Thermal crack growth modeling in refractory linings of metallurgical installations

Andrew V. Zabolotsky

Abstract — A cracks growth in metallurgical installations refractory linings under thermal shock was investigated with mathematical modeling methods. As an example a standard periclasse – chromite refractory lining of DH-degasser was taken. Two types of thermal shock were considered – during heating and cooling of the lining. Thermal stress while preheating process was also calculated. A dynamic heat field was an initial data for thermal stress calculating. A finite elements method was choused for all calculations. The size of lining damages was calculated with method of «heat displacement». The moments of crack appearance were determinate with 3-dimentional stress field modeling. The calculating results are in good correspondence with real damage sizes, measured after finish of installation usage.

Keywords — computer simulation, finite elements method, mathematics modeling, thermal shock, crack, metallurgy, refractory lining.

I. 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, more dangerous, than chemical and mechanical tear and wear of the lining. It can become a reason of a sudden failure of the lining at the very beginning of its company.

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).

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Also, thermal shock has great effect at elements of continuous casting installations: ladle shroud, submerged nozzles, slide plates and so on: These elements commonly are situated outside of installation, so their preheating is very expensive, this is the reason of their exposition for thermal shock.

Thermal shock influences on refractory materials in all situations: during preheating of the refractory lining, during the metal melt gets into cold installation (heating thermal shock) and during after-melt lining cooling (cooling thermal shock). 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 with average usage conditions. Also, it helps to determinate refractory lining quality (thickness, character and size of damages) in concerned moment of time with help of outer surface temperature measurements [1]. 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 [2], [3]. The detailed report on cracks growth in solid bodies from historical point of view can be found in [4]. This report overviews models of cracks appearance and growth since Leonardo da Vinci times up to recent models and methods, including finite elements method and others. Modeling results allows providing new stable designs of metallurgical equipment linings. For example, Japanese engineers, with help of computer simulation, fixed the most dangerous areas in RH-degasser tube lining [5]. The result of lining scheme changes, based on the simulation data, is the increasing of in-service time approximately with 10 % (more than 5000 US dollars economy per complete set of degasser refractory lining).

In other fields of engineer science mathematical methods (finite elements method for example) are also widely used for modeling of temperature fields: [6] – a calculation of temperature field for pantograph contact with wire, [7] – temperature field simulating for gas cutting of copper.

The present paper illustrates mathematical methods usage for modeling of thermal shock refractory lining failure. Features of both thermal shock types (occurred during rapid heating and fast cooling of lining) were discussed. An algorithm of thermal stress calculation was suggested. This algorithm includes such methods as finite elements method and theory of "heat likeness" for temperature calculations inside solid material and on its surfaces respectively. Methods of applied mechanics were used for forecasting of cracks sizes, appearing in refractory lining as a result of thermal shock. Also, the moment of crack appearance was predicted with mechanical analysis methods.

The initial data for crack size calculation and the moment of crack appearance obtaining are 3-dimentional temperature and stress fields in material of refractory lining of metallurgical installation, calculated with finite elements method.

A standard refractory material of MgO-Cr_2O_3 system, used with standard working conditions was chosen as a calculation object. MgO-Cr_2O_3 materials are often used for linings of degassers and linings of installations, commonly exposed to rapid temperature changes.

II. Physical Base of Thermal Shock and Calculation Method

Thermal shock is one of the causes of thermal stress appearance in metallurgical installation refractory lining. The direct cause of thermal stress is thermal growth or compression of refractory lining materials. Thermal conductivity of most ceramics and refractory materials is relatively low (less than 10 W/m·K) [8], 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 between these points) 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 working surface 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, in winter and in summer respectively).

At the same time refractory materials have rather high coefficient of thermal growth ($1 – 2 \cdot 10^{-5}$ K^{-1}) [9]. 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. In the case of lining cooling – a powerful tensile strength appears in more rapidly cooling parts of the lining.

