Раздел 1. «Металлургия»

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Features of modeling the process of researching the thermally stressed state of bowls for transporting liquid slag

As is known, in metallurgical shops of blast furnace and steelmaking processes, slag carriers are used to drain slag and transport it. The main and most expensive part of a slag carrier is the bowl, which is a steel casting in the form of a thick-walled shell of various configurations.

Currently, in blast furnace shops, the most widely used bowls are 16 m3 in volume, based on frames with carriages and moved by biaxial railway-type undercarriages. At the same time, automobile-type slag carriers carrying one bowl began to be introduced at metallurgical enterprises.

The average service life of the bowls is insignificant and on average it is 500-1000 fillings, depending on the chemical composition of the slag, its temperature and a number of other factors. The main reasons for the failure of slag bowls are changes in their shape during operation, expressed in the formation of an annular or local narrowing in the area of the support ring, as well as the appearance of longitudinal and transverse cracks in the walls. Automotive-type bowls last much less due to the frequent failure of the axles, by means of which the axle is mounted on the body of the slag carrier.

The above defects appear as a result of cyclic thermal effects caused by natural technological processes in the operation of slag carriers.

In a solid body, uneven thermal expansion cannot occur freely and causes thermal stresses, which, in combination with mechanical ones from external forces, can cause significant plastic deformations, leading to complete or progressive destruction of the structure.

Knowledge of the magnitude and nature of the distribution of thermal stresses is necessary for a comprehensive analysis of the strength of the structure, and in-depth studies of the thermally stressed state of bowls during their operation will make it possible to develop and adopt engineering solutions to increase their service life.

Keywords: slag bowl, thermal stress, deformation, temperature, thermal resistance

Introduction.

Temperature stresses are of great practical interest for the metallurgical industry. The struggle for further development of metallurgy, for metal saving is connected with maximum reduction of rejects of liquid slag transport bowls due to temperature stress cracks and other bowl defects arising from temperature loads.

A direct way to build the theory of temperature stresses for different shapes and designs of slag bowls would be to write equations for elastic and plastic zones and to solve these equations jointly taking into account boundary conditions. However, to solve this problem to date there is not enough data on the distribution of elastic stresses in the walls of slag bowls, nor on the parameters of temperature loads on the slag bowl in the process of slag pouring and its transport, nor on the understanding of changes in physical and mechanical properties in the bowl material when reaching the temperature at which the metal loses its elastic properties and temperature stresses begin to dissipate.

As mentioned above, slag bowls fail as a result of changes in shape (formation of circular or local constriction in the area of the support ring (railway-based bowls) and destruction of support trunnions for road-based bowls), as well as from cracks in the walls. These defects are caused by the cyclic temperature effects of slag. Uneven expansion due to high temperatures causes thermal stresses in the bowl wall, which, either by themselves or in combination with mechanical stresses from external forces, cause plastic deformations. Variable elastic-plastic deformations lead to thermal bulging of thin-walled structures, cracks appear, and failure occurs. Repeated exposure to high temperatures causes thermal fatigue of the bowl walls.

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With the development of computer technology, research methods based on numerical methods for solving differential equations have become available. In conjunction with three-dimensional modelling, the finite element method is widely used in practice. However, the algorithm for solving the static problem using this method of investigation and the thermal problem differ significantly. This is due to significant temperature deformations of the investigated object, as well as the presence of the contact boundary between the two media.

Methods and Materials.

The tasks of determining the temperature stresses arising in metallic structures have been relevant since the end of the century before last. The formation of thermal stresses is caused by the fact that individual parts of the heated object cannot change their dimensions in accordance with the expansion temperatures. When metal is heated, it expands and increases in volume. With increasing complexity and uneven temperature loading, the most heated parts of the object expand more than the less heated parts. This in turn leads to stretching of the material within the heated structure [1].

The tasks of determining the temperature stresses in metallurgical equipment and, accordingly, the problem of improving their thermal resistance were actively engaged in the staff of the Department of Theoretical Mechanics of the National Metallurgical Academy of Ukraine, as well as PKTI PJSC "Dneprotyazhmash".[2].

Investigations of thermal stressed state of bowls for liquid slag transportation of different designs were carried out using strain gauge method of research. The results of the conducted studies indicated that the temperature of the bowl surface, during its operation, can reach $500°$ C, and the stresses arising in the structure - in the range of 120-150MPa.

