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Temperature and Thermal Stress Analysis of Refractory Products

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Abstract: Firstly current status of temperature and thermal stress research of refractory product at home and aboard are analyzed. Finite element model of two classical refractory products is building by using APDL language. Distribution law of temperature and thermal stress of two typical refractory products-ladles and tundish are analyzed and their structures are optimized. Stress of optimal structure is dropped obviously, and operation life is increased effectively. *Copyright © 2013 IFSA.*

Keywords: Refractory product, Thermal stress, Temperature field, Ladle, Tundish.

1. Introduction

Refractory products (industrial furnaces and all kinds high temperature container, parts) are indispensable part of high-temperature industrial. They are widely used in many industrial sectors, such as metallurgy, machinery, chemicals and building materials, etc. The refractory lining determines their life, thus the normal operation of the entire production process is affected. The damage mechanism of refractory includes two main parts: chemical erosion and thermo-mechanical stress. The former is the refractory is eroded and scoured by the melt, gas, dust, and there have been a lot of research in this regard. The latter refers to result in the lining internal stress is generated due to the expansion caused by the temperature and a certain intrinsic chemical reaction which exceeds its strength to cause damage. Damage by the thermal stress is the main reason for the refractory lining cracking damage. So, it is necessary to analyze the temperature and thermal stress on the refractory products.

2. The Current Situation of Temperature and Thermal Stress of Refractory Products' Research at Home and Abroad

Refractory materials are widely used in the industries of metallurgy, machinery, chemicals, building materials and other high-temperature container pieces, which condition of use determine the service life of these important devices, and ultimately affect the normal operation of the entire production process. And the thermal stress is the main reason for the damage of the refractory products.

At present, thermal stress study has been carried out abroad. For example, Yoshino Ryoichiand and others, Shinagawa Refractories, Japanese, increase the slide gate's life expectancy of 30-40 %, although they only minor changed skateboard brick after angle based on the thermal stress of the slide gate [1]. Maupin et al, U.S. National Steel, confirmed the reason of its short life due to the lining of thermal stress and shell damage by calculating RH degassing refining equipment [2]. Osamu Nomura and his colleagues, Japanese, has modified converter lining's design according to calculating relations between the coefficient of expansion and thermal stress of the converter lining by finite element method [3]. A Gasser Professor, French, achieved good results through the design of the fluidized bed and the anchorage member lining [4]. Since this approach can extend the life of the product, material savings, which has brought huge economic benefits.

Domestic research has been carried out in this regard. Such as those used in the metallurgical industry converter lining design, converter stress concentration is primarily caused by the incorrect geometric shape and material of the expansion joints, and the areas of stress concentration caused by the traditional ladder masonry is mainly transition zone of the converter. Calculated by the finite element analysis, ladder masonry is replaced by wedge masonry or puzzle arch masonry, which successfully resolved stress concentration problems in converter transition zone [5]. The former Ministry of Metallurgical Industry Building Research Institute has done thermal strain test on refractory, and there is an experimental basis on the case of high temperature refractory test. In recent years, in the study of thermal stress, literature published at home and abroad mainly related to a lot of refractory products used under high-temperature in the blast furnace, converter, skateboards, in package slag dam submerged nozzle and so on, and the study achieved good results, improved production efficiency, reduced production costs.

3. Basic Theory

The stress calculation process can generally be divided into the following steps: firstly, we can calculate the deformation (the deformation displacement of various points within electric furnace roof) under a specific constraint condition, according to the temperature distribution of the electric furnace roof and the various parts of the electric furnace roof's the coefficient of thermal expansion ; then calculate the strain of electric furnace roof points by using geometric equations by the deformation displacement; finally, we calculated stress points of the electric furnace roof by strain based on the physical equation of the material (stress and strain relationships).

