There were high alumina brick, dolomite firebrick, magnesia brick and magnesia-carbon brick. Temperature distribution and heat loss were analyzed.

The result showed that initial preheating temperature, stamping and time of refining and pouring were main influence factors of temperature control when magnesia brick and magnesia-carbon brick were adopted to working layer of ladle. Heat Transfer Analysis of ladles with different adiabatic linings was made[11]. Using two-dimensional cross section of ladle as analysis model. Lining temperature gradient and temperature distribution of three different types of ladles were analyzed. There were traditional ladle, heat preservation ladle and low thermal conductivity ladle. The result showed that temperature level of heat preservation ladle was higher than traditional ladle. And its heat was same as traditional

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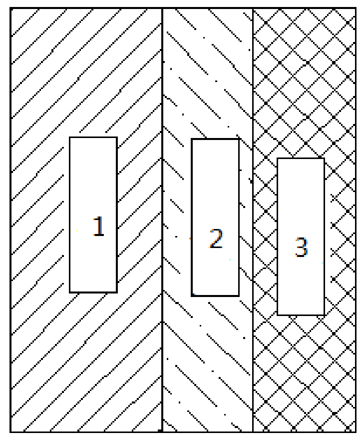
ladle in the condition of steel holding. Finite element method was adopted to simulate highly intensive adiabatic lining and traditional lining[12]. The performance of two ladles was compared in heat loss and stress distribution. The result showed that the performance of ladle with highly intensive adiabatic lining was better than traditional one.

It can be seen from the research of kinds of new structure ladles that heat loss can be reduced and thermal insulation can be improved by adding cover in molten steel surface,adding ladle cover in casting and putting ladle model of multi-contact surface on lining structure[13]. While the effect of stress distribution on shell of ladle and varies of lining materials was studied, research results showed that stress distribution was unsatisfactory. Meanwhile, it was found that high stress of ladle will make ladle material and welding bead crack, and the hot metal infiltration and break out while casting. Therefore, finite element method was used in this paper to analyze stress field of new structure ladle under the condition of steel holding, and the effect of physical parameters of heat insulation nano-material lining, such as, thermal conductivity, elastic modulus and thermal expansion coefficient on ladle was studied to optimize lining structure of new structure ladle and prolong service life of new structure ladle.

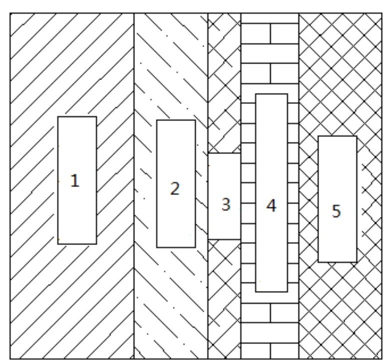
2 ESTABLISHMENT OF NEW STRUCTURE LADLES FINITE ELEMENT MODEL

2.1 Lining structure of new structure ladle

Structure of lining including working layer of aluminum (magnesia carbon), permanent layer (high alumina) and shell (low-carbon steel). While thermal insulation of lining is unsatisfying. And its shell temperature is around 300°*C*, which causes a lot of heat loss and energy profligacy. With the development of adiabatic material, its thermal insulation was enhanced. Structure of traditional ladle was shown in Figure 1. Three layers structure cannot meet the requirement. With more and more nanometer adiabatic material used in industrial smelting equipment, structure of ladle is altered adaptively[14]. Structure of new structure ladle includes working layer of aluminum (magnesium carbon), permanent layer (high alumina), protection layer (low-carbon steel), nanometer heat insulating layer, and shell (low-carbon steel). The new structure ladle studied in this paper, shown in Figure 2. The total height of ladle is 5.210 meter. The height of inner cavity is 4.285 meter. Its external diameter is 3.956 meter and its inner diameter is 3.294 meter. The ladle is five layer structure. There are 170mm magnesium carbon layer, 105 mm high aluminum brick as the permanent layer, 5 mm Q345B as the protection layer, 20 mm nanometer heat insulating layer, and 32 mm Q345 as shell. And its coffering is welded by Q345B plate. Nanometer heat insulating material of gas phase oxidation of silicon and technical preparation of calcium silicate was utilized in thermal insulating nano-material layer. It have good thermal insulation performance, mechanical properties and flame blocking performance. It can be utilized in 1000°*C* working condition. The biggest difference between traditional ladle and new ladle is the fact that nanometer adiabatic material used in lining of new ladle, which improves its thermal insulation performance.