In analytical methods of solution, the authors represented the slag bowl as a thin-walled shell of rotation of constant thickness under the action of external contour forces and temperature field distributed symmetrically about the axis [2]. The following calculation scheme was used. The bucket was conditionally divided into three parts: upper conical, cut off at the level of stops, middle conical and lower spherical. External forces with bending moments were applied to the parts, and the problem was solved using the equations of elasticity theory.

The results of the work done give a definite but not complete picture of the thermoelastic state of slag bowls but are of great interest in terms of experimental results.

With the development of electronic-computing machines, the finite element method [3-8] has been used to solve problems in mechanics concerning the study of the stress-strain state of various elastic bodies.

So in [3] comparative results of research of thermal stress state of slag bowls of domestic and German production are presented. The work shows that the maximum stresses occurring in the walls of the bowl are 200 MPa.

Studies of thermal stress state of bowls for liquid slag transportation are also presented in a number of papers [4]. The authors conducted a number of studies to determine the stresses in the bowl wall when it is filled with slag. As a result of these studies the values of maximum stresses occurring in the slag bowl are indicated, the dependences of temperatures occurring in the bowl wall on the time at which the molten slag is in the bowl are presented. Ways of solving the problem of increasing the resistance of slag bowls at their intensive operation are presented.

The determination of temperature stresses in an elastic body requires the use of several key formulas related to thermo-deformation and the laws of elasticity. The following are the fundamental formulae required to calculate thermal stresses.

The generalised Hooke's law is a system of linear equations relating stresses and strains in a material. It is used to calculate the stress-strain state in elastic materials, taking into account both mechanical loads and temperature effects [9].

$$\sigma_{ij} = \lambda \delta_{ij} \left(\varepsilon_{kk} - 3\alpha\Delta T \right) + 2\mu \left(\varepsilon_{ij} - \alpha\Delta T \delta_{ij} \right), \tag{1}$$

σ_{ij} - stress tensor components

ε_{ij} - strain tensor components

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λ, δ - coefficients

δ_{ij} - Kronecker symbol

α - coefficient of linear thermal expansion

ΔT - temperature change

$$\lambda = \frac{E \cdot v}{(1+v)(1-2v)} \tag{2}$$

$$\lambda = \frac{E}{2(1+v)} \tag{3}$$

The equations of equilibrium can also be used to solve the problem of the thermal stress state of the slag bowl. Differential equations of equilibrium in the theory of elasticity describe the balance of forces in an elastic body. These equations provide the condition under which the internal stresses in the body are in equilibrium with the applied external forces.

For the case of temperature deformations, the differential equations of equilibrium in displacements can be generalised and presented in the following form

$$\varepsilon_x = \frac{1}{E} \cdot \left[\sigma_x - v \cdot \left(\sigma_y + \sigma_z \right) \right] - \alpha \cdot \Delta T \tag{4}$$

$$\varepsilon_y = \frac{1}{E} \cdot \left[\sigma_y - v \cdot \left(\sigma_x + \sigma_z \right) \right] - \alpha \cdot \Delta T \tag{5}$$

$$\varepsilon_z = \frac{1}{E} \cdot \left[\sigma_z - v \cdot \left(\sigma_x + \sigma_y \right) \right] - \alpha \cdot \Delta T \tag{6}$$

Where – $\sigma_x, \sigma_y, \sigma_z$ normal stresses, Pa

In the quasi-static problem of thermoelasticity, the effect of coupling of the temperature and strain fields, as well as the inertia forces due to the unsteady temperature field, are not taken into account, and time t plays the role of a parameter.

The first stage of solving static and quasi-static problems of thermoelasticity consists in determining the temperature field T. It is reduced to solving Eq.

$$\lambda \nabla^2 T - c \cdot \rho \frac{\partial T}{\partial t} + W = 0, \tag{7}$$

where λ is the heat transfer coefficient,

c - specific heat capacity,

ρ - density,

W - intensity of heat sources attributed to the unit volume.

After solving the equation under certain thermal initial and boundary conditions, the thermoelastic stress state is determined. The boundary conditions depend on the temperature operating conditions and the design of the object under study.

