Proper Arrangement of Reinforcing Ribs for Elimination of Thermal Deformations in Metallurgical Products

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Abstract: The operation of large-sized equipment at high temperatures leads to the appearance of residual deformations. This reduces the service life of the products and safety of their use. To improve the service life of such products, reinforcing ribs fixed by welding can be used. The technology of strengthening of a large-sized product is shown by the example of a cinder car slag-pot, the improvement of which allows reducing the deformation of the case by 4-5 times.

Key words: Reinforcing ribs, thermal deformations, welding, metallurgical equipment, high temperatures, increase of service life

1. Introduction

Metallurgy uses a significant number of products operating at high temperatures. Thermal and dynamic loads during their operation can lead to a change in the initial geometry of the product and premature equipment failure. For example, during work slag-pots receive residual plastic deformations, which can lead to cracks (see Fig. 1) and which creates the possibility of emergencies in the enterprise and reduces the safety of technical personnel. The safety in operation is a requirement for any enterprise, and in metallurgy - in particular, due to the high temperature of transported materials (molten slag temperature is 1500-1600 °C). Depending on the working conditions of the enterprise, the outside surface temperature of the slag-pot case may be 400-500 °C. In the event of technological delays, the temperature of case near the stub axle is increased to 630 °C due to shielding of heat sink by support elements of the slag car design. At such temperatures, the material properties (cast steel 30L, 35L) are significantly reduced, creating a problem of preservation of the initial geometry of the product during operation. In the manufacture of slag-pots and other three dimensional frame structures, the casting method is generally used as the most economical, despite the low quality of the metal with cast structure and numerous metallurgical defects. First of all, these products require additional methods of strengthening. The solution of the problem of counteracting deformations of large-sized products is difficult because of their massiveness. The use of technical solutions using expensive materials increases the cost of products and is often economically unprofitable, because expensive components are expended on the whole mass of the product, while only small areas are subject to maximum thermal loads. So in slag-pots with a total mass of 21-24 tons with an overall height of the product of about 3500 mm, a section of about 400 mm in height near the stub axles requires strengthening. At the same time, the loss of metal from the premature destruction of the slag-pots at one metallurgical plant is approximately 700-900 tons per year. In this regard, consideration and solution of this problem is relevant both for slag-pots and for other three dimensional frame structures which operate at high temperatures.

1.1 Analysis of possible methods of the structure strengthening for operation at high temperatures

Strengthening of three dimensional frame structures to counteract their thermal deformation can be provided in various ways. The main directions of improvement of the products under consideration are the following:

1.Product design improvement.

2. Casting alloying.

3. Application of welding methods for strengthening of structures.

Increasing the thickness of either the whole product or its individual nodes is an unpromising direction. Experimental studies of the operation of slag-pots of experimental designs show that increasing the thickness of the slag-pot case by 20-30% does not solve the problem. The resistance of slag-pots increases by 5-7% with a significant increase in the metal consumption of equipment and its cost. This increase in resistance is found both on slag-pots with a common wall thickening and reinforced locally in the area of greatest deformations. The structure can be technologically alloyed in different ways. Alloying of all castings results in a significant increase in the cost of the product due to the high cost of the additional chemical components used, which is unprofitable for any industrial production. A promising direction is the use of local alloying of product, while the cost of expensive components can be reduced by dozens of times. Currently, the industry lacks reliable mass production techniques with the use of local alloying of large castings. Despite all the prospects for this direction, its implementation is currently difficult.

Among other methods of strengthening of structures the one of the most technologically convenient and reliable method is the use of welding technologies, and in particular, the creation of composite structures. This makes it possible to combine a cheap method of manufacturing a three dimensional frame structures by casting method with a reliable and technically simple joining by welding of small additional reinforcing elements. The shape and strength characteristics of such elements can be selected by designers by calculation, based on requirements to the fixed loads that arise during operation. Among the reinforcing elements, reinforcing ribs fixed by welding were widely used in the industry [1, 2]. The practice of using such reinforcing elements shows that different types of structure of such reinforcing elements can provide options for manufacturing products that differ in strength by several times.

