Computer simulation of thermal shock in refractory linings of metallurgical installations.

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Abstract

A destruction of metallurgical installations lining under thermal shock was investigated with mathematical modeling methods. As an example a periclasse – chromite lining was taken. Two types of thermal shock were considered – during heating and cooling of the lining. It was determinate, that these two types of thermal shock cause a different character of damage. A dynamic heat field and thermal stress of the lining during the thermal shock were calculated with finite elements method. Also, the size of lining damages was calculated with method of «heat displacement». The most dangerous moments of installation usage were found by computer simulation of lining destruction. The calculating results are in good correspondence with damage sizes, measured after finish of installation usage.

Key words: computer simulation, finite elements method, mathematics modeling, thermal shock

Introduction

The development of computer technique gives new opportunities for engineers in exploration of different technological processes. Modern computer technique allows carrying out complicated calculations of installation work under various stresses in a relatively short time. Processes, which take place in complicated conditions, such as high temperature or a very short time, attract a special interest for modeling, because of difficulties in direct supervision. One of such effects is a thermal shock in refractory linings of metallurgical installations.

The thermal shock occurs, than object temperature changes much in a short time. It is one of the common reasons of refractory lining damages. Installations of periodical usage are mostly exposed to thermal shock (casting ladle, degasser, and blast oxygen furnace). Not so sensitive for thermal shock are installations of continuous process or with effective heating between melts (electric arc furnace, Martin process furnace or blast furnace). Also, thermal shock has great effect at elements of continuous casting installations: ladle shroud, submerged nozzles, slide plates and so on. Thermal shock influences on refractory materials in both situations: during the metal melt gets into cold installation (lining heating) and during after-melt lining cooling. However, the characters of damages, appearing after thermal shocks, which took place in these different conditions are not similar.

Mathematics modeling of refractory lining destruction under thermal shock allows choosing safe conditions of installations usage. The modeling can be used for a forecasting of lining in-service time or to determinate it condition (thickness, character and size of damages) in concerned moment of time. Such calculations require the following data: temperature inside and outside installation, durations of different periods of installation usage and its outer surface temperature. Also, mathematic models give opportunities of different parameters calculation, which can give useful indirect data about cracks growth. For example, these methods allow fixing the most thermal shock exposed areas, which need permanent acoustic control or establishing of outer surface temperature dependence on the lining thickness and its integrity.

Presently, mathematics modeling of thermal stresses in refractory linings is rapidly developing all over the world [1], [2]. Modeling results allows providing new stable designs of metallurgical equipment lining. For example, Japanese scientists, with help of computer simulation, fixed the most dangerous areas in RH-degasser tube lining [3]. The result of lining scheme changes, based on the simulation data, is the increasing of in-service time approximately with 10 %.

The present paper illustrates mathematical methods usage for modeling of thermal shock lining failure. Features of both thermal shock types (occurred during rapid heating and cooling of lining) were discussed. An algorithm of thermal stress calculation was suggested. Methods of applied mechanics were used for forecasting of cracks sizes, appearing in refractory lining as a result of thermal shock.

A standard refractory material of MgO-Cr_2O_3 system, used with standard working conditions was chosen as a calculation object.

Physical base of thermal shock and calculation method

Thermal shock is the cause of thermal stress appearance in metallurgical installation lining. The direct cause of thermal stress is thermal growth or compression of lining material. Thermal conductivity of most ceramics and refractory materials is relatively low (less than 10 W/m·K) [4], it effects in appearance of temperature gradient (or its rapid change) during one-side heat treating (during thermal shock, for example). Temperature difference in neighboring points (with distance of few millimeters) in such conditions can reach several hundreds of degrees. Rapid heating of linings working surface can be a result of hot metal pouring (with temperature 1550 – 1700 °C) into relatively cold lining, which has temperature of 900 °C or sometimes less after installation preheating or cooling between melts. Other side, hot lining, can contact with cold surrounding air after metal treating (air temperature can be between - 40 °C and + 40 °C, depending on season).

At the same time refractory materials have rather high coefficient of thermal growth ($1 – 2 \cdot 10^{-5}$ K^{-1}) [5]. This brings to a situation, than more heated parts of material feel the powerful compressing stress from parts with lower temperature and on the contrary. Also, if there is not enough space for material growth, the lining feels extra compressing from other elements of lining and installation casing.