The well-known law establishing the relationship between strains and stresses allows us to obtain the following expression relating the strain from thermal expansion to the temperature stress:

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$$\sigma = \frac{\alpha \cdot E}{1-v} \cdot \Delta T \, , \tag{8}$$

where α is the coefficient of linear expansion of the material

ΔT - temperature difference in the research area,° C

E - modulus of elasticity, Pa

v - Poisson's ratio

This expression allows us to determine the stresses in the object under study, when it is uniformly heated, with respect to the plane problem. It is not possible to use expression (8) to investigate the volumetric thermal stress state taking into account the application of external forces to the body.

The determination of temperature stresses in a three-dimensional object is a complex problem, for which in most cases an analytical solution is not possible due to a number of reasons and the above mentioned. Also, three-dimensional objects, to which the slag bowl belongs, have complex and inhomogeneous geometry. As a consequence, a heterogeneous temperature field will be formed in the bowl, which, together with the need to solve a system of differential equations (equations of equilibrium, joint deformation and generalised Hooke's laws) in partial derivatives, reduces the problem to the category of unsolvable.

The finite element method, as a numerical method for solving differential equations based on three-dimensional computer modelling, is optimally suited to solve this problem.

Results and Discussion.

When analysing the thermal stress state of objects experiencing thermal effects, which include slag bowls, a number of conventions must be taken into account.

When modelling the location of molten slag in the bowl, the following assumptions must be taken into account:

1. The physical and mechanical parameters of liquid slag are assumed to be constant and independent of temperature.

2. The physical and mechanical parameters of the material from which the slag bowl is made vary with temperature.

3. Temperature resistance is present at the slag-bowl interface due to the application of lime mortar to the bowl.

4. The slag bowl and slag mirror are in contact with the environment, resulting in heat exchange

Unlike classical finite element calculations for determining the stresses and deformations of an object arising in the elastic zone, the algorithm for analysing temperature stresses is somewhat different. Firstly, in order to obtain temperature stresses, it is necessary to determine the temperature field arising in the object under study. This is a kind of applied load on the object under study, and in some cases the temperature field causes stresses in the structure greater in magnitude than mechanical forces.

In the study of structures, equipment of metallurgical plants, which include slag bowls, ladles, iron and steel ladles, then in them it is necessary to take into account the temperature resistance arising between the product and the liquid medium. Thus, Fig. 1 shows the final process of draining liquid slag from a slag ladle. The figure shows the precipitation of the slag crust formed when the slag cools and reacts with the inner lining of the ladle. This "crust" serves as a temperature resistance protecting the bowl from overheating [10].

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Fig. 1 Garnish falling out of the slag bowl on the truck during slag draining process

Fig. 2 shows the results of computer modelling of the dynamic temperature field of the slag bowl at the same moment of time equal to 30 minutes after pouring at different values of the temperature resistance of the bowl.

As practice shows, when operating a slag lorry, slag stands idle in the bowl of a railway slag lorry for 40-80 minutes on average [2-4]. Thus, the temperature field of the bowl will be dynamic and change in time. Experimentally it was found that the temperature of the bowl wall obtained in experimental studies presented in [2, 3], as well as in computer modelling are close at the temperature resistance between slag and bowl $4 \cdot 10^{-4} \dfrac{K}{Bm}$ (Fig. 2.a).

The figure shows that when the temperature resistance is reduced to 8 times of the set temperature resistance (Fig. 2.d), the maximum bowl temperature increases by 167° C, which is 23% at 1800 seconds of bowl operation. When the temperature resistance is reduced to $10^{-4} \dfrac{K}{Bm}$ (Fig. 2.c), the maximum bowl temperature increases by 140° C, which is 19.5%. When the temperature resistance is reduced to $2 \cdot 10^{-4} \dfrac{K}{Bm}$ (Fig. 2.b), - the temperature of the bowl increases by 67° C, which is 9%.

Thus, it is shown that the temperature resistance between the slag and the bowl directly affects the characteristics of the temperature field of the bowl, which in turn entails certain values of temperature stresses.

An important factor in the study of thermal stress state of slag bowls is to take into account the dependence of physical and mechanical parameters of the material on temperature (tab. 1). Thus, Fig. 3 shows the results of the study of the thermal stressed state of slag bowls at temperature-dependent material parameters (Fig. 3.a) and material parameters at a temperature of 20° C, specified in Table 1 (Fig. 3.b).

