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DETERMINING THE THERMALLY-STRESSED STATE OF MOTOR-DRIVEN BOWLS FOR TRANSPORTING LIQUID SLAG

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Slag bowls were chosen as the object of research, as important components of blast furnace, steelmaking, and ferroalloy shops of metallurgical enterprises. The main problem of operation of any slag trucks is their limited durability and frequent destruction of slag bowls. The reason for these problems is changes in the shape of the bowls during operation, manifested in the formation of narrowing places in the area of the support ring – for rail-mounted bowls, destruction of supporting pins – for rail-mounted slag trucks, or cracks in the walls. Those defects appear as a result of cyclic thermal effects of liquid slag on the bowl. Based on the results of computer simulation, it was established that the main role in the destruction of the support pins of motor-driven slag bowls belongs to temperature changes. The temperature stresses arising in the bowl are localized in the area of the slag mirror (200–250 MPa for 25L steel, 280–350 MPa for 30HML steel). The results provide grounds for improving the presented slag bowl to reduce temperature stresses in its walls and structures of the supporting trunnions. The results reported here are explained by the fact that with uneven heating of elastic bodies, temperature stresses appear, which, under certain configurations of temperature loads, lead to the destruction of structures. The findings from these studies are recommended to be used at enterprises for the design and manufacture of slag bowls, as information on the localization of dangerous places of the structure. In addition, the data presented here could be useful for metallurgical enterprises for detailed technical diagnosis of bowls in their dangerous places

Keywords: slag bowl, blast furnace slag, thermal stresses, temperature, bowl thermal resistance

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1. Introduction

The study of phenomena related to temperature stresses in slag bowls is of great practical interest for the metallurgical industry. Saving of metal during production is possible by maximally reducing the number of destructions of slag bowls during operation. The destruction of the bowls is due to the occurrence of cracks that arise from thermal stresses and other defects of the bowls that appear as a result of temperature loads.

The mathematical model for constructing the theory of temperature stresses for various shapes and designs of slag bowls implies solving the system of equations for the elastic and plastic zones, taking into account the boundary conditions.

At some metallurgical plants, motor-driven slag trucks have become widespread (Fig. 1). One of their main advantages is the possibility of transporting liquid slag to the dump without downtime. This prevents the formation of a slag crust and, as a result, eliminates shock loads that are applied to the heated bowl in the process of knocking out the crust.

Slag bowls fail because of the appearance of cracks in the walls of the bowls. In addition, in rail-mounted slag trucks, bowls are destroyed because of a change in geometric shape (formation of an annular or local constriction in the area of the bowl's support ring). In motor-driven slag trucks, the support pins are destroyed while driving.

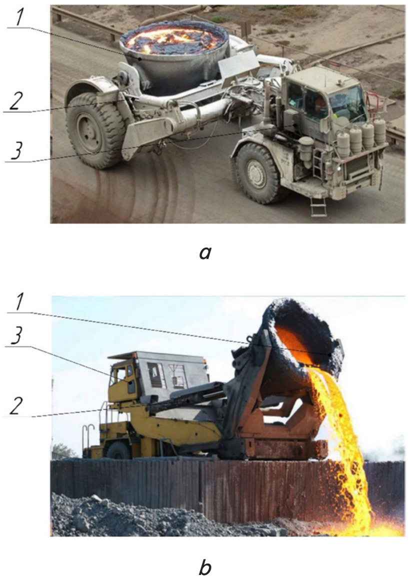


Fig. 1. Motor-driven slag trucks: *a* — 4×2-wheel formula; *b* — 6×2-wheel formula; 1 — bowl with slag; 2 — hydraulic mechanism for overturning the bowl; 3 — driver's cabin

Uneven thermal expansion caused by high temperatures causes thermal stresses in the wall of the bowl, which by themselves, as well as in combination with mechanical stresses from external forces, cause plastic deformations. Time-varying elastic-plastic deformations lead to the thermal loss of stability of thin-walled structures, the appearance of cracks, and subsequent destruction. Cyclic exposure to high temperatures causes thermal fatigue of the bowl wall material.

Therefore, taking into account the importance of slag bowls for enabling the full functioning of metallurgical production, an area of actual scientific and practical research emerged.

2. Literature review and problem statement

With the development of electronic computing technology, numerical methods for solving differential equations began to be used in practice, including for temperature stress calculations. For example, in [1], the results of research on temperature stresses in cylindrical structures were published. The work reports a complex mathematical apparatus that minimizes obtaining results when solving similar applied problems. On the other hand, this work is fundamental for both thermal calculations and calculations taking into account computer simulations.