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

$$\sigma_n = \varepsilon \cdot E , \quad (1)$$

σ_n – stress in material, ε – relative elongation of the sample, E – modulus of material elasticity. At the same time:

$$\varepsilon = \frac{\Delta l}{l} , \quad (2)$$

Δl – absolute thermal elongation of the sample: during thermal processes it is equal to thermal growth or compression of the element (the sample elongation can appear as a result of outer tensile or compressing load, but it is not a task of thermal analysis), l – starting length of the sample.

$$\Delta l = l \cdot \Delta T \cdot \alpha , \quad (3)$$

ΔT – temperature change of material, α – coefficient of element material thermal growth. So, relative elongation depends on temperature change as following:

$$\varepsilon = \Delta T \cdot \alpha , \quad (4)$$

Thermal stress can be calculated with the following equation:

$$\sigma_0 = \Delta T \cdot \alpha \cdot E , \quad (5)$$

σ_0 – thermal stress in material.

However, a slow temperature change does not give an effect of thermal stress growth, because of stress relaxation effect [10]. The stress disappears with the course of the time, according to the following [11]:

$$\sigma = \sigma_0 \cdot e^{-\frac{\tau \cdot E}{K_1}} , \quad (6)$$

σ – real stress in material, σ_0 – stress in material without relaxation consideration (thermal stress (5)), τ – time, passed after relaxation beginning, K_1 – a variable, which characterizes relaxation velocity, depending on materials ability for plastic deformations. This variable for refractory materials differs from 10^{15} at room temperature down to 10^7 – 10^9 at working temperature (1550 – 1700 °C) and down to 10^2 – 10^3 at materials melting temperature [12]. The K_1 variable can be written as:

$$K_1 = 10^{K_2} , \quad (7)$$

The mathematical power K_2 for equation (7) can be calculated for different types of materials, using their characteristic data, such as temperature of melting beginning (so-called temperature of refractoriness, measured with pyroscope method – this is the temperature of liquid phase appearance in the sample) and temperature of melting finish and some other points. For example, for MgO-Cr_2O_3 material, used for degasser lining we had obtained the following approximate equation:

$$K_2 = 15.32 - \frac{0.04 \cdot t}{\ln t} , \quad (8)$$

t – temperature of the lining element of the mesh node for finite element method calculations.

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 refractory linings 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).

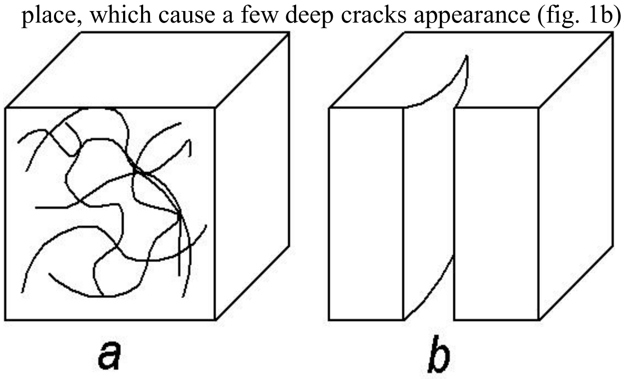

Fig. 1. Character of refractory working layer destruction: a – during rapid heating; b – during fast cooling.

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») [13]. This method idea is to obtain a surplus energy (a type of potential energy), accumulated in some volume of material, due to thermal stress:

$$U = \sigma \cdot V\,, \quad (9)$$

U – surplus energy, σ – thermal stress in material, considering relaxation (6), V – volume of material, considered. At the next step we need to fix an amount of chemical bonds, for which destruction this surplus energy could be spent:

$$n = \frac{U}{U_0}\,, \quad (10)$$

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 bond destruction energy). Surface of one chemical bond is an initial data of full crack area calculation:

$$S_c = n \cdot S_0\,, \quad (11)$$

S_c – full crack surface area, S_0 – area of one chemical bond (also, for material with different types of chemical bonds we need to use average values for bonds area).

The data about chemical bonds areas and their energy of destruction can be found in a special literature, [14] for example. During calculation it is necessary to consider, that each crack provides two new surfaces. Equation (11) allows calculating full area of these two surfaces. It is important for transformation of the crack area into crack depth:

$$l_c = c_f \sqrt{S_c}\,, \quad (12)$$

l_c – cracks length, c_f – coefficient of form for crack, depending on character of stress (tensile or compressing) and materials modulus of elasticity and viscosity (K_1, according to equation (7)).

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. The temperature dependence of mentioned material properties makes task of dynamic heat field calculation more complicated.

A finite elements method [15] was used for a dynamic heat field fixing. A heat exchange features at inner and outer installation surfaces were considered [16], [1].