From the results of studies presented in Figure 3, it follows that the nature of stress distribution in the bowls has a similar character. Significant stress difference for both cases is observed in the zone of slag mirror location. This phenomenon is well explained by expression (8). At a significant temperature difference in the bowl wall, which just happens in the zones of slag mirror location, the temperature stresses will be the greater, the greater will be the temperature difference.
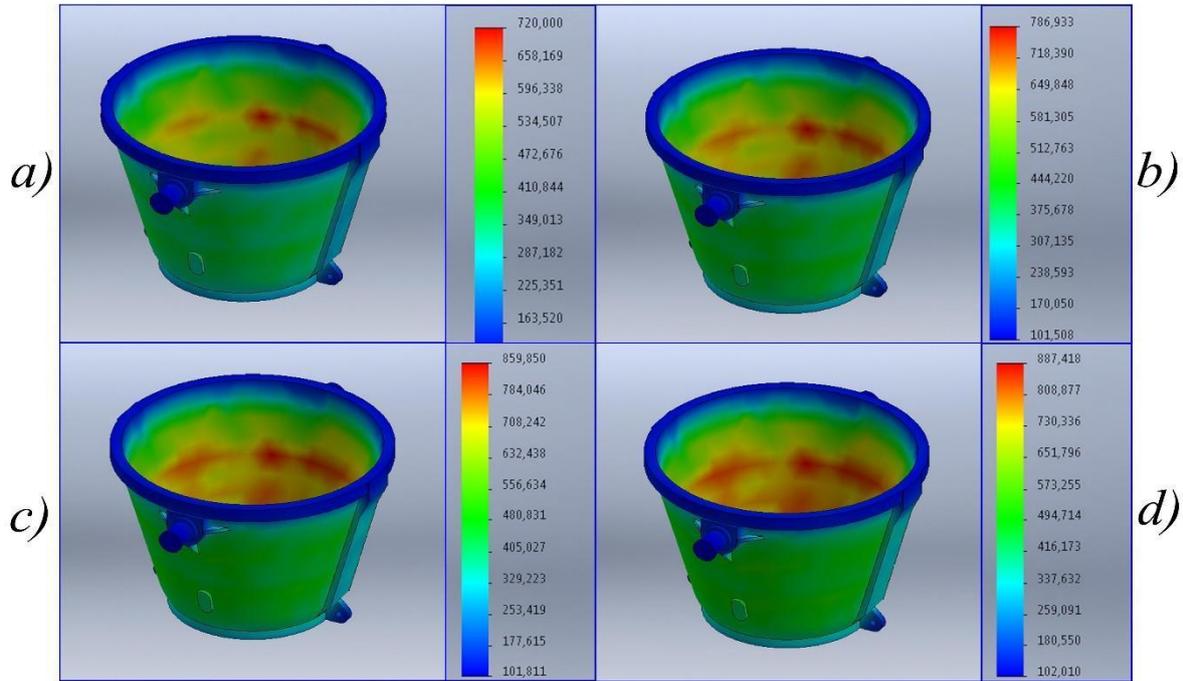
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Figure 2. Temperature field of the slag bowl at different temperature resistances:

$$a)\,4 \cdot 10^{-4}\,\frac{K}{Bm}\;;\;b)\,2 \cdot 10^{-4}\,\frac{K}{Bm}\;;\;c)\,10^{-4}\,\frac{K}{Bm}\;;\;d)\;5 \cdot 10^{-5}\,\frac{K}{Bm}$$

Table 1

Temperature dependence of physical and mechanical parameters of the bowl

Temperature,° C	Modulus of elasticity, 10^5 MPa	Coefficient of thermal expansion, 10^{-6} (1/degree)	Thermal conductivity, W/(m· deg)	Specific heat capacity, J/(kg· deg)
Steel 25L GOST 977-88				
20	1,98	11,5	52	400
100	1,96	12,2	51	470
200	1,91	13	49	483
300	1,86	13,7	46	500
400	1,63	14,3	43	521
500	-	14,7	40	571
600	-	15	36	-
700	-	15,2	32	-
800	-	-	26	-

As for the maximum values of stresses occurring in the bowl wall, their values differ by more than a factor of two. This can be explained using the theory of thermal stresses. When heating a metal, thermal stresses arise due to temperature differences. The more heated layers tend to expand and are in compression. Colder layers are subject to tensile forces. If these stresses do not exceed the elastic limit of the heated body, the thermal stresses disappear as the temperature equalises.