Work [2] describes studies of the thermally stressed state of bowls for the transportation of liquid slag, which were carried out using the tensometric research method (Fig. 2).

The results of the reported studies indicate that the temperature of the surface of the bowl, during its operation, can reach 500 °C, and the stresses arising in the structure are within 140–180 MPa. The disadvantages of these studies include the selective attachment of the sensors to the bowl and obtaining stress values at certain points. It is also unclear whether the dependence of the physical and mechanical properties of the bowl material on temperature changes was taken into account during stress calculations. Analytical methods of solution, in the same work, represented a slag bowl as a thin-walled shell of rotation of constant thickness under the action of external contour forces and a temperature field distributed symmetrically about the vertical axis. The following calculation scheme was used: the bucket was conditionally divided into three parts: the upper conical, which is cut off at the level of the stops, the middle conical, and the lower spherical. External forces with bending moments were applied to the parts, and the problem was solved using the equations of the theory of elasticity.

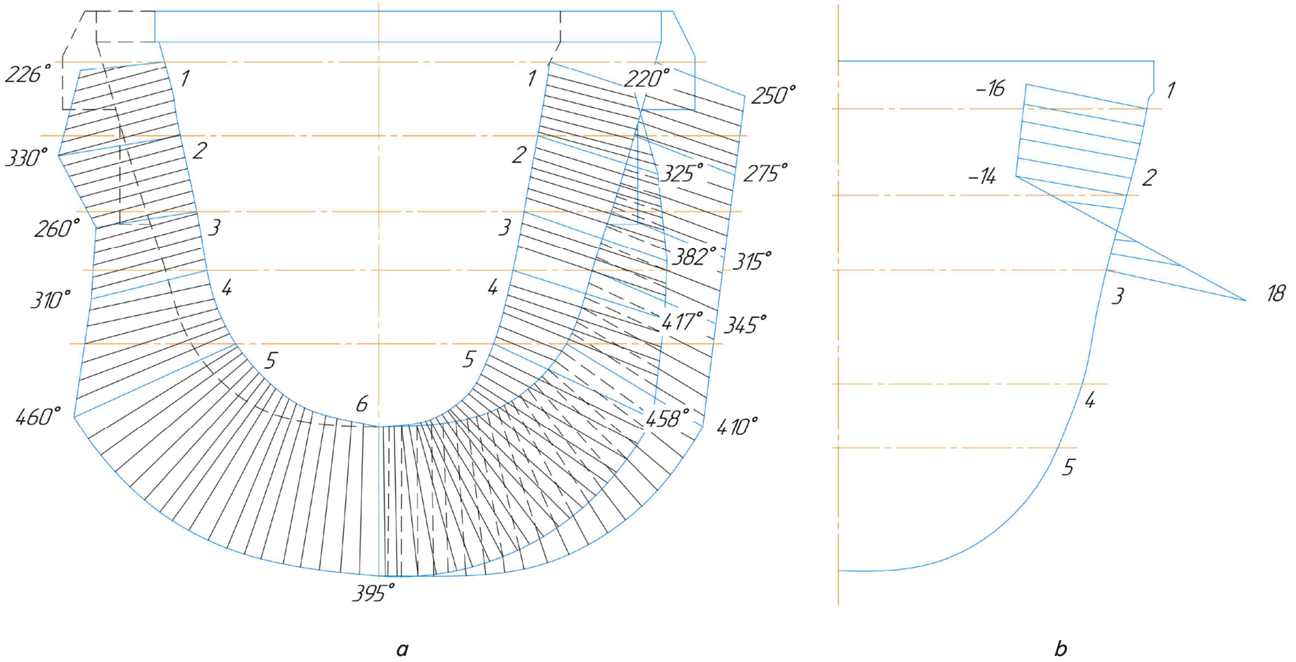


Fig. 2. Distribution of temperatures and stresses in bowls of oval design [2]: *a* — temperature distribution, °C; *b* — stress diagrams, kgf / mm^2

The results of the work provide a massive database, but not a complete picture of the thermoelastic state of slag bowls. At the same time, the above work is of great interest from the point of view of the results of experimental studies on the determination of temperatures and temperature stresses occurring in slag bowls.

With the development of electronic computing machines, the finite element method began to be used to solve the problems of mechanics related to studies of the stressed-strained state of elastic bodies. For example, work [3] reports the results of research, using the finite element method, of temperature stresses in a body that changes from a liquid state to a solid state. The materials are interesting from the point of view of the analysis of temperature stresses of slag bowls. During solidification of liquid slag, phase transitions occur while reverse processes occur in the inner parts of the walls of the bowls where the material loses its elastic properties.