1.Working layer
2.Permanent layer
3.Shell of ladle
Figure 1. Lining structure of traditional ladle



1.Working layer
2.Permanent layer
3.Protection layer
4.Nanometer heat insulating layer
5.Shell of ladle
Figure 2. Lining structure of the new structure ladle

2.2 Establishment of finite element model

The three-dimensional model was built in meters, shown in Figure 3. The SOLID185 element was chosen to analyze stress field of new structure ladle in ANSYS13.0. Automatic mesh generation was chosen; element size was 0.1; 112663 meshes and 23913 nodes were gotten. The finite element model was shown in Figure 4.

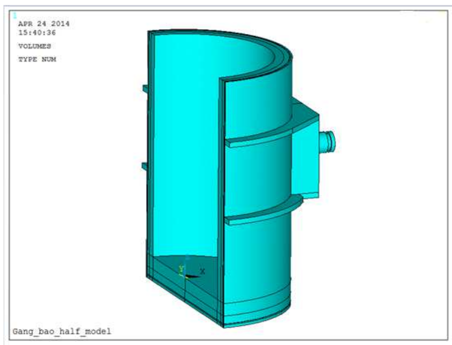


Figure 3. 3D model of the new type ladle

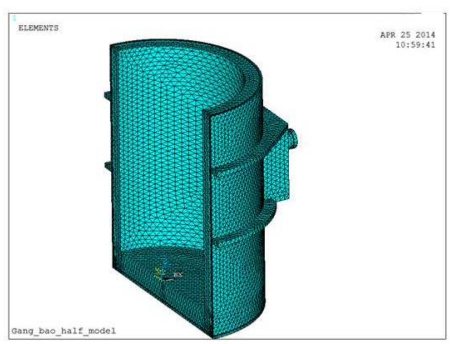


Figure 4. Grid graph of the new type ladle

2.3 Determination of new structure ladles physical parameters

By looking up the relevant literatures[15]-[20] and choosing specific value of physical parameters in specific temperature, heat transfer process of ladle can be truly mirrored. Physical parameters were used in the research, shown in Table 1-2.

Table 1: Material physical property parameters of each lining layer of ladle

Physical parameters	Elastic modulus $E\,(pa)$	Poisson ratio μ	Thermal expansion coefficient $\alpha\,(K^{-1})$	Density $\rho\,(kg/m^3)$
Working layer	6.3e9	0.21	8.5e-6	2950
Permanent lining	5.7e9	0.21	5.8e-6	2800
Protective layer	2.06e11	0.3	13e-6	7800
Thermal insulating nano-material layer	2e9	0.01	1.2e-6	400
Shell of ladle	2.06e11	0.3	13e-6	7800

Table 2: Thermal conductivity of each lining layer of the new structure ladle at different temperature

Lining \ Temperature ($^\circ C$)	20	40	800	1200
Working layer	1.15	1.3	1.51	1.6
Permanent lining	0.5	0.63	0.75	0.9
Protective layer	54	42	31	31
Thermal insulating nano-material layer	0.023	0.028	0.034	0.038
Shell of ladle	54	42	31	31

2.4 Boundary conditions

There are two ways of heat dissipation for ladle surface.The one is heat convection coefficient of ladle shell and surrounding environment, the other is heat dissipation of ladle shell by radiation.[21,22]Convective heat transfer and radiation heat transfer exist in each working stage. Radiation heat transfer coefficient is introduced to calculate engineering heat transfer. Radiation heat transfer value is expressed by Newton cooling formula[23]:

$$\Phi_r = Ah_r\left(t_w - t_f\right) \tag{1}$$

And, heat transfer Φ_f of radiation

$$\Phi_f = A\varepsilon\sigma\left(t_w^4 - t_f^4\right) \tag{2}$$

Therefore, the equivalent coefficient h_f of radiation heat transfer and heat transfer is

$$h_r = h_f = \varepsilon\sigma\left(t_w^2 + t_f^2\right)\left(t_w + t_f\right) \tag{3}$$

where A is the heat transfer area, t_w is the outer surface temperature of the ladle shell, t_f is the room temperature, ε is the blackness, and σ is the StefanBoltzmann constant, and its value is $5.67\times10^{-8}W/\left(m^2\cdot K^4\right)$.
Heat transfer of natural convection is expressed as

$$\Phi_z = Ah_c\left(t_w - t_f\right) \tag{4}$$

The total heat could be conveniently expressed as

$$\Phi_r = Ah_r\Delta t + Ah_c\Delta t = A\left(h_r + h_c\right)\Delta t \tag{5}$$