All metals and alloys have elastic properties up to a certain temperature. For most steel grades this temperature ranges from 450-500° C. Above this temperature, metals and alloys go into a plastic state and the thermal stresses generated in them cause plastic deformation and disappear. Consequently, thermal stresses should be taken into account during heating and cooling of steel only in the temperature range from room temperature to the point of transition of this metal from the elastic state to the plastic state [11].

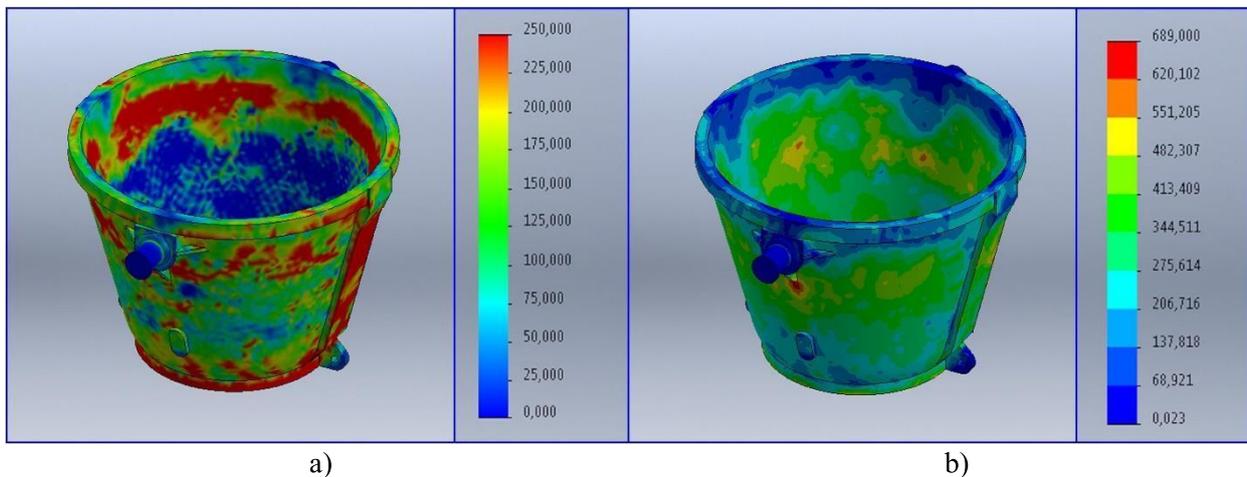a)   b)

Fig. 3 Comparison of stresses (MPa) in slag bowls on a car under different conditions of material indication: a - temperature-dependent material parameters; b - constant material parameters at different temperatures

Thus, taking into account that the slag bowl in certain zones is heated to temperatures exceeding 500°C and the material has a constant value of elastic modulus, the obtained stress values will be significantly different from the real ones, which is observed in Fig. 3.

The most important feature of modelling the thermal stress state of slag bowls, according to the authors, is the consideration of significant temperature deformations and, as a consequence, the boundary conditions. When defining the boundary conditions, it is necessary to take into account possible significant expansions of the material. In case of rigid fixation of the three-dimensional model, the modelling results may not correspond to the real state of affairs.

In order to compare the values of maximum stresses at different boundary conditions, a test problem was developed and executed. For its solution two identical ring models were created. The rings were aligned by planes, thermal resistance was set between them, the upper ring was heated up to 500 ° C, the lower ring was at room temperature. Computer modelling assumed heat dissipation from the lower ring in order to create a significant temperature difference in it (Fig. 4.a). The study was carried out for a certain time interval. Fig. 4.b shows the temperature fields arising in the lower ring due to the above conditions. Figs. 4.c, 4.d show, respectively, the values of stresses arising in the rings when fixed with no possibility to deform freely and fixed on pliable springs, which allows the model to deform freely.