The dynamic heat field can be transferred into dynamic stress field, using equations (5) and (6). Both these fields could be shown as a 3-dimentional models – the dependence of temperature or stress on time and coordinates. In complicated situations, when heating or cooling takes place from two or more sides, we can obtain up to 5-dimentional models of fields, but in real objects situation is commonly not so complicated.

One of such complicated tasks is to calculate a temperature field around argon tube of RH-degasser. Argon tube is situated in the lining of inspiration pipe of degasser, orthogonal to the axis of the pipe and is used for metal enriching with argon, while treating in degasser. So, we receive a system, where are one heating (working surface of refractory lining) and two cooling surfaces (outer surface of the pipe and inner surface of the argon tube). The suggested algorithm allows calculating not only the temperature in all points of solid material around tube (fig. 2), but also a temperature field of the gas inside argon tube (fig.3).

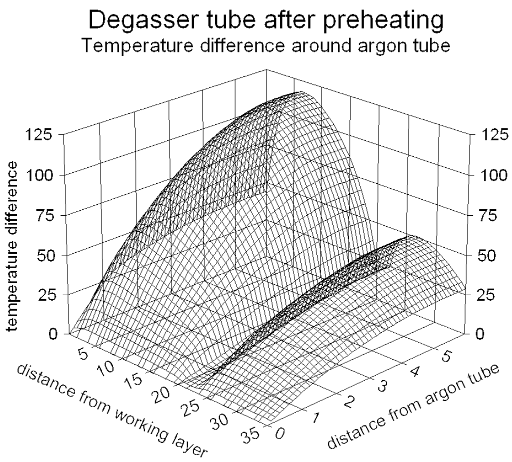

Fig 2. Temperature field around argon tube.

It is important, that values at fig 2. are the following: all lengths are in centimeters, temperature difference is in Celsius degrees. An the difference is between the temperature of the wall of argon tube and temperature of the point inside lining.

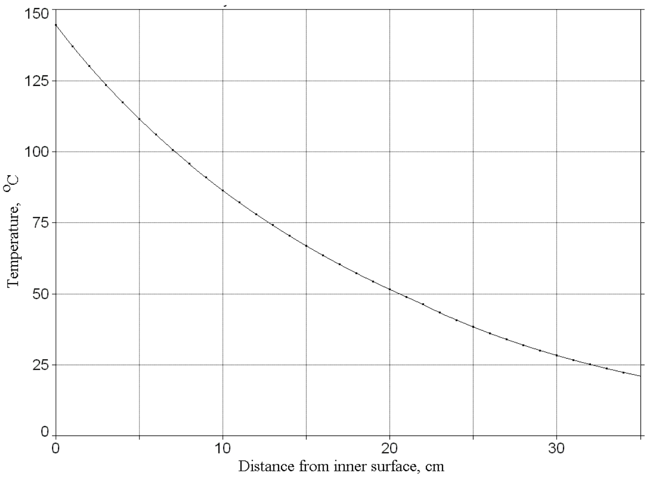

Fig 3. Temperature field of gas in argon tube.

At fig 3. distance is measured from the inner (hot) surface of the lining (0-point).

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 realized here. Surface or inner heat carrier temperatures can be calculated, using values of heat stream inside the lining and coefficient of heat exchange:

$$T_s = T_a - \frac{Q}{\alpha_o} \quad (13)$$

$$\alpha_o = \alpha_r + \alpha_c \quad (14)$$

$$\alpha_r = 5.67 \cdot 10^{-8} \varepsilon_s \frac{T_a^4 - T_s^4}{T_a - T_s} \quad (15)$$

$$\alpha_c = Nu_a \lambda_a d^{-1}, \quad (16)$$

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 (13) was written for situation, when heat carrier is more hot, than surface (for situation of preheating or metal treating, at the inner surface of the installation). In opposite situation (after-melt cooling or for the outer surface of the installation) 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 of elements, their heat conductivity and sizes:

$$Q = \frac{\sum Q_i}{n_e}, \quad (17)$$

Q_i – heat stream in element of the mesh (it can be calculated, using temperatures of surrounded elements and calculating element size and heat conductivity), n_e – an amount of elements in the mesh. Also, it is necessary to consider, that heat conductivity and coefficients of heat exchange depend on temperature of the process.

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:

$$dT = \frac{\lambda}{\delta} \cdot dQ, \quad (18)$$

dT - temperature change in the layer, δ and λ – thickness and heat conductivity of walls layer respectively, dQ – heat stream inside the layer [17]. The values of Q_i in equation (17) and dQ in equation (18) are equal.

