ЛИТЕЙНОЕ ПРОИЗВОДСТВО

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IDENTIFYING THERMAL STRESSES IN A STEEL CYLINDRICAL ROD

Abstract. *The paper studies longitudinal strains occurring along the height of a cylindrical object as a result of the temperature difference along the cylinder radius. The authors identified mathematical relations ensuring calculations of normal, tangential, and equivalent stresses. Such procedure may