The geometry equation of electric furnace roof stress field, which characterize the strain - displacement relations equation. Formula 1 (in matrix form).

$$\varepsilon=\begin{bmatrix} \frac{\partial}{\partial x} & 0 & 0 \\ 0 & \frac{\partial}{\partial y} & 0 \\ 0 & 0 & \frac{\partial}{\partial z} \\ \frac{\partial}{\partial y} & \frac{\partial}{\partial x} & 0 \\ 0 & \frac{\partial}{\partial z} & \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial x} \end{bmatrix} v \quad (1)$$

In the formula, $\varepsilon=\left[\varepsilon_x\ \varepsilon_y\ \varepsilon_z\ \gamma_{xy}\ \gamma_{xz}\ \gamma_{yz}\right]^T$ is the strain at any point within the furnace roof; $\upsilon=[u\ v\ w]^T$, u / v / w respectively represent the displacement along the x, y, z direction. According to the above strain - displacement relations, strain of its points within refractories products will be calculated by the displacement of each point of the products (caused by thermal expansion deformation).

The physics equations of furnace roof stress field, which characterize the stress–strain relations equation. Based on Hooke's law, the stress σ of material is proportional to strain ε of material, as Formula 2 shows:

$$\sigma=E\varepsilon, \quad (2)$$

For complex solid models, according to the generalized Hooke's law, the relationship between stress and strain can be described for:

$$\sigma=\frac{E(1-\upsilon)}{(1+\upsilon)(1+2\upsilon)}\begin{bmatrix} 1 & \frac{\upsilon}{1-\upsilon} & \frac{\upsilon}{1-\upsilon} & 0 & 0 & 0 \\ \frac{\upsilon}{1-\upsilon} & 1 & \frac{\upsilon}{1-\upsilon} & 0 & 0 & 0 \\ \frac{\upsilon}{1-\upsilon} & \frac{\upsilon}{1-\upsilon} & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2\upsilon}{2(1-\upsilon)} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2\upsilon}{2(1-\upsilon)} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2\upsilon}{2(1-\upsilon)} \end{bmatrix}\varepsilon, \quad (3)$$

In the formula, E is the elastic modulus, and υ is Poisson's ratio. According to the above stress - strain relations, any stress of each point is calculated by each point of its inner strain obtained from the previous step, and products are the object of the force, the force meeting the balance equation.

3.1 Stress equilibrium equations

General refractory products is a three-dimensional model, and its inner any point along coordinates x, y, and z-direction of the force balance equation are shown in Formula 4.

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + f_x = 0$$
$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + f_y = 0 \quad (4)$$
$$\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_z}{\partial z} + f_z = 0,$$

In the formula, f_x, f_y, f_z are the body force components per unit volume of the furnace cover in the x, y, z direction.

In the work process, the inner wall of the refractory products are not in direct contact with molten steel, so thermal shock which is exposed to should be derived from the thermal radiation of the molten steel and arc, therefore, this effect should be considered to in the finite element analysis. In this article, the ANSYS software is used for numerical simulation of temperature and stress field of refractory products, and its basic analysis process is shown in Fig. 1.

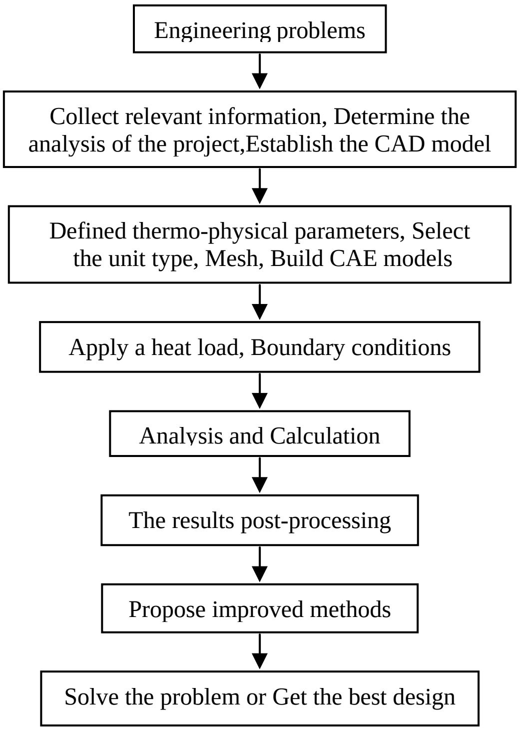

Fig. 1. ANSYS thermal analysis flowchart

4. The Ladle Heat Stress Analysis

The ladle is an important container in the metallurgical industry, and used to store and transport molten steel, also conducted secondary refining, etc. Ladle in the process of using, the most common failure is the pitting and bursting of the refractory lining, resulting in the penetration of the molten steel. The causes of refractory lining damage include chemical erosion, thermal mechanical stress. And the cause of the breakdown of the refractory lining is the thermo-mechanical stresses.