Heat exchange between hot wall and surrounding air at the outer installation surface also takes place with radiation and convection. Equations (13) – (16) are used for this 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.

The coefficient of heat exchange calculation for the outer surface of the installation is not a trivial task. Several books and articles were devoted to the methods or results of such calculations. For example a handbook by H. Y. Wong [18] with recommendations for this coefficient calculations for different surfaces (different forms and space orientations of surfaces are considered in this handbook) or investigations by L. Hou et. al. [19], [20], [21].

Heat fields obtained, allow calculating thermal stress in any point of the lining at any moment of time (3-dimentional stress field), according to the equations (5) - (6).

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. This was explained above by the influence of surrounding elements and thermal growth or compressing of materials.

III. 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 and stress fields were built with help of finite element method in supposition, that preheating of the lining up to 1350 °C was held more than for 48 hours and after that the lining was exposed not less than for 24 hours at this temperature. First 10 hours of preheating process are exposed at fig. 4 as a 3-dimentional stress field.

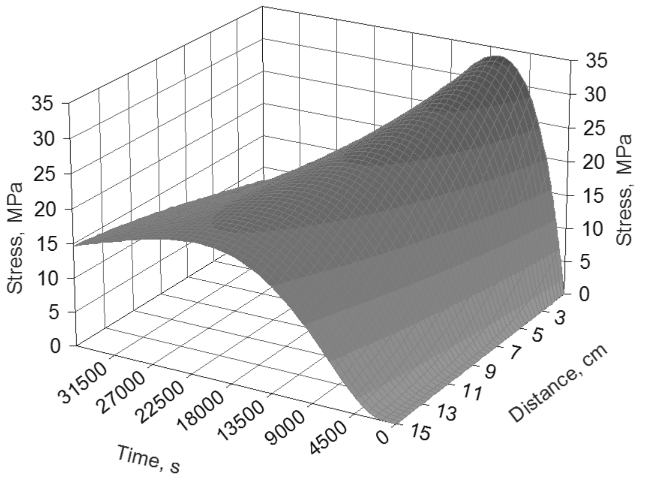

Fig. 4. 3-D stress field while first 10 hours of lining preheating.

At fig. 4 we can see, that strength while preheating has extremum character, and its maximum value is about 30 MPa. The ceramics compressing strength is about 30-40 MPa, but there is no danger of crack appearance, while lining preheating, because velocity of stress growth is very law. As it is shown at the figure, this value of stress appears during 2 or 3 hours of preheating, at the same time, while strength testing of materials, we load it with 0.2 – 2 MPa per second.

A pouring of metal with temperature 1570 °C or more into preheated installation, with refractory lining working layer temperature of 1350 °C was considered as thermal shock, during lining heating. Damages of metal pouring into a refractory lining with surface temperature less than 1350 °C would be much greater. In this case we can loose several centimeters of lining thickness during only one cycle of such usage. Fig. 5 [22] 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 (6) – (8). 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. 5 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.

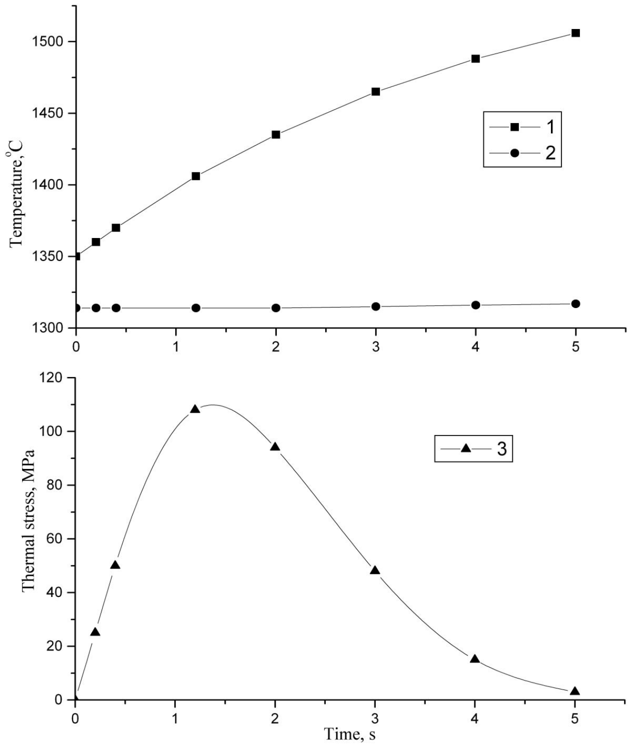

Fig. 5. Lining layers temperature and thermal stress change, after metal pouring. 1 – working layer temperature. 2 – temperature at the 10 mm depth. 3 – thermal stress at the working layer.