The results of the modelling showed that the stresses occurring in the lower ring, under boundary conditions with no possibility of free deformation, are 4 times higher than in the ring whose boundary conditions allow free in-plane movements.
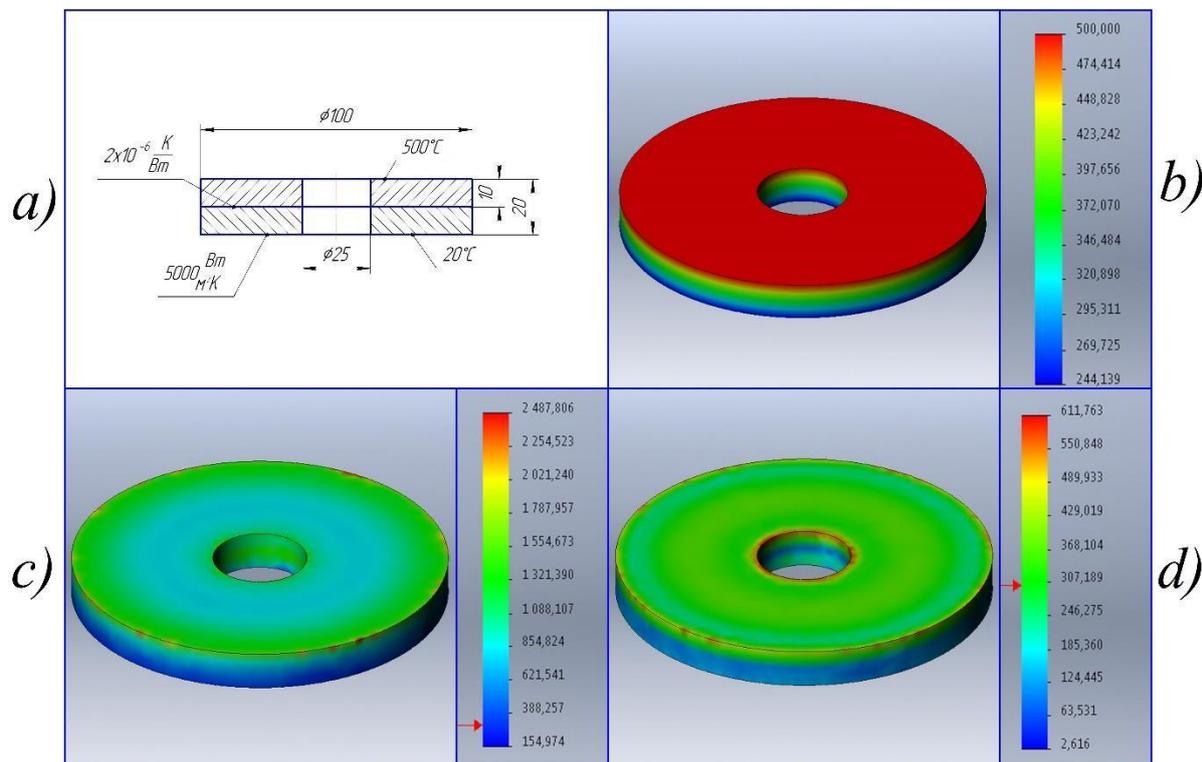
Figure 4. Towards an analysis of anchoring conditions:
a) scheme and conditions of interaction of two rings; b) temperature field of the lower ring after 450 seconds after the beginning of heat exchange; c) fields of equivalent temperature stresses of the lower ring at its fixation on three coordinates (MPa); d) fields of equivalent temperature stresses of the lower ring at its fixation on one coordinate (MPa);

Conclusions

Determination of temperature stresses of thermally loaded elements of metallurgical equipment is not an easy task even today. Widely known equations of elasticity theory and mathematical physics do not allow to solve the problem analytically and, as a consequence, it is necessary to resort to numerical methods of solving differential equations using three-dimensional modelling. At the same time, the accuracy of the obtained results will be influenced not only by a competently constructed model, which is important for similar static calculations, but also by a number of other factors. These include the conditions of fixation of the investigated model, the presence of temperature resistance between different models, the indication of material characteristics as temperature dependent.

The results of the modelling show the dependence of the above-mentioned factors on the values of stresses occurring in the slag bowl. Temperature resistance affects the homogeneity of the temperature field and its maximum values, improper fixing conditions can increase the maximum stresses by 4 times, and the presence of material whose physical and mechanical parameters do not depend on temperature - increase the stresses by another 2 times.

Thus, the analysis of the thermal stress state of slag bowls is a more complex and cumbersome task in comparison with static calculation, not only because of the need to separately solve the problem of determining the temperature field as a factor of external influence, but also because of the presence of additional conditions necessary to obtain an adequate result.