4.1. The Original Ladle Thermal Stress Distribution

250 ton ladle in a steel mill was selected as the analysis object. Ladle was lined by a variety of materials and the structure of the ladle bottom and ladle wall lining was adjusted without changing the texture, and the structures of the smaller level of stress distribution in ladle bottom and ladle wall lining could be obtained. The program of finite element model could be written in APDL language generated, then ladle model was analyzed. The stress distribution of the original ladle bottom structure is shown in Fig. 2.

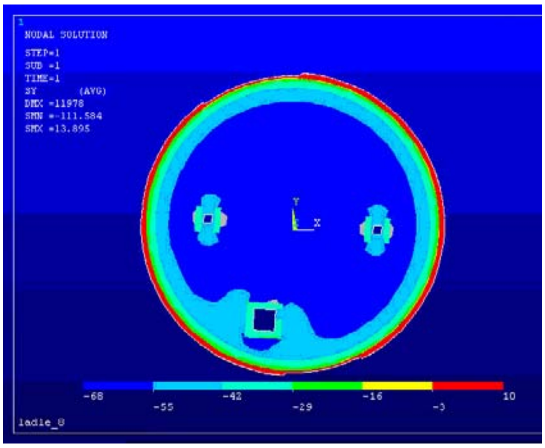

Fig. 2. The original ladle thermal stress distribution cloud.

4.2. The Thermal Stress Distribution of Ladle after Optimization

The ladle bottom hot surface stress in radius is generally higher than that near the center part, because the heat loss close to the wall of the ladle is bigger than that close to the center portion, and caused the premises the temperature gradient larger than close to the central portion, thus creating a greater thermal stress. Thermal expansion coefficient of micro-expansion high alumina bricks in ladle lining material permanent layer is small, so increasing a circle of high aluminum lining in the ladle bottom peripheral will help to reduce the package bottom thermal stress value.

Ladle will be subject to the molten steel's impact when the molten steel is poured into it, first which come into contact with molten steel is the impact block, and installing high aluminum lining around it can also reduce lining bricks instant expansion which causes the thermal stress value increasing. As increasing circle of high aluminum lined brick in the periphery of the package bottom nozzle brick, which is the optimization of the ladle, and reduce the compressive stress of nozzle brick subjected. Its stress distribution cloud is shown in Fig. 3.

By the thermal stress analysis, the circle high aluminum lining bricks with smaller coefficient of thermal expansion are increased the periphery original ladle bottom, so the thermal stress value and the compressive stress value in this region is smaller than the stress value of the lined region of the intermediate aluminum-magnesium carbonous 10 MPa. Ladle bottom structure after optimization reduced the stress around the nozzle brick, and effectively alleviated the nozzle brick extent of the damage.

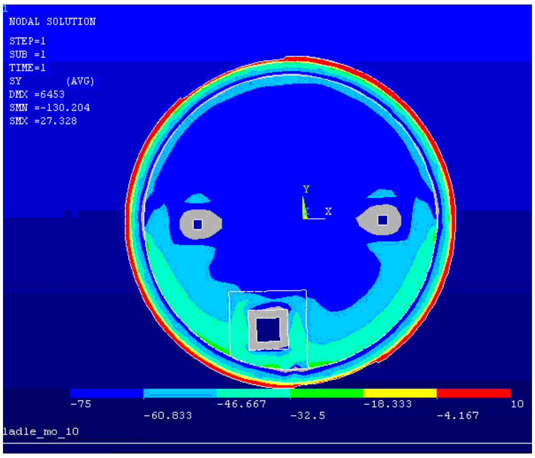

Fig. 3. The ladle after optimization thermal stress distribution cloud.