The total convective heat transfer coefficient of the integrated heat transfer is

$$h_t = h_r + h_c \tag{6}$$

The average temperature of the ladles shell is taken as 275°C (is 548 K), room temperature as 30 °C (is 303 K), and the blackness of the surface of the ladles shell as e=0:8, and then it can be calculated by equation

$$\begin{aligned} h_r &= \varepsilon\sigma\left(t_w^2 + t_f^2\right)\left(t_w + t_f\right) \\ &= 0.8\times5.67\times10^{-8}\times\left(548^2+303^2\right)\times\left(548+303\right) \\ &= 11.604W/\left(m^2\cdot{}^\circ C\right) \end{aligned} \tag{7}$$

The ratio of the cylinders diameter and its height (0.3) is the boundary of infinite or limited space natural convection heat transfer. The ratio of the ladles diameter and its height is 3.294/4.285=0.7687>0.3, so the ladle can be seen as infinite space natural convection heat transfer. Through table look-up and calculation,$Nu = 129.267$ and $\lambda = 3.64\times10^{-2}$, so the surface coefficient of heat transfer is

$$\begin{aligned} h_c &= \frac{Nu\cdot\lambda}{l} = \frac{129.267\times3.64\times10^{-2}}{4.285} \\ &= 1.098W/\left(m^2\cdot{}^\circ C\right) \end{aligned} \tag{8}$$

where Nu is the Nusselt number and is the air thermal conductivity coefficient $W/(m\cdot K)$.
According to equation, the total convective heat transfer coefficient of the ladles integrated heat transfer can be calculated as follows

$$h_t = h_r + h_c = 11.604 + 1.098 = 12.702W/\left(m^2\cdot{}^\circ C\right) \tag{9}$$

3 STRESS FIELD OF NEW STRUCTURE LADLE IN THE CONDITION OF STEEL HOLDING

The studies of ladle is main for the improvement of thermal insulation performance. And the studies of thermal insulation performance is main for the analysis of stress field. Compared to traditional ladle, a layer of nanometer adiabatic materials is added to new structure ladle. The new ladle is better than traditional ladle in structure. [24,25]It is found that stresses distribution of new structure ladle is better than traditional ladle by analyzing stress filed of new structure ladle.

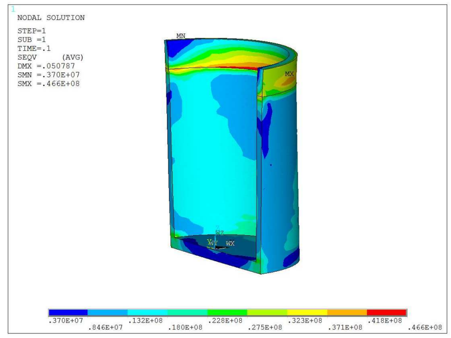


Figure 5. Stress distribution in working layer of the new structure ladle during steel holding

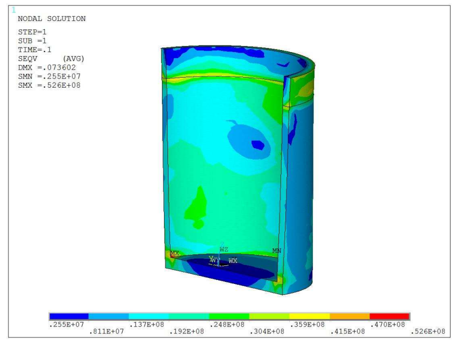


Figure 6. Stress distribution in working layer of traditional ladle during steel holding