1.2 Application of reinforcing ribs for the structure strengthening at high temperatures

Practice shows that the application of reinforcing ribs is an economically accessible and technologically convenient way to increase the rigidity and strengthening of the structure. This method is widely used in the construction industry. In metallurgy, this method is most rationally applicable for products with large dimensions and complex shapes. Under conditions of combined loading in such products, the stresses in different parts of the structure may differ tenfold. In this regard, the strengthening method of the specific product, which implies the increasing the strength of certain given sections of the product, is of particular importance. At the same time, different options of the strengthening method in varying degrees affect the service life and overall durability of the most critical area and the whole product. The analysis shows that the improvement of the design is most rational to begin with consideration of the emergent defects and the stressed state of the structure, which makes it possible to identify the critical sections determining the service life of the whole product. For example, the analysis of operating conditions and stressed state of metallurgical cinder cars shows that the most loaded node is the slag-pot, which primarily fails. The narrowing of the circle of consideration of individual parts or structure nodes reduces the total time for the design study when the product is improved. This makes it possible to simplify the procedure for creating models and to consider the largest number of loading options. With respect to metallurgical cinder cars, the modelling of behavior of the most loaded node-the slag-pot-made it possible to establish the following:

1. Loads and stresses along the slag-pot case are unevenly distributed.

2. Under conditions of combined loading of the cinder car slag-pot the thermal stresses are the main ones (percentage of stresses from mechanical loads is no more than 10%).

3. The greatest stresses from thermal loads correspond to the section of local overheating in

the area of the stub axle of the support ring, which leads to the wall bending of the slag-pot case.

4. The structural strength of slag-pots is not completely exhausted; the rigidity of their cases can be increased due to additional structural elements.

In this regard, the application of additional reinforcing elements in different sections of the structure can provide different efficiency of the operation of the product. In general, each product has an individual set of technical characteristics that ensure the execution of technological functions. So for the cinder car slag-pot, one of the main criteria for safe operation is the strength and rigidity of the case at high temperatures, the absence of significant residual deformations and cracks. In the event of a significant local overheating of the case, increasing the temperature significantly increases the occurrence of deflections of the wall, since the deformations in a solid are generally related to the temperature by the ration [3, 4]:

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \alpha \cdot \Delta T \\ \alpha \cdot \Delta T \\ 0 \end{Bmatrix},$$

Where

$$\varepsilon_x = \frac{\partial u}{\partial x},$$

$$\varepsilon_y = \frac{\partial v}{\partial y},$$

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x},$$

u – is a function of temperature in the cross-section of the slag-pot wall, depends on the coordinates and time, K,

x, y – are coordinates of the node under consideration in the cross-section of the wall, m,

α – is a thermal expansion coefficient, 1/K,

ΔT – is differential temperatures between adjacent nodes, K.

To find the temperature distribution in the product case, the solution of differential heat conduction equation with several spatial variables in second-order partial derivatives was considered [5, 6]. The solution of the heat conduction equation in a given volume of the solid model of the slag-pot was obtained, which allowed modeling the distribution of deformations for the maximum thermal loads (see Fig. 2).

Analysis of the results obtained in modeling the behavior of the slag-pot under maximum technological loads showed that with the existing design of cinder cars, local overheating of the slag-pot case in the area of the support ring is unavoidable. When overheating of the case is above 600 °C, the properties of the metal (case material) are significantly reduced, which causes the deflection of the wall and the appearance of residual deformations. Calculations of temperature fields for slag-pot models with other wall thicknesses show that under the same boundary conditions of the problem, increasing the wall thickness in the range of 5 ... 30% practically does not affect the values of deflections and residual deformations. Therefore, the effective improvement of the structure can be ensured not by the thickness of the case, but by the application of additional reinforcing elements. The simplest variant of execution of such elements is the reinforcing ribs fixed by welding. These ribs should be installed in the area of greatest deformations and should have a predetermined strength level. Cast ribs cannot perform this function reliably due to internal casting defects. Strengthening of the product can be ensured in the case of using ribs from rolled billets with a predetermined level of mechanical properties. The welding method should ensure secure mounting of ribs and absence of macrostructure defects.