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Сұйық шлақтарды тасымалдауға арналған таулардың термиялық кернеулі күйін зерттеу процесін модельдеудің кейбір ерекшеліктері

Белгілі болғандай, домна және болат балқыту процестерінің металлургиялық цехтарында қожды ағызу және оны тасымалдау үшін қож тасушылар қолданылады. Қож тасушының негізгі және ең қымбат бөлігі - әртүрлі конфигурациядағы қалың қабырғалы қабық түріндегі болат құйма болып табылатын тостаған.

Қазіргі уақытта домна цехтарында вагондары бар рамаларға негізделген және екі осьті теміржол типті асты арбаларымен қозғалатын 16 м3 көлемдегі тостағандар кеңінен қолданылады. Сонымен бірге металлургиялық кәсіпорындарда бір тостағанды тасымалдайтын автомобиль типті қож таситын машиналар енгізіле бастады.

Тостағандардың орташа қызмет ету мерзімі шамалы және қождың химиялық құрамына, оның температурасына және басқа да бірқатар факторларға байланысты орта есеппен 500-1000 толтыруды құрайды. Қож тостағандарының істен шығуының негізгі себептері жұмыс кезінде олардың пішінінің өзгеруі, тірек сақинасының аймағында сақиналы немесе жергілікті тарылудың пайда болуымен, сондай-ақ қабырғаларда бойлық және көлденең жарықтардың пайда болуымен көрінеді. . Автомобильдік типтегі тостағандар осьтердің жиі

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істен шығуына байланысты әлдеқайда аз қызмет етеді, оның көмегімен ось шлак тасушының корпусына орнатылады.

Жоғарыда аталған ақаулар қож тасушылар жұмысындағы табиғи технологиялық процестерден туындаған циклдік жылу әсерлерінің нәтижесінде пайда болады.

Қатты денеде біркелкі емес термиялық кеңею еркін жүруі мүмкін емес және сыртқы күштердің механикалық әсерлерімен бірге құрылымның толық немесе үдемелі бұзылуына әкелетін елеулі пластикалық деформацияларды тудыруы мүмкін жылу кернеулерін тудырады.

Термиялық кернеулердің таралу шамасы мен сипатын білу құрылымның беріктігін жан-жақты талдау үшін қажет, ал тостағандардың жұмыс кезінде термиялық кернеулі күйін терең зерттеу инженерлік шешімдерді әзірлеуге және қабылдауға мүмкіндік береді. олардың қызмет ету мерзімін ұзарту.

Түйін сөздер: шлагтай, термиялық керселіс, деформация, температура, жылық керсімділік

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Особенности моделирования процесса исследования термонапряженного состояния чаш для транспортировки жидкого шлака

Как известно, в металлургических цехах доменного и сталеплавильного производств для отвода шлака и его транспортировки используются шлаковозы. Основной и наиболее дорогостоящей частью шлаковоза является чаша, представляющая собой стальную отливку в виде толстостенной оболочки различной конфигурации.

В настоящее время в доменных цехах наиболее широко используются чаши объемом 16 м3, установленные на рамах с каретками и перемещаемые двухосными ходовыми частями железнодорожного типа. В то же время на металлургических предприятиях начали внедряться шлаковозы автомобильного типа с одной чашей.

Средний срок службы чаш незначителен и в среднем составляет 500-1000 наполнений, в зависимости от химического состава шлака, его температуры и ряда других факторов. Основными причинами выхода из строя шлаковых чаш являются изменения их формы в процессе эксплуатации, выражающиеся в образовании кольцевого или локального сужения в области опорного кольца, а также в появлении продольных и поперечных трещин в стенках. Чаши автомобильного типа служат гораздо меньше из-за частого выхода из строя осей, с помощью которых ось крепится к корпусу шлаковоза.

Вышеуказанные дефекты появляются в результате циклических тепловых воздействий, вызванных естественными технологическими процессами при эксплуатации шлаковозов.

В твердом теле неравномерное тепловое расширение не может происходить свободно и вызывает тепловые напряжения, которые в сочетании с механическими воздействиями внешних сил могут вызвать значительные пластические деформации, приводящие к полному или прогрессирующему разрушению конструкции.

Знание величины и характера распределения термических напряжений необходимо для всестороннего анализа прочности конструкции, а углубленные исследования термонапряженного состояния чаш в процессе их эксплуатации позволят разработать и внедрить инженерные решения для увеличения срока их службы.

Ключевые слова: шлаковая чаша, термическое напряжение, деформация, температура, термическое сопротивление

Раздел 1. «Металлургия»

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