Similar studies were described in [4], in which the results of modeling temperature stresses in elements of blast furnaces at the boundary of liquid and solid materials are reported.

Works [3, 4] demonstrate a general scientific focus on determining temperature stresses at the boundary of two environments. For applied use, for the purpose of studying slag bowls, they need to be refined in the area of both material characteristics and the construction of a three-dimensional model of the slag bowl.

Paper [5] reports the comparative results of studies of the thermally stressed state of slag bowls with a volume of 16.5 m^3 and 24 m^3. The work shows that the maximum stresses that occur in the walls of the bowl are 200 MPa. The disadvantage of this work is a significant reduction of the peak stress values that occur in the bowls, together with the results obtained due to the presence of sharp edges, inaccuracies in modeling and calculation features. This can be seen in the stress fields presented in this work, they lack smooth stress transitions, which somewhat reduce the accuracy of the analysis. The reason for this may be too strict calibration of the results, inherent in this type of research.

Work [6] describes the results of research into the thermally stressed state of bowls for transporting liquid slag. The paper shows graphs of temperature changes in the bowl over time, obtained in various studies, as well as temperature stress fields. It is shown that the maximum temperatures in the bowl walls can vary in the range of 400–800 °C, the stresses in the bowl walls reach 200 MPa. Ways to ensure the stability of slag bowls during their intensive operation are presented.

The work does not contain the results of solving the temperature problem, which is a very important step in finding temperature stresses, there is no information about the thermal resistance caused by the application of lime and other solutions on the inner surface of the bowl. Also, the work reports the results of research on a bowl on a support ring, which is structurally different from bowls on support pins. This entails a change in the load distribution and, as a result, in the simulation results.

Paper [7] describes both analytical research results and experimental results using optical pyrometers. It is shown that the maximum temperatures when filling the cup reach 500 °C. Special attention was paid in the work to the contact zone between the liquid slag and the bowl, where the dimensions of the finished elements were very carefully selected. However, to determine the temperature resistance, it is enough to make variable studies of the temperature field with further comparisons on natural objects. The paper also presents the results of computer simulation for determining stresses in slag bowls. In the work, emphasis was also placed on phase transitions, as well as on the study of changes in the microstructure of castings after a certain cycle of operation of the bowls. The research results indirectly indicate that the maximum stress values near the supporting pins are far from critical. The work does not present stresses in dangerous places of the bowl, as well as in the supporting pins. At the same time, the presented design of the slag bowl is unique compared to the designs reported in works [2, 5, 6].

In work [8], studies of temperature stresses occurring in slag bowls with a bias towards probabilistic aspects of the calculation were reported. The work also includes studies of temperature effects, thermal shock, and chemical effects on the slag bowl during operation. The dependences of the change in the microstructure of the bowl material on the operating conditions are presented. Comparisons of real operational defects of the bowls and the results obtained using the finite element method are given. As in the above works, the results of these studies are unique in view of the fact that they were conducted for bowls of certain designs and a given volume. Attention was not focused on the nature of the distribution of stresses, as well as stresses near the supports. These questions remain open.

In [9], referring to the study of the effect of a quasi-static temperature field on the material of the slag bowl, measures are presented to reduce the temperature stresses in the walls of the bowl. The work has a more engineering focus. It shows measures to increase the rigidity of slag bowls. At the same time, insufficient attention has been paid to the question of the nature of stress distribution in the bowl and the places of their concentration.

Work [10] reports the results of studies on the stressed-strained state of slag rail-mounted bowls. Separately, important experimental studies of the temperature field of bowls using a thermal imager with an optical pyrometer should be noted, conducted by analogy with work [7]. But, as in most cases, the cited studies are valid for not motor-driven bowls, and the issue of localization of maximum stresses is not sufficiently disclosed in the work.

Summing up, it should be noted that not enough attention has been paid to researching the thermally stressed state of motor-driven slag bowls. At the same time, in all the cited works, the slag bowls had a unique design. In the design of the bowl in [7], no attention was paid to the supporting pins. The bowls described in works [2, 5, 6, 10], by their design, are installed with four brackets on a support ring, they have different volumes and different design features.

In comparison with regular studies of the stressed-strained state, the reasons for the localization of maximum stresses in given places are not indicated in the above studies. There is also no clear research algorithm for slag bowls. The dependence of the maximum temperature stresses on the initial conditions is not specified.