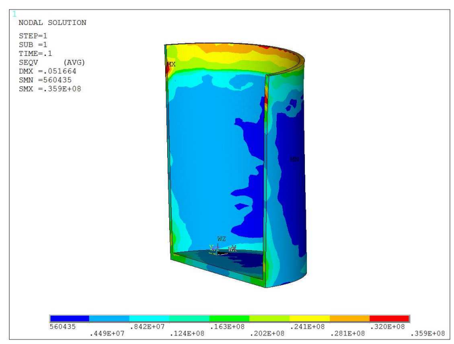


Figure 7. Stress distribution in permanent layer of the new structure ladle during steel holding

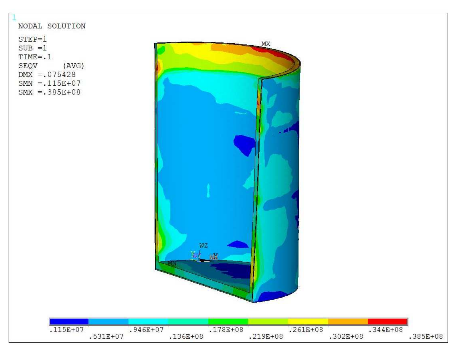


Figure 8. Stress distribution in permanent layer of traditional ladle during steel holding

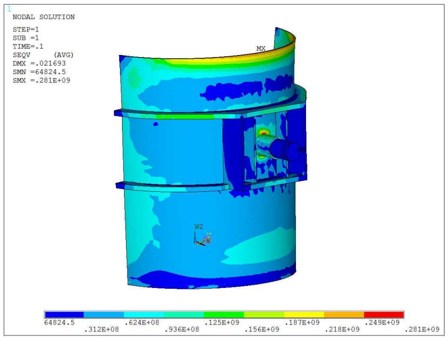


Figure 9. Stress distribution in the shell of the new structure ladle during steel holding

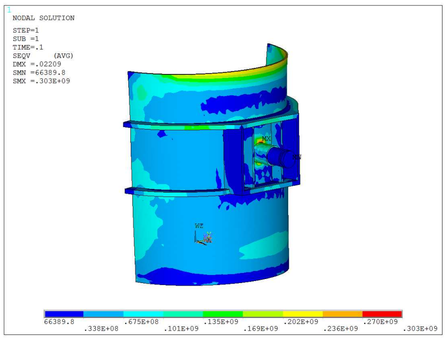


Figure 10. Stress distribution in the shell of traditional ladle during steel holding

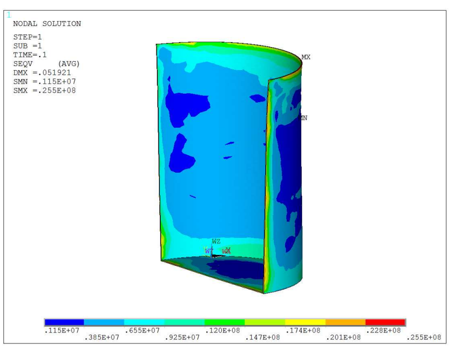


Figure 11. Stress distribution in the thermal insulating nano-material layer of the new structure ladle during steel

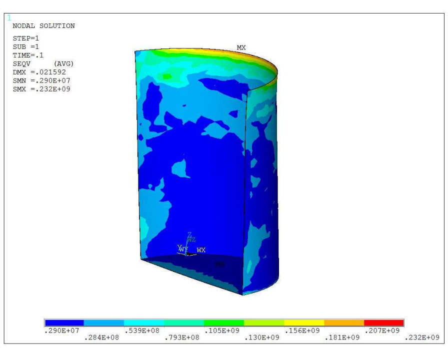


Figure 12. Stress distribution in the thermal insulating nano-material layer of traditional ladle during steel holding