Stresses inside refractory lining, which appear as a result of rapid temperature field change, can be calculated according to Hooke equation:

$$\sigma_0 = \Delta T \cdot \alpha \cdot E\,, \tag{1}$$

σ_0 – stress in material, ΔT – temperature change of material element, α – coefficient of material thermal growth, E – modulus of material elasticity.

However, a slow temperature change does not give an effect of thermal stress growth, because of stress relaxation effect [6]. The stress disappears with the course of the time, according to the following [7]:

$$\sigma = \sigma_0 \cdot e^{-\frac{\tau \cdot E}{K_1}}\,, \tag{2}$$

σ – real material stress, σ_0 – stress in material without relaxation consideration (1), τ – time, passed after relaxation beginning, K_1 – a variable, which characterizes relaxation velocity, depending on materials viscosity. This variable for refractory materials differs from 10^{15} at room temperature down to 10^7 – 10^9 at working temperature (1550 – 1700 °C) [8].

This fact determinates an absence of thermal stress in linings, which were preheated before first melt with velocity of 200 °C/h and lower (with standard conditions for metallurgical installations preheating).

During rapid temperature changes, thermal stress has not enough time for reduction by relaxation. As a result – thermal stress in lining grows fast and exceeds destructive value for some elements.

Rapid temperature increasing or decreasing causes lining destruction which has different character, depending on temperature change trend (fig. 1):

- During heating – the working layer of the lining feels compressing stress. The result is an appearance of thin cracks net on refractory brick surface (fig. 1a).
- In another situation – during lining cooling tensile stress has place, which cause a few deep cracks appearance (fig. 1b).

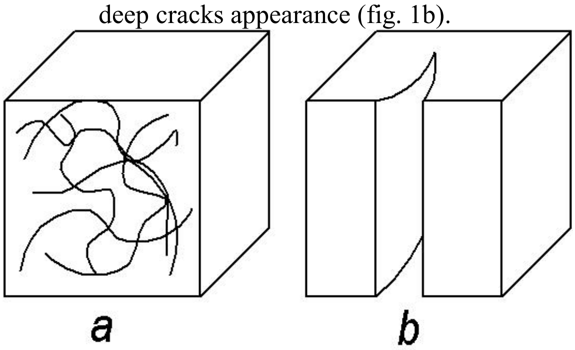

Fig. 1. Character of refractory working layer destruction: a – during rapid heating; b – during fast cooling.

In both cases it is possible to calculate the full area of cracks, using thermal stress values and material energy of destruction (so called «method of heat displacement») [9]. This method idea is to obtain a surplus energy, accumulated in some volume of material, due to thermal stress:

$$U = \sigma \cdot V\,, \tag{3}$$

U – surplus energy, σ – thermal stress in material, considering relaxation (2), *V* – volume of material, considered. At the next step we need to fix an amount of chemical bonds, for which destruction this surplus energy would be spent:

$$n = \frac{U}{U_0}\,, \tag{4}$$

n – an amount of chemical bonds destructed, U_0 – energy, required for one bond destruction (if different bonds are presented in material, we need to use average values of destruction energy). Surface of one chemical bond is an initial data of full crack area calculation:

$$S_c = n \cdot S_0\,, \tag{5}$$

S_c – full crack surface area, S_0 – area of one chemical bond. The data about chemical bonds areas and their energy of destruction can be found in a special literature, [10] for example. During calculation it is necessary to consider, that each crack provides two new surfaces. Equation (5) allows calculating full area of these two surfaces.

A dynamic heat field, appearing in the metallurgical installation lining during its heating or cooling, is an initial data for thermal stress calculation, together with heat capacity, heat conductivity and materials modulus of elasticity. The «dynamic heat field» means that it contains information about coordinates of calculation nodes, temperature in nodes and temperature changes in these nodes with time.

A finite elements method [11] was used for a dynamic heat field fixing. A heat exchange features at inner and outer installation surfaces were considered [12], [13].