3. The aim and objectives of the study

The purpose of our study is to determine the thermal stress state in the walls and supporting pins of motor-driven slag bowls based on specified temperature and mechanical loads. This will make it possible to find ways to solve the task of increasing the operational resource of automobile slag bowls in the context of identifying potentially dangerous structures where destruction is possible.

To achieve the goal, the following tasks were set:

– to conduct an analysis of the stressed-strained state of the bowl without taking into account the influence of temperature and determine the stress in the supporting pins of the bowl;

– to determine the temperature fields acting on the bowl when it is filled with liquid slag;

– to determine the temperature stresses and the corresponding deformations that occur in the bowl.

4. The study materials and methods

The object of this study is bowls for transporting liquid slag. First of all, during the classical solution of similar problems [11], the temperature fields of the object of research were obtained depending on the temperature loads. In the second stage, on the basis of the temperature field, the stresses themselves were determined directly.

The hypothesis of this study is that the maximum temperature stresses will be localized in the walls of the bowl in the zones of geometric transitions. The stresses in the zones of the support pins will have lower values.

The finite element method was chosen to solve the problems. The following assumptions were adopted in the modeling process:

1. The physical and mechanical parameters of liquid slag (Table 1) were considered constant and independent of temperature. The initial temperature of blast furnace slag reaches 1600 °C. The total mass of slag filling the bowl is 15,000 kg, and the gravitational force acting on the bowl due to the weight of the slag is 150 kN, respectively.
2. The physical and mechanical parameters of the material from which the slag bowl is made (Table 2) depend significantly on temperature [12].
3. Temperature resistance ($4 \cdot 10^{-6}$ K/W) is taken into account at the slag boundary and the inner surface of the bowl, which occurs as a result of applying a lime solution to the bowl [10].
4. The slag bowl and slag mirror are in contact with the environment, resulting in heat exchange (20 W/($m^2 \cdot$K)).
5. When fixing the three-dimensional model of the bowl, the possibilities of thermal expansion were taken into account to compensate for elastic movements in order to obtain an adequate modeling result. The model was fixed on support pins in accordance with the conditions of its operation.
6. The study of the stress-deformed state of the slag bowl was carried out using two materials: 25L steel, from which slag bowls are made, and 30 HML steel – a promising material for bowls, which has higher ultimate mechanical properties compared to 25L steel.

Table 1

Physical and mechanical properties of liquid slag of blast furnace production [13]

Density, kg/m^3	Coefficient of thermal expansion, 10^{-6} (1/degree)	Thermal conductivity, W/(m·K)	Specific heat capacity, J/(kg·K)
1400	0.1	50	1000

Table 2

Dependence of the physical and mechanical properties of the bowl material on temperature

Temperature, °C	Elasticity module, 10^5 MPa	Coefficient of thermal expansion, 10^{-6} (1/degree)	Thermal conductivity, W/(m·degree)	Specific heat capacity, J/(kg·degree)
Steel 25L DSTU 8781:2018				
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	–
Steel 30 HML DSTU 8781:2018				
20	2.15	–	47	–
100	2.12	12.2	44	479
200	2.07	12.6	42	500
300	2.03	13.4	40	512
400	1.92	14.3	37	529
500	1.79	14.5	34	550
600	1.66	14.6	31	580
700	1.41	14.7	28	617
800	1.3	12.2	27	689
900	–	12.7	27	685

When constructing the mesh of finite elements, special attention was paid to the zones where destruction occurs. In these zones, a grid was built with a finite element size of 20 mm for the possibility of repeating the shape of the model. These elements were built on the support studs and near them, as well as in the area of the stiffeners and near them. The maximum size of the element is 100 mm, and it is located on even areas of the walls and inside the bowl. The ratio of the increase in the size of the finite element is 1.3. The grid geometry was built based on mixed curvature, given that the slag bowl has a complex structure.

The following algorithm was used to construct a grid of finite elements based on automatic design systems. On the three-dimensional model, the zones with the minimum size of the finite element and also the zones with the maximum size of the finite element were selected. Due to the scale factor, the transition between zones was made automatically by the automatic design system and, as a result, the number of elements was also selected automatically. The total number of elements that came out is 56,675. The total number of nodes is 94,773. When compiling the grid, trial calculations were carried out with changes in the parameters of the grid in order to assess the discrepancy of the results.

The main rule of our research is that the grid for the temperature problem should be identical to the grid for the stress determination problem.