The main process of thermal shock takes place in a working layer of the lining within depth of 10-20 mm. The fig. 6 illustrates a 3-dimentional stress field of the 20 mm of working layer during first 1.5 s of the process. A like result for the time of thermal stress maximum was received in [23].

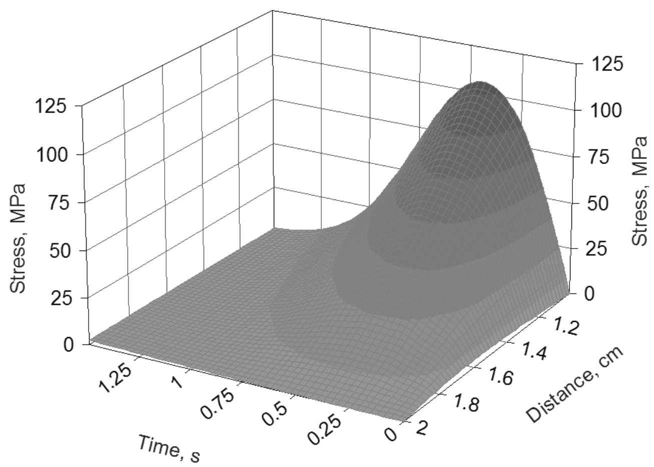

Fig. 6. 3-D model of stress in a working layer of the lining, during first 1.5 s after metal pouring.

Fig. 7 shows the dangerous time and depth zone of thermal shock, while lining heating. Visible graph surface includes only coordinates and moments of time with thermal stress above 30 MPa – minimal compressing strength for refractory lining materials. Obvious, that this dangerous period lasts about 0.8 s but stress becomes more than 2-3 values of material strength. It is enough for material destruction. Some difference between values at fig. 5 and fig. 6-7 can be explained by the different approach to K_1 calculations, used for these two models (equations (8) – (9)).

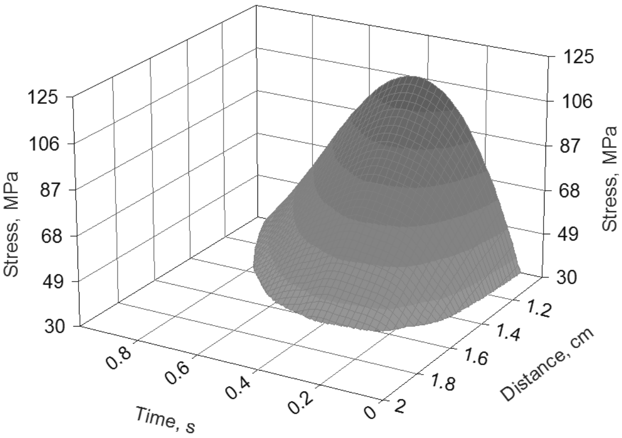

Fig 7. A zone of dangerous stress while heating thermal shock.

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 1-1.5 s of the process, the value of compressive strength becomes higher than material strength more than twice (calculating results are 100-120 MPa and 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. 8) – the main destructive force is a tensile stress inside the working layer of the refractory lining [22]. After working layer temperature falls below than 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 (with temperature falls), 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.