1.3 Analysis of structural modeling at high temperatures

The bending moment in the wall under conditions of temperature differences, which leads to the bending of the wall, can be balanced by additionally installed elements (ribs) (see Fig.4).

1 –slag-pot wall section,

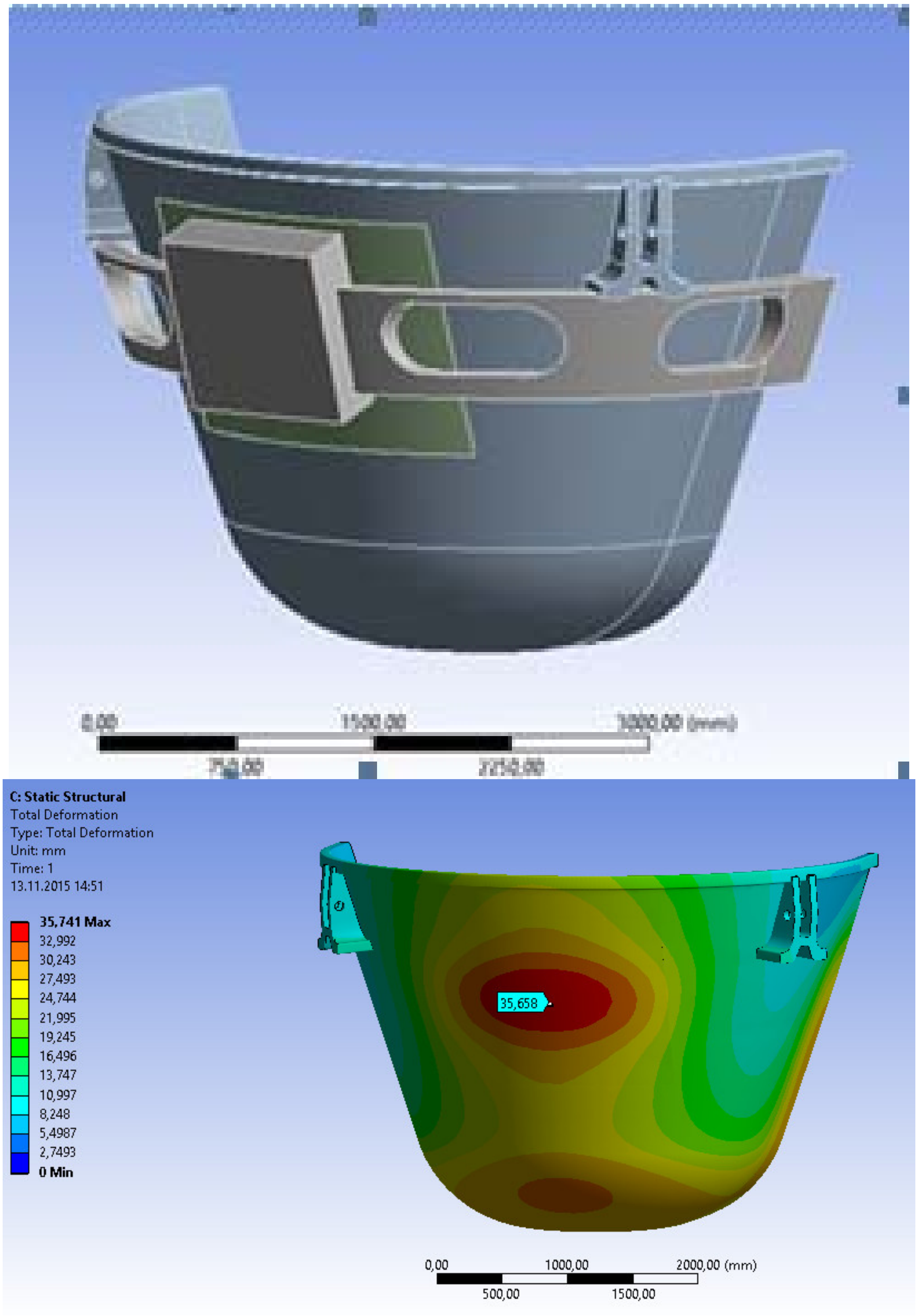
2 – reinforcing rib,

3 – support ring.