The above grid parameters were chosen considering the fact that the bowl has a large size and the elements with the maximum size will provide the required accuracy on even areas. In turn, with the help of small elements, all complex geometry was taken into account, as well as places of destruction of the bowl.

When analyzing the results, a well-known law was used that establishes the relationship between temperature changes and temperature stresses [14]:

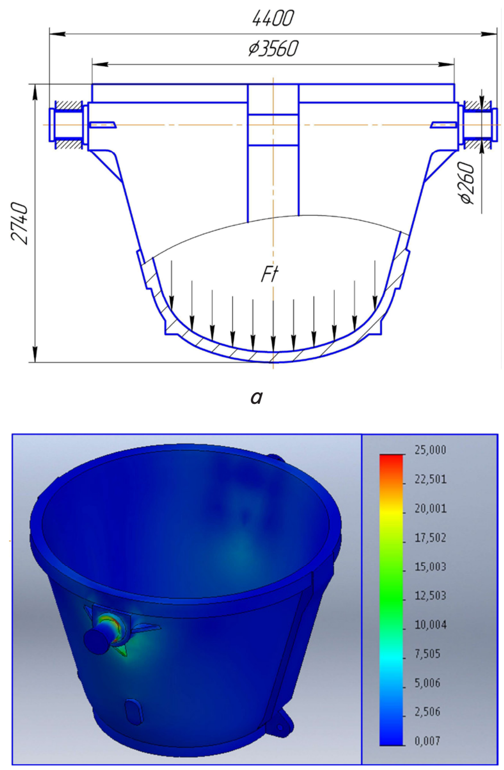
$$\sigma = \frac{\alpha \cdot E}{1-\nu} \cdot \Delta t, \qquad (1)$$

where α is the coefficient of linear expansion of the material, 1/°C; Δt – temperature difference in the research area, °C; E – modulus of elasticity, Pa; v is Poisson's ratio.

5. Results of investigating the stressed-strained state of the bowl for transporting liquid slag

5. 1. Analysis of the stressed-strained state of the bowl without taking into account temperature loads

In order to conduct studies to determine the stresses in the wall of the motor-driven bowl for transporting liquid slag, as well as in its trunnions, static studies were first conducted to determine the stresses arising from the force of gravity applied to the bowl from the weight of the slag. Fig. 3, *a* shows the calculation scheme for fixing and loading the bowl for transporting liquid slag. During computer simulation, the trunnions of the bowl were fixed in such a way that the structure was statically determined, and the gravitational force from the liquid slag (*Ft*) was evenly distributed over the entire contact surface of the slag with the bowl.



a

b

Fig. 3. Investigating stresses in the slag bowl supports from a static load imitating the slag mass: *a* — calculation scheme; *b* — fields of equivalent stresses (MPa) arising in the bowl

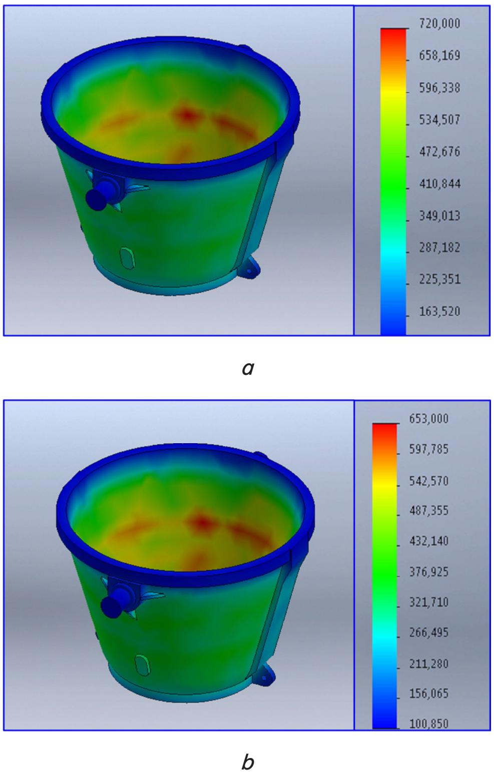
The results of computer simulation of the static load of a slag bowl (Fig. 3, *b*) show that the places of maximum stress concentration occur in the support pins. This result confirms the expediency of further research given that the places of destruction coincide with the places of maximum stresses. However, the stress values that occur in the places of maximum concentrations reach 25 MPa.

The research results indicate a significant margin of strength, and the stress values that occur in the trunnion do not even exceed the fatigue strength limit. Thus, in order to determine the complete picture of the stress-deformed state of the slag bowl, it is necessary to conduct similar studies taking into account the temperature loads due to the effect on the liquid slag bowl and analyze the resulting data.