A heat exchange between metal melt and refractory lining (during metal treating) or between air and lining, (at the periods of preheating and cooling between melts) takes place at the inner installation surface. Both ways of heat exchange (radiation and convection) could be seen here. Surface or inner heat carrier temperatures can be calculated, using values of heat stream inside the lining and coefficient of heat exchange:

$$T_s = T_a - \frac{Q}{\alpha_o} \tag{6}$$

$$\alpha_o = \alpha_r + \alpha_c \tag{7}$$

$$\alpha_r = 5.67 \cdot 10^{-8} \varepsilon_s \frac{T_a^4 - T_s^4}{T_a - T_s} \tag{8}$$

$$\alpha_c = \mathrm{Nu}_a \lambda_a d^{-1}, \tag{9}$$

T_s – surface temperature, T_a – inner heat carrier temperature, *Q* – heat stream inside lining, α_o – full coefficient of heat exchange, α_r – radiation coefficient of heat exchange, α_c - coefficient of convection heat exchange, ε_s – blackness of the lining surface, Nu_a – Nusselt criterion for inner heat carrier, λ_a – heat conductivity of inner heat carrier, *d* – characteristic size of installation. Equation (6) was written for situation, when heat carrier is more hot, than surface. In opposite situation (after-melt cooling) we need to change mathematics operator «-» to «+». Approximation of heat stream value inside refractory lining can be obtained according to the following equation, using temperature difference between inner and outer heat carriers and heat conductivity of lining materials:

$$Q = \frac{T_{a1} - T_{a2}}{\sum \frac{\delta}{\lambda} + \frac{1}{\alpha_i} + \frac{1}{\alpha_o}}, \quad (10)$$

T_{a1} and T_{a2} – temperatures of inner and outer heat carriers, δ and λ – thicknesses and heat conductivities of lining layers, α_i and α_o – coefficients of heat exchange for inner and outer surfaces.

Heat exchange inside lining (which can be considered as a multilayer wall) depends on heat conductivity of layers. Temperature calculation inside lining can be realized according to the following equation:

$$dT = \frac{\lambda}{\delta} \cdot dQ, \quad (11)$$

dT - temperature change in the layer, δ and λ – thickness and heat conductivity of walls layer respectively, dQ – heat stream inside the layer [14].

Heat exchange between hot wall and surrounding air at the outer installation surface also takes place with radiation and convection. Equations (6) – (9) are used for calculation, but after respective operator change, because temperature of the surface in this case is higher than air temperature, and heat stream has another direction.

Heat fields obtained allow calculating thermal stress in any point of the lining at any moment of time, according to the equations (1) - (2).

To obtain moments, which are dangerous from thermal destruction point of view, it is necessary to compare thermal stresses in the lining at different moments with strength of material. In the case of heating – a compressive strength must be used and during lining cooling – tensile strength.

Results and discussion

The both types of thermal shock were calculated: during rapid heating and cooling of the refractory lining. It was considered; that before first melt and during cooling between melts the lining surface temperature is 1350 °C (this temperature is usually held by gas heating of lining). The dynamic heat field was built with help of finite element method in supposition, that preheating of the lining up to 1350 °C was held for 48 hours and after that the lining was exposed for 24 hours at this temperature.

A pouring of metal with temperature 1570 °C into installation, with refractory lining working layer temperature of 1350 °C was considered as thermal shock, during lining heating. Fig. 2 illustrates temperature change for working surface of the lining (line 1) and lining layer, which is situated at the depth of 10 mm (line 2). These conditions effect in material viscosity reducing (with temperature increasing) and thermal stress relaxation velocity growth respectively (2). At the same time, temperature difference between metal and lining surface decreases, that also reduces motive power and velocity of lining heating. The line 3 at fig. 2 illustrates the value of thermal stress in the working layer of the lining. It is evident, that thermal stress receive its maximum value approximately in 1,5 s after metal pouring.

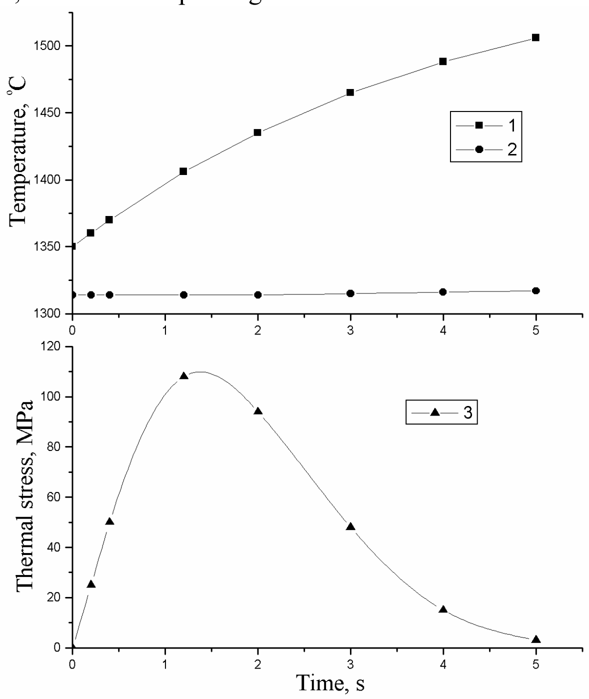

Fig. 2. Lining layers temperature and thermal stress change, after metal pouring. 1 – working layer temperature. 2 – temperature at the 10 mm depth. 3 – thermal stress at the working layer.