When calculating the deformation of the slag-pot section in the form of a plate under the action of opposite moments in equilibrium, the magnitude of its curvature introduces a fractional error. To solve the problem, the schematization of the geometric shape and mechanical properties of the object is usually applied. Therefore, in order to determine the balancing force that must act on the side of the additional reinforcing rib, the design wall section was conditionally represented as an edge-stiffened rectangular plate. The value of the elastic component of the case deformation s_k depends on the parameters of the reinforcing rib and is specified by a function or numerical series. The values for the numerical series are determined experimentally on the basis of measurements of the deflection values of the walls of the slag-pots of industrial cinder cars. The value of the absolute offset of each section $\Delta r_к$ in the cross-section of the wall can be represented as:

a) b)

Fig.1. Fragment of cinder car slag-pot with deformed case (a) and cracks in the area with the greatest deformations of slag-pot (b)



a) b)

Fig.2. 3D-model of slag-pot (a) and distribution of deformations in its case (b)

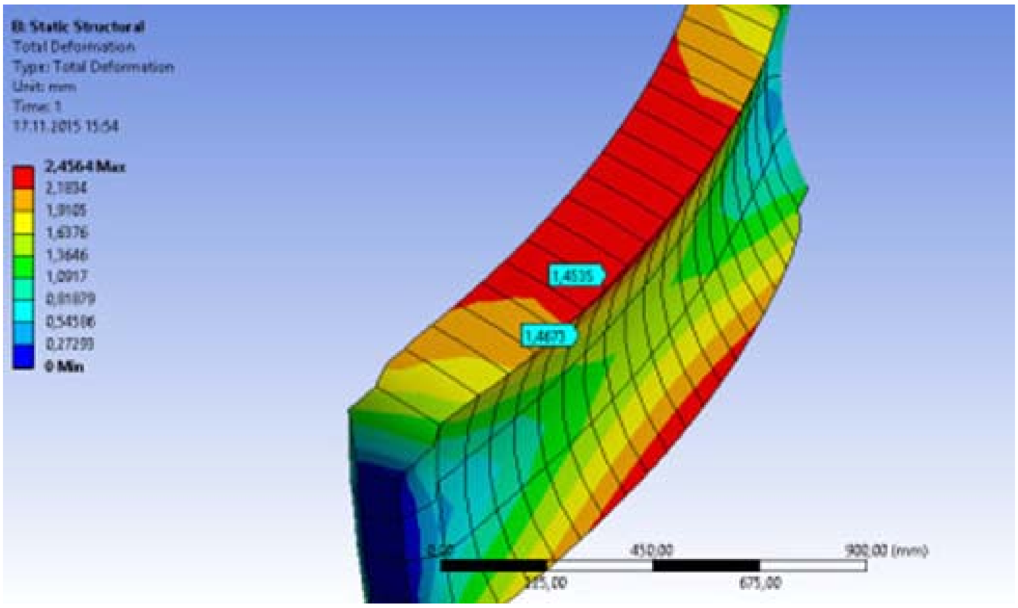


Fig.3. Model of case section with maximum deformations

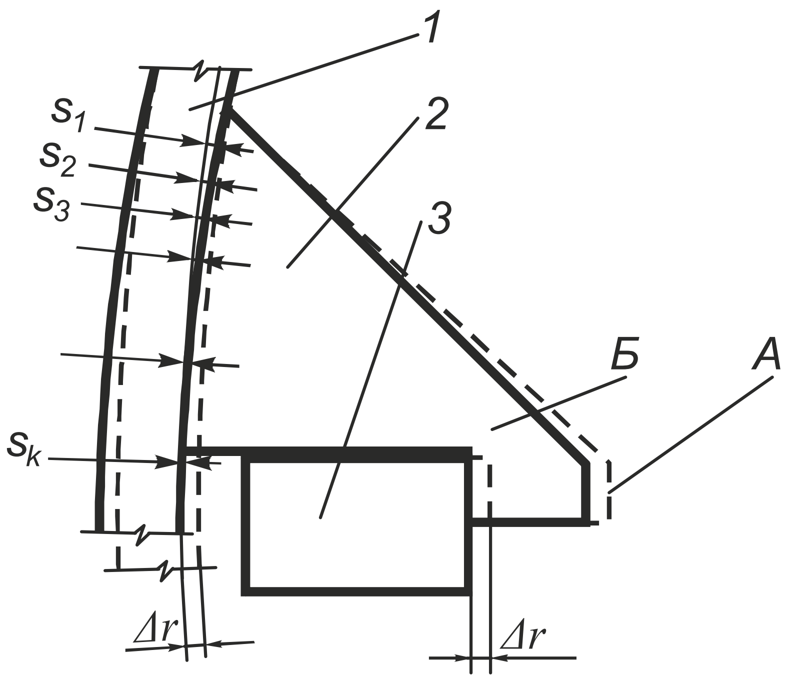


Fig.4. Scheme for calculating the reinforcing rib with a gap Δr (A - position at the time of installation with a gap, B - in operation):