5. 2. Determining heat loads acting on the bowl when it is filled with liquid slag

To determine temperature stresses, according to the classic scheme of similar calculations, the most necessary step is to obtain parameters of the temperature field [15]. The temperature field, in computer simulation, is not only an informative indicator of temperature distribution in the structure but also the additional load acting on the slag bowl.

The results of computer simulation of the temperature field, obtained using the finite element method, are shown in Fig. 4.



a

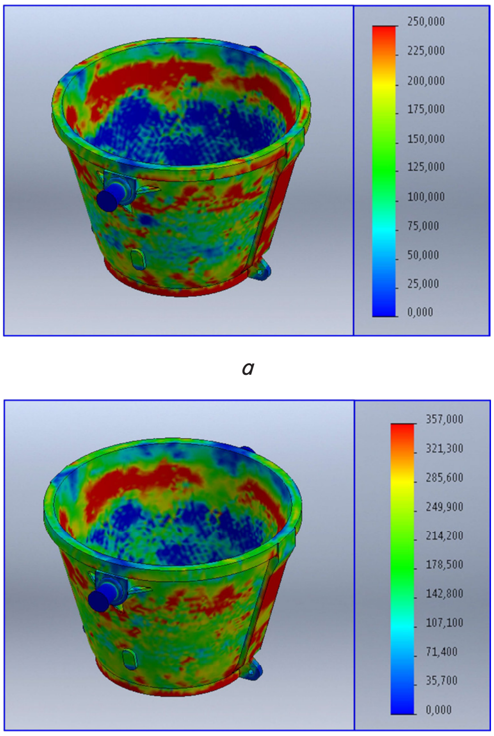
b

Fig. 4. Fields of temperatures (°C) in slag bowls made of different grades of steel under the same operating conditions: *a* — steel 25L, *b* — steel 30 HML

During the analysis of our results, it was found that the temperatures that occur in the walls of the bowl are in the range of 250–470 °C. This testifies to the adequacy of the model built, as well as the reliability of results, since they are consistent with the values of temperatures in the walls of the bowl obtained earlier, in other studies, using thermocouples [2, 5]. Based on the results of our studies, it was established that the temperatures in the trunnions themselves practically do not change, but on the inner part of the trunnion, where it can come into contact with slag during transportation, temperatures can reach 350 °C. This is enough to open the gap between the trunnion and the bowl and increasing temperatures to the specified values. However, no significant temperature differences are observed in the area where the pins are located, and therefore the predicted stresses near the pins will have small values.

5. 3. Determining temperature stresses and corresponding deformations occurring in the bowl

Fig. 5 shows the stress fields obtained as a result of temperature effects on a bowl with liquid slag. The results of our studies indicate that the maximum stresses that occur in the bowls are close to the values of the yield point (294 MPa for 25L steel, 392 MPa for 30HML steel). It should be noted that in some of its sections, stresses can reach 250 MPa (bowl made of 25L steel) and 357 MPa (bowl made of 30HML steel). After a certain number of cycles, this leads to the formation of cracks. At the same time, it is worth noting that during the stress determination, the results were analyzed for the presence of singularities – physically unrealistic high stresses, which are obtained in connection with the discretization of the calculation model used in the finite element method.



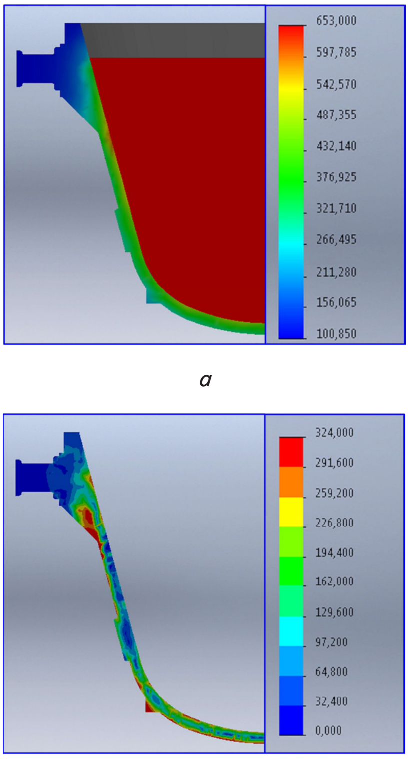
b

Fig. 5. Stress fields (MPa) arising in slag bowls from different grades of steel under the same operating conditions: *a* – steel 25L, *b* – steel 30 HML

Such phenomena often occur when solving engineering problems using finite element analysis. The most common reason for the occurrence of singularities is sharp corners: theoretically, infinitely large stresses occur in them if the radius of rounding is close to zero [16].