It can be seen in Figure 5 that the maximum stress of working layer is 46.6Mpa in the condition of steel holding, while the traditional one is 52.6Mpa in Figure 6. It can be seen in Figure 7 that the maximum stress of permanent lining is 33.9Mpa in the condition of steel holding, while the traditional one is 38.5Mpa in Figure 8. It can be seen in Figure 9 that the maximum stress of shell of ladle is 281Mpa in the condition of steel holding, while the traditional one is 303Mpa in Figure 10. Stress level of new structure ladle is almost same with traditional ladle, but the maximum stress is 303Mpa. It can be seen that stress level of new structure ladle is less than traditional one 22Mpa, the simulation result shows that new structure ladle has better insulation effect and longer life. It can be seen in Figure 11 that the maximum stress of thermal insulating nano-material layer is 25.5Mpa. [26]The maximum stress of working layer, permanent lining, and thermal insulating nano-material layer is within tolerable bounds. It can be seen in Figure 12 that the maximum stress of protective layer is 232Mpa. New structure ladle suffers the impact of liquid steels gravity and thermal stresses in the condition of steel holding. Protective layer and shell of ladle are common carbon structure steel, its thermal expansion coefficient is higher than adiabatic materials,so its thermal deformation is larger in same temperature. Deformation is restricted by other parts, which generates thermal stresses in internal structure.[27]The stress distribution of new structure ladle and traditional ladles each lining layer is showed in Table 3 and Table 4.

Table 3: Stress distribution of each lining layer of new structure ladle during steel holding

Stresses (Mpa) / Lining	Range	Max-imum	Min-imum	Yield limit
Working layer	13.2-41.8	46.6	3.7	70
Permanent lining	8.42-32	35.9	0.56	60
Protective layer	28.4-207	232	2.9	345
Thermal insulating nano-material layer	6.55-22.8	25.5	1.15	25
Shell of ladle	31.2-249	281	0.6	345

Table 4: Stress distribution of each lining layer of traditional ladle during steel holding

Stresses (Mpa) / Lining	Range	Max-imum	Min-imum	Yield limit
Working layer	5.11-47	52.6	2.55	70
Permanent lining	5.37-34.4	38.5	1.15	60
Shell of ladle	33.8-270	303	0.6	345

4 ANALYSIS OF INFLUENCE FACTORS IN STRESS FIELD OF NEW STRUCTURE LADLE

Thermal conductivity, elastic modulus, and thermal expansion coefficient have great effect on stress field of new structure ladle in physical parameters of heat insulation nano-material[28]. Meanwhile, shell of ladle can be seen as a carrier of measuring index for stress distribution of ladle[29]. Therefore, the effect of thermal conductivity, elastic modulus, and thermal expansion coefficient of heat insulation nano-material on shell of ladle was analyzed in the condition of steel holding.

4.1 Influence of heat insulation nano-materials thermal conductivity on stress field of new structure ladle

It can be found that the stress of ladle shell and protective layer was high through the initial stress field distribution of new structure ladle. Stress field of new structure ladle was studied to get the influence law of thermal conductivity on stress field of new structure ladle.

Table 5: Stress distribution in the shell after the decrease of thermal conductivity of heat insulation nano-material

Decreased percentage of thermal conductivity of nanometer materials	Stress of ladles shell(MPa)		
	Min-imum	Max-imum	Most area
Unaltered	0.6	281	31.2-249
20%	0.38	271	30.1-241
40%	0.53	267	29.8-238
60%	0.49	252	28.1-224
80%	0.45	248	27.4-221

The maximum and minimum stress of ladle shell was shown in Table 5 when the thermal conductivity of nanometer adiabatic materials decreased. The decreasing extent is not high. The stress margin of ladles shell was enough. The security of new structure ladle is strengthened. The stress distribution of ladle shell and protective layer was shown in Table 5. It can be seen that the maximum stress of ladle shell and protective layer showed a decreased tendency in view of the maximum, the minimum and the range of stress. Thermal resistance increased, which made the heat transferred to the layer of nanometer adiabatic materials decreased and the heat of ladles shell decreased. So its deformation and thermal stress was small. Ladle shell and protective layer had the same kind of material and same macroscopic manifestation. Generally speaking, the smaller the thermal conductivity of nanometer adiabatic materials are, the smaller temperature and stress are, which have a positive effect on service life and energy saving.