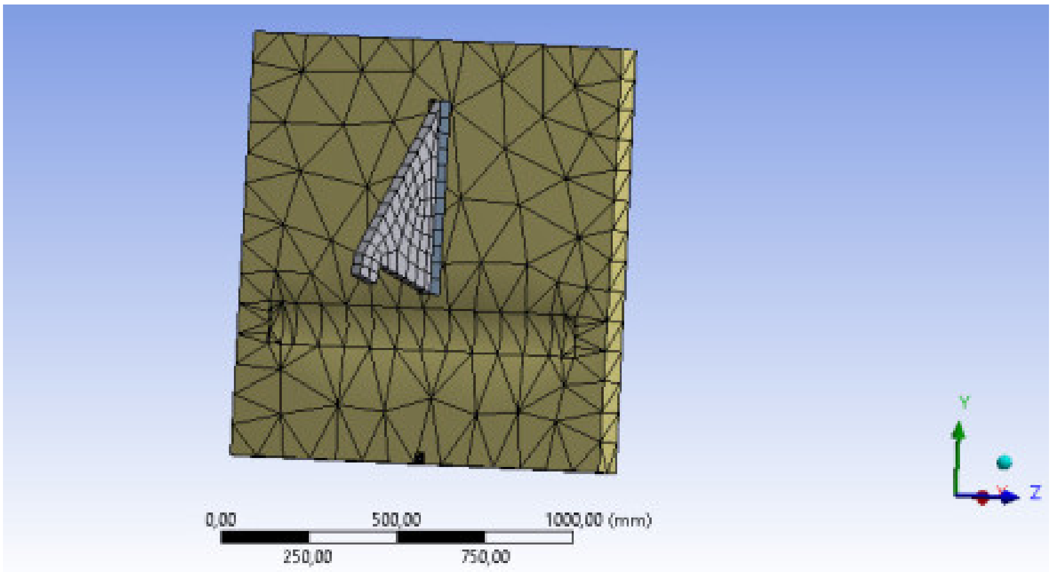
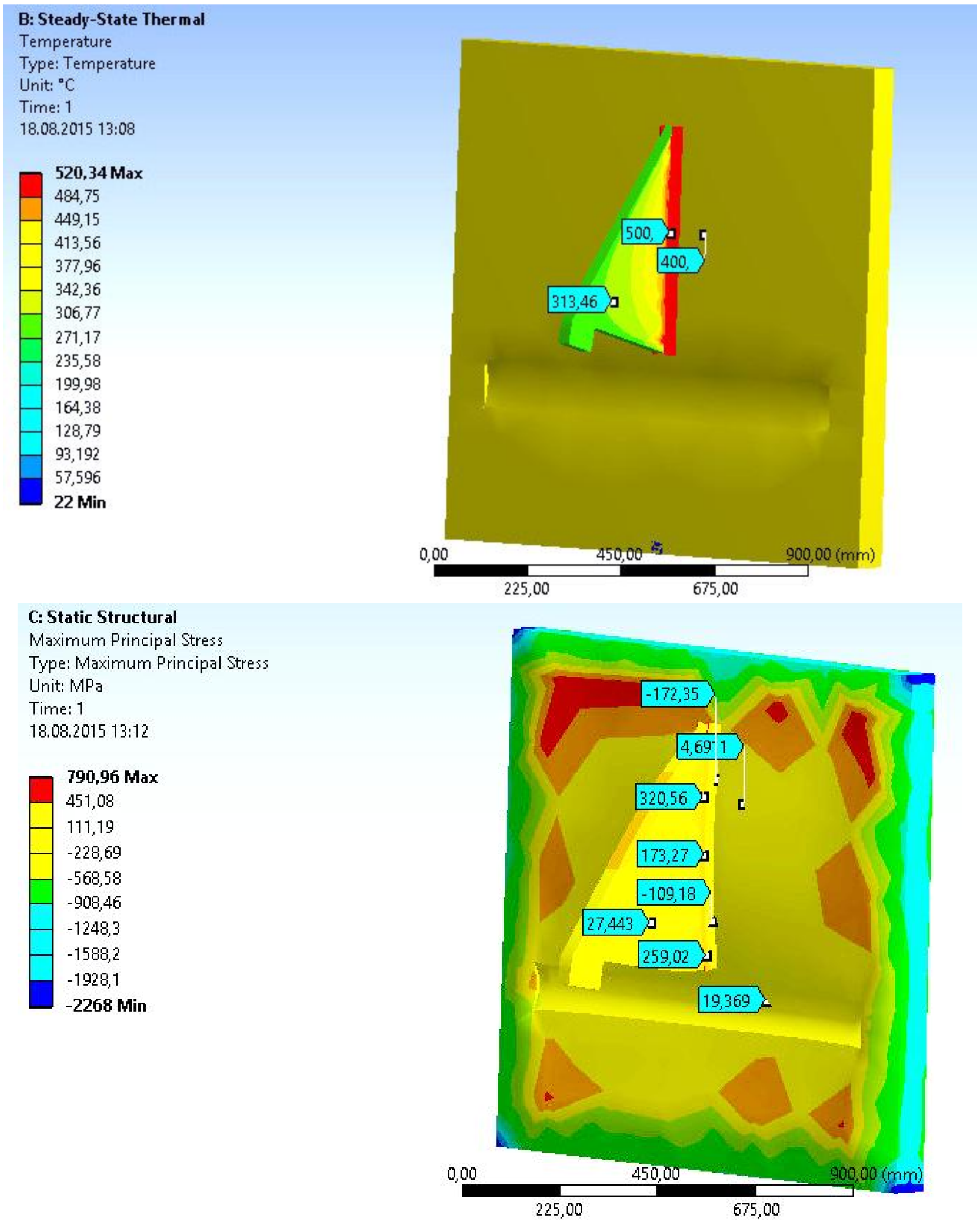


Fig.5. Scheme of calculating the section of the slag-pot by the finite element method.



a) b)

Fig.6. Distribution of temperatures (a) and stresses (b) in the wall model of case and rib