For a more detailed study of the nature of stress distribution in the walls of the bowl, axial sections of the bowl with the slag level are shown (Fig. 6).

Analyzing the results shown in Fig. 5, 6, it can be concluded that the places of concentration of temperature stresses during the operation of a slag bowl are localized in the region of the formation of the slag mirror. The maximum temperature difference also occurs in these places. It follows from formula (1) that when the temperature difference increases, the stress value also increases. However, the peak stress values also occur on the central stiffening rib, upper and lower ribs. This phenomenon can be explained by a change in geometry and sharp corners, which in turn leads to stress concentration.



b

Fig. 6. Comparison of temperature fields and temperature stresses at a given level of slag for steel 30 HML: *a* – temperature field, °C, *b* – stress fields, MPa

Worth noting is a significant increase in the maximum stresses in the bowl made of steel 30 HML, which is probably related to the presence of the modulus of elasticity of the material at high temperatures, which is not observed when using the material of steel 25L.

6. Discussion of results of investigating the thermal stressed state of bowls for transporting liquid slag

As a result of investigating the thermally stressed state of the slag bowl, temperature fields were established, as well as stress and deformation fields for the following materials: steel 25, steel 30HML. Stress fields and their comparison are of greatest interest.

The stress fields obtained under static loading (Fig. 5, 6) show that, without temperature loading, the bowl and supporting pins as a whole have a sufficient margin of strength.

When analyzing the results of the temperature fields of the slag bowls, it was established that the maximum temperature values are significantly lower than the initial temperature of the slag. This is explained by the fact that the temperature resistance between the slag and the bowl was specified during the modeling. The maximum values of the obtained temperatures in bowls of different materials (Fig. 4) differ by 10–12 % and depend on the physical and mechanical properties of the material of bowls (Table 2).

When using steel 30HML, the maximum stresses are 43 % higher compared to the stresses occurring in steel 25L (Fig. 5). At the same time, in the percentage ratio, the strength limit of 30HML steel is 33 % greater than the strength limit of 25L steel. These results can be explained by referring to formula (1) and Table 2. When the value of the modulus of elasticity decreases, the values of temperature stresses also decrease but, at the same time, this affects the stability of the bowl.

It was established that the places of concentration of temperature stresses are localized in the wall of the bowl near the slag mirror (Fig. 5, 6). This phenomenon can also be described using formula (1), where the greatest temperature difference gives, accordingly, the greatest stresses. This phenomenon is also observed in other similar studies [3, 5].

A comparison of the obtained stress results (150–250 MPa on the wall of the bowl) with the results reported in [2], which are 80–190 MPa in the given places where the sensors were attached, testifies to the reliability of the results. Also, the values of the maximum temperatures correspond to the results in [6, 10], in which the temperature in the walls of bowls of various designs and volumes reaches 500 °C. This can also be confirmed by the fact that the maximum stresses in the walls of the bowl occur in the area where the slag mirror is located. This can be seen in Fig. 2, *b* and is reported in the results of research [5]. In a similar way, it is possible to compare the values of the maximum temperatures that occur in the bowl.

The destruction of the supporting pins of a slag bowl is not related to the maximum values of temperature stresses but is related, first of all, to significant constant temperatures in the zone of their location and significant temperature deformations.

To extend the service life of these slag bowls, it is necessary to change the design of the bowl itself. Another option for solving this problem is to make the support pins from a material that has a higher coefficient of thermal expansion than the bowl itself. Thus, during heating of the entire structure, tension will occur on the contact area of the trunnion with the bowl, which will prevent premature failure of the support trunnions. At the same time, the trunnions are located at the place of conditional formation of the slag mirror and, as shown in Fig. 5, 6, in these places there is a significant temperature difference, which entails the occurrence of concentrations of temperature stresses.

Determining the temperature stress fields of slag bowls is a very complex study, given the fact that factors and parameters that may change over time must be taken into account. These parameters include the physical and mechanical parameters of the bowl steel, the physical and chemical parameters of the slag, the presence of bowl defects, the thickness of the protective layer of limestone inside the bowl, which serves as a temperature resistance, changes in the structure of the bowl material, the amount of poured slag, and others.