4.2 Influence of heat insulation nano-materials elastic modulus on stress field of new structure ladle

Elastic modulus is a physical quantity, which can measure the capacity that material resists deformation. It aims at revealing the result of force that object generate to against outside force. It was determined by material itself and didnt have an effect on ladles temperature[20]. There had the double effects of liquid steels heat and weight in the condition of steel holding. The relationship between the result and elastic modulus of material was a research object. Elastic modulus of material was studied to obtain stress distribution law in the condition of steel holding. Elastic modulus of material was 2e9 Pa. Elastic modulus of material was altered and other physical parameters remained unchanged to observe the effects of temperature and stress field. Elastic modulus of working layer and permanent lining materials were 6.3e9 Pa and 5.7e9 Pa, respectively. To embody the excellent properties of nanometer adiabatic materials, elastic modulus of working layer and permanent lining materials shouldnt be very close. Elastic modulus of nanometer adiabatic materials were set as 1e9 Pa, 1.5e9 Pa , 2.5e9 Pa , 3e9 Pa.

Table 6: Stress distribution in the shell after the change of elasticity modulus of heat insulation nano-material

Elastic modulus of nanometer materials (pa)	Stress of ladles shell(*MPa*)		
	Minimum	Maximum	Most area
1e9	0.648	304	33.8-270
1.5e9	0.6	289	32.1-256
Unaltered(2e9)	0.6	281	31.2-249
2.5e9	0.612	274	30.5-243
3e9	0.608	263	29.3-234

The maximum and minimum stress of ladle were shown in Table 6 when elastic modulus was altered. It can be found that the maximum stress of ladle shell decreased as the elastic modulus of nanometer adiabatic materials increase. That is, with the same force, the bigger elastic modulus is, the smaller deformation is. When elastic modulus of nanometer adiabatic materials increased, the capability of resisting deformation increased and the corresponding deformation decreased. Deformation of thermal insulating nano-material layer decreased and its restriction on other lining decreased. Finally, total deformation of ladles lining decreased, mechanical stress generated by gravity action of liquid steel on shell of ladle decreased.

4.3 Influence of heat insulation nano-materials thermal expansion coefficient on stress field of new structure ladle

Solids mostly expand in response to heating and contract on cooling. This response to temperature change is expressed as its coefficient of thermal expansion. In the larger sense, thermal expansion coefficient of new structure ladle can be discussed by observing the deformation of ladles lining. Thermal expansion coefficient has influence on stress field of ladle and no effect on temperature field. Stress field of ladle should be concerned only. [30]With other boundary conditions unchanged temperature and stress field of new structure ladle were observed when thermal expansion coefficient decreased to $1.0e^{-6}\cdot K^{-1}$, $0.8e^{-6}\cdot K^{-1}$, $0.6e^{-6}\cdot K^{-1}$, $0.4e^{-6}\cdot K^{-1}$.

Table 7: Stress distribution in the shell after the change of thermal expansion coefficient of heat insulation nano-material

Thermal expansion coefficient K^{-1}	Stress of ladles shell(MPa)		
	Minimum	Maximum	Most area
Unaltered(1.2e-6)	0.6	281	31.2-249
1.0e-6	0.6	276	30.7-245
0.8e-6	0.59	274	30.5-244
0.6e-6	0.56	273	30.3-242
0.4e-6	0.55	271	30.2-241

The maximum and minimum stress of ladles shell were shown in Table 7 when thermal expansion coefficient was altered. It could be seen that stress of ladles shell had a little change when thermal expansion coefficient was altered. The maximum stress decreased to 5MPa , 7MPa , 8MPa , 10MPa. Coefficient of thermal expansion was small. Thats to say, volume change was small at the same temperature. Deformation of nanometer adiabatic materials was small, which led total deformation of ladles lining small. And its macro behavior was that stress decreased.

5 CONCLUSIONS

(1) Because of the interaction of temperature and gravity of liquid steel, the stress level of ladle shell was higher during steel holding. The stress distribution of new structure ladle with heat insulation nano-material lining was obviously better than traditional ladle and the maximum stress of the new structure ladle shell was lower than that of the traditional one 22MPa.

(2) Thermal conductivity, elastic modulus and thermal expansion coefficient of nanometer adiabatic materials were research objects in this paper. Each physical parameter was studied in the condition of steel holding. The results showed that in a special range the proportionality of stress field could be improved by reducing thermal conductivity and thermal expansion coefficient of nanometer materials and increasing its elastic modulus properly to improve ladles thermal insulation. Hence, it is of great significance to analyze numerical simulation of influence factors in stress field of new structure ladle. It provides structural optimization of new structure ladle for theoretical support.

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