5. The Law of the Tundish Temperature Distribution

The early stages of development in the Continuous Casting Technology, the tundish just used as storage and distributor of liquid steel. The role of tundish is not only the distribution of liquid steel. but also temperature and composition can be uniformly, and remove inclusions. The flow of molten steel in the tundish may be a non-isothermal flow state under many conditions. The study of the flow characteristics of the molten steel in the tundish non-isothermal state is a very significant problem of research topics in the flow within the tundish.

5.1. Temperature Distribution of the Molten Steel in the No Flow Control Device within the Tundish

Fig. 4 is a temperature distribution of the tundish liquid steel that without any flow control device. From the analysis shows, no flow control device, isotherms of the liquid steel in tundish in the form of horizontal push forward, which is consistent with characteristics of “less reflux "and" more than a short circuit flow” of tundish flow field. And the temperature of the liquid steel in the tundish is very unevenly distributed, in the figure, the proportion of the "Green Line" is more, and the liquid steel between note orifice and the outlet of is quite different. When casting for a long time, the molten steel will be stratified in this case, that the high and low temperature layer. The tundish temperature instability will exacerbate mold shell growth in homogeneity, which is not conducive to the floating separation of the inclusions in the tundish liquid steel, even lead to serious pull leakage. So it is necessary to make the appropriate improvements to the tundish.

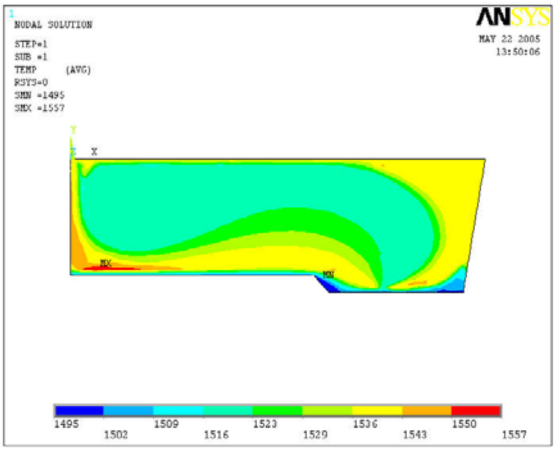

Fig. 4. The temperature isoline of molten steel in the no flow control device tundish.

5.2. The Temperature Distribution of the Liquid Steel inside Tundish after Optimization

Due to the temperature difference between the liquid steel tundish and outside heat, the temperature of the molten steel in the tundish enabled would drop, but when the tundish was taken certain measures, the temperature distribution would be greatly improved. Fig. 5 is a temperature distribution of the liquid steel in the tundish after setting the weir dam, compared to Fig. 3, we can found that the temperature of the molten steel are more evenly distributed, and the temperature at the outlet is the lowest, at the entrances to the temperature difference between the liquid steel is reduced to 12 °C. A layer of fluid near the wall, the temperature is very low, annular, because of the presence of the fluid reflux.

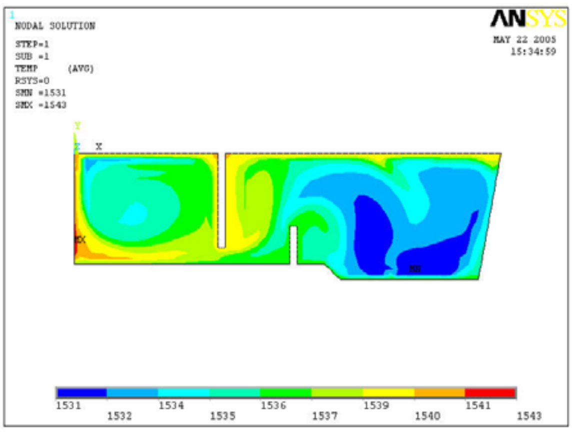

Fig. 5. The temperature isoline of molten steel in the tundish after setting the weir dam.

6. Conclusion

Refractory products are widely used in high-temperature industries, and its service life directly affects the normal operation of the entire production process. The damage to the thermal stress is the direct cause of the refractory lining cracking damage. Using Finite element model of two classical refractory products is building by using APDL language, and the analysis showed that temperature and thermal stress of two typical refractory products-ladle and tundish had its special distribution pattern. It is a good reference to explore ways and means to reduce the thermal stress, to optimize the structure of refractory products, and to provide guidance for the actual production.

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