Works [1, 14] describe a complex mathematical apparatus that is already embedded in modern tools of three-dimensional computer simulation with a finite-element base. In these studies, only a small number of mathematical regularities were used to explain the processes occurring in the walls of the bowl.

When studying the thermally stressed state of the motor-driven slag bowl, the peculiarities of the transition of slag from a liquid to a solid state were not taken into account, which is very carefully described in works [3, 4]. Attention to the issue of determining temperature stresses at the boundaries of liquid and solid media was carefully considered in [7, 8]. Studies [8, 9] report more specific measures regarding how the design of the bowl should be improved.

The shortcoming of our study of the thermally stressed state of motor-driven slag bowls is the lack of natural studies. The results are not confirmed by experimental studies using a laboratory base but are compared with already known similar results. The change over time of the temperature field and, as a result, temperature stresses was not presented.

The main difference between the current studies and those known from [2, 5–10] is that they are conducted on bowls of different designs, different volumes, and different types of bases. These studies are united by the fact that the liquid slag, being in the bowl, leads to the appearance of microcracks in the walls with subsequent destruction.

Our studies of the thermally stressed state of motor-driven slag bowls expand the understanding of ideas, concepts of processes occurring in the walls of the bowl. First, the locations of temperature stress concentrations are localized in the zone of the slag mirror. This gives an understanding of the optimal level to which it should be filled with liquid slag. Secondly, the algorithm for solving this problem and the results provide a scientific basis for further in-depth studies of the thermally stressed state of slag bowls on the subject of the relationship between the stresses that occur in the bowl and the physical and chemical composition of the transported slag (Table 1). Together with the change of slag, its initial temperature also changes, which primarily affects the temperature stresses in the bowls. For example, for blast furnace slag, the temperature may reach 1,000–1,600 °C, for steel slag 1,300–1,600 °C, and the temperature of ferroalloy slag is 1,500–1,800 °C, in some cases 2,000 °C. In this way, it becomes possible to research bowls for different types of slag and design them in a targeted manner, based on the results of the research.

It is worth noting that during the research, only the mechanical component was considered, in relation to temperature stresses. The structural changes in the material, the uneven application of a limestone layer on the slag bowl in order to obtain temperature resistance, which will entail variable resistance and some inconsistency of research with real processes, were left out of consideration. Changes in the structure of the material and microgeometry in the case of knocking out the slag crust from the bowl are not taken into account in the work. All this indicates that the results of our studies show the tendency of stress while the actual pattern may change slightly with each new slag pouring.

When using the results at the design stage, as well as during the manufacture of slag bowls, it seems possible to change the design in such a way as to reduce the maximum values of stresses in the walls of the bowl. Recommendations for setting the level of the slag mirror could also extend the life of the slag bowl. The most important thing is that the results of this research will be useful for systematic studies of slag bowls of various shapes and different types of basing on the dependence of temperature stresses on the characteristics of the slag and its initial temperature.

7. Conclusions

1. Analysis of the stressed-strained state of a bowl for the transportation of liquid slag without taking into account temperature loads showed that the maximum stresses in the support pins reach 30 MPa. The results indicate that the slag bowl in these zones has a large coefficient of safety margin.

It also indicates that the problem of bowl failure near the support pins is unrelated to static strength.

2. The thermal effect of molten slag on a bowl for transporting liquid slag was simulated. During the research, it was established that the maximum temperatures that occur in the design of the bowl can reach 720 °C inside the bowl, 200–400 °C on the wall of the bowl, as well as 250–300 °C in the contact zone of the support pins and the bowl itself. This temperature is sufficient to open the gaps between the bowl and the supporting pins and the beginning of the destruction of the structure. The temperature fields are well correlated with the results of experimental studies on the determination of temperatures and stresses in bowls for transporting liquid slag, carried out using tensometry.

3. We have obtained stress and deformation fields of slag bowls under thermal load. The maximum stresses are localized in places of increased stiffness, as well as along the ring in the zone of slag mirror formation and are 250 MPa for 25L steel, 357 MPa for 30 HML steel. It is shown that the places of concentration of maximum stresses occur near the zone of the slag mirror. This is explained by the fact that in this zone, according to the results of the analysis of temperature fields, a significant temperature difference is observed. As for the deformation fields, the deformations that occur near the support pins have large values and, in combination with significant temperatures, can lead to the destruction of the bowls in given places. Our results on the stresses arising in the walls of the bowl are well correlated with the results of experimental studies on the determination of stresses carried out using tensometry (200–250 MPa in computer simulations, 140–180 MPa in tensometry).

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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