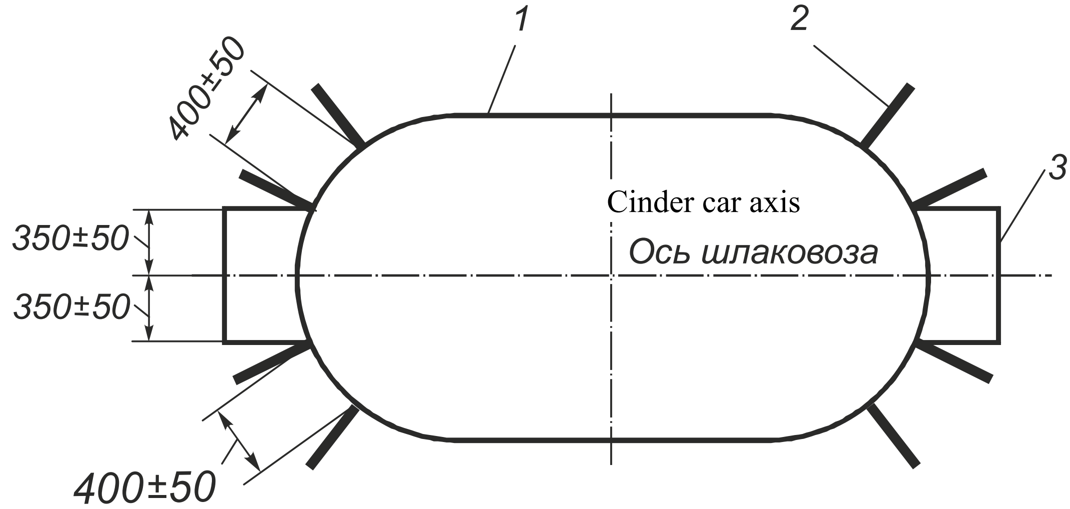


Fig.7. Installation scheme of additional reinforcing ribs, fixed by welding, on the slag-pot:

The analysis of structural modelling found that the practical task is to increase the rigidity of the small section of case (see Fig. 3).

$$\Delta r_k = \Delta r - s_k ,$$

Where Δr_k – is an absolute offset of each i –th contact area of rib and slag-pot wall, m;

Δr – is a gap when installed between the rib and the support ring, m;

s_k – is a value of elastic component of offset, m;

κ – is a number of the contact area of rib and slag-pot wall.

The solution of the problem by numerical methods (finite element method) made it possible to determine the values of the balancing forces, the application of which allows preserving the initial profile of the most loaded section of the slag-pot. The equilibrium of the case wall, as an object in the design scheme, is provided by additional reinforcing ribs (see Fig. 5).
Analysis of the model made it possible to distribute temperatures and stresses in the wall model of case and rib (see Fig.6).

The dimensions of the most dangerous section in terms of the development of deformations, obtained by calculation, are refined taking into account the experimental measurements of the actual residual deformations of the blast-furnace slag-pots of the operating metallurgical plant. Calculations show that a rational consumption of materials and a minimum scope of welding works will be provided for the cast weldments made according to the scheme shown in Fig.7.

1 – slag-pot,

2 - additional reinforcing ribs,

3 – stub axle.

On experimental cinder cars, improved by this technology and tested at the operating metallurgical plant, 8 additional reinforcing ribs of 30 + 2 mm thick made of 09G2C steel were installed along the perimeter and fixed by welding on the slag-pots with weight of about 24 tons. [7] Thus, due to the forces transferred to the case of the pot by ribs, the deformation of the wall bending was reduced almost to a minimum. Based on the results of 1.5 years of operation, the thermal deformation of the slag-pot case was reduced 4-5 times. In addition, significantly reduced costs for maintenance and repair of cinder cars, which reduces the cost of the final metallurgical products.

1.4 Results and discussion

The causes of the appearance and development of defects in the operation of slag-pots intended for the transport of molten metallurgical slags are determined. The results obtained in the study of the operating conditions of the cinder car and the stressed state of its most loaded node, slag-pot, make it possible to determine effective methods for extending the service life and improving the reliability of this equipment. The operational life of slag-pots can be increased and safety in the use of cinder cars is greatly improved during the minor structural modification using welding methods.

1.5 Conclusions

When operating large-sized equipment at high temperatures, the strength characteristics of the material are reduced, which leads to the occurrence of residual thermal deformations and a decrease in the service life of the products. The operational life can be increased by using additional reinforcing elements. Cast metal has insufficient reliability, so it is necessary to use reinforcing elements with a predetermined strength level (rolled billets), fixed by welding. The shape and arrangement of reinforcing elements for each type of equipment should be determined by calculation taking into account the stress-strain state of the structure and the dynamics of its loading.

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