A compressive stress appears in the working layer of the lining, because of the resistance for material growth from the deeper layers of the refractory brick and pressure from the neighbor elements of the same layer in described conditions. A characteristic result of destruction under compressive stress is shown at fig. 1a. It is important, that during first 1,5 s of the process, the value of compressive strength becomes higher than material strength more than twice (typical compressing strength of refractory materials is between 30 and 50 MPa).

During rapid cooling of the lining we can see an opposite result (fig. 3). After working layer temperature falls below deeper layer temperature (5 – 6 s after cooling beginning) tensile stresses begin to grow in the working layer. At the same time the material viscosity increases, as the result – relaxation velocity falls and thermal stress becomes more than material strength in 2 – 3 s (7 – 10 s from the cooling begin). This causes of a few deep cracks growth (fig. 1 b). The typical tensile strength of refractory materials is about 8 – 12 MPa.

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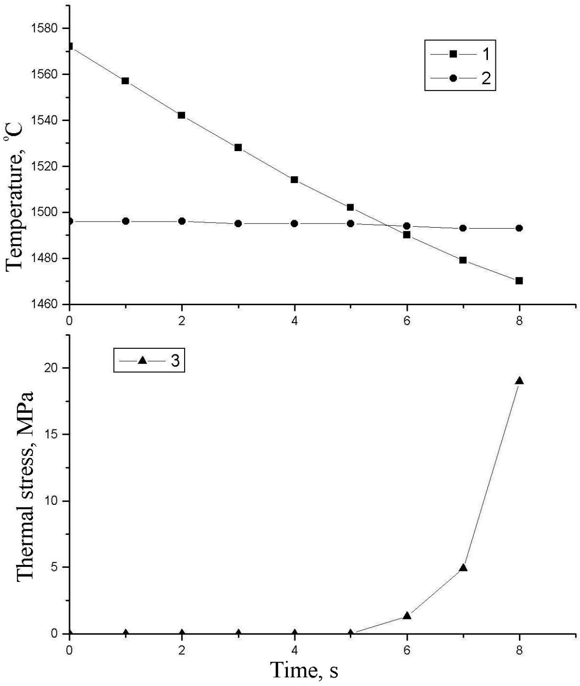

Fig. 3. Lining layers temperature and thermal stress change, during after-melt cooling. 1 – working layer temperature, 2 – temperature at the 10 mm depth, 3 – thermal stress at the working layer.

Deepness of material destruction can be fixed, using (3) – (5) equations. During metal pouring, a net of micro-cracks 4 – 5 mm depth appears at the working surface of the lining. At the case of cold air penetration into installation (during after-melt cooling), the depth of cracks can reach approximately 120 mm in one cycle of cooling.

Conclusion

The destruction of metallurgical installations linings under thermal shock was investigated with mathematics modeling methods. A calculating algorithm, based on finite elements method, was suggested for crack size calculation. The character of thermal stress was fixed for both cases – heating and cooling of the lining.

It was fixed, that thermal shock during rapid heating, causes the appearance of compressing stress, which have an extremum character. The result is – numerous surface cracks growth, cracks sizes are about 5 mm deep. These cracks appear approximately after 1 – 3 s from the moment of metal pouring. Otherwise, thermal shock during rapid cooling of the lining provides the stress, which grows permanently for a long time. The material feels tensile stress and a few deep cracks appear. These cracks deepness can reach approximately 120 mm. They appear after 7 – 10 s from the cooling beginning.

Character of destruction of existing metallurgical installations corresponds with calculation results, described in this paper. The exploration of crack form and size at the real equipment has objective difficulties, because of impossibility of detail inspection of the lining after each cycle of heating or cooling. However, such indirect data as velocity of wear of lining and casing surface temperature shows that calculation error is within permissible limit.

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