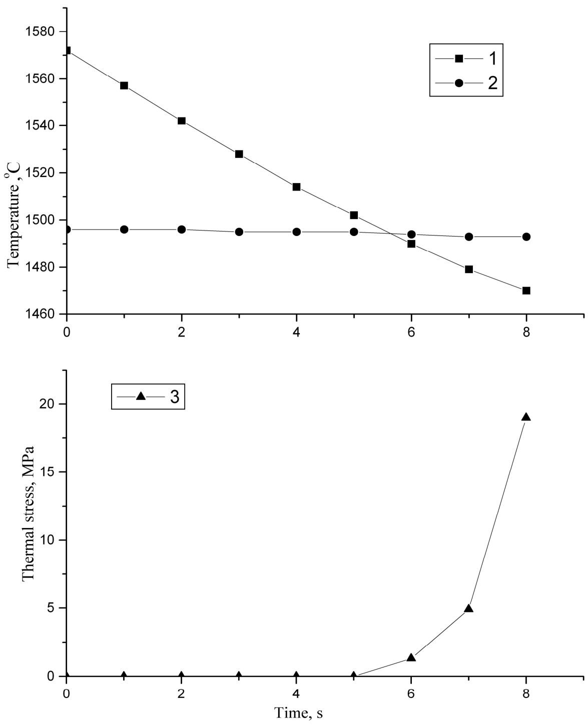

Fig. 8. Lining layers temperature and thermal stress change, during after-melt cooling. 1 – working layer temperature, 2 – temperature at the 10 mm depth, 3 – thermal stress at the working layer.

First 15 minutes of the cooling thermal shock are shown as 3-dimensional dynamic stress field for a working layer of the lining at fig. 9. The stress after 15 minutes can reach the value of 300 MPa and more. Surely, it is not possible, because of cracks appearance. The crack growth will use all the surplus energy of refractory lining thermal size decrease (compression while cooling) for creating of new crack surfaces (equations (9) – (11)). At the figure we can see calculating results for the working lining layer, 20 mm thick.

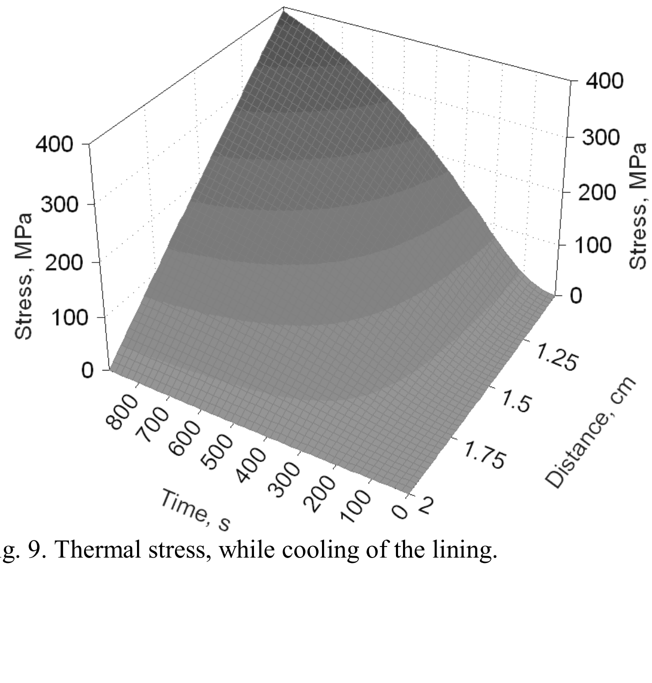

Fig. 9. Thermal stress, while cooling of the lining.

Deepness of material destruction can be fixed, using equations (9) – (12). 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 rapid cooling.

IV. 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. This new algorithm is based on a well known mathematics methods such as finite elements method and theory of "heat likeness" – for the calculation of heat exchange parameters at the surfaces of installation.

A 3-dimentional temperature and stress fields were built by finite elements method to obtain the moments of appearance and depth of material damages. These fields are results of algorithm usage and an initial data for the damage sizes calculations with methods of applied mechanics.

The same algorithm can be used for complicated calculations with two or more surfaces of heat exchange. For example argon tube of RH-degasser pipe. In this case we can obtain temperature fields for both solid and gas phases.

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 (several tens of minutes). The material feels tensile stress and a few deep cracks appear (commonly at places with inner damages or places where stress concentration exists, such as brick corners, for example). These cracks deepness can reach approximately 120 mm (within conditions, taken for calculations). In some extreme situations crack depth can become more than full thickness of the refractory lining. Cracks appear approximately after 7 – 10 s from the cooling beginning.

Character of refractory linings 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 (or during) 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 limits.

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He had prepared and published more than 10 papers for different journals in Russia and other countries. He was a participant of several international conferences (for example IAS Conference in 2009 at Buenos Aires, Argentina, Moscow conference of refractories and metal producers (2010), Kiev mathematics conference (2010)). At the present time he is working with problems of heat exchange and thermal failure in refractory linings of metallurgical installations. Main interest at the present time is in building forecasts of refractory linings failure with help of mathematics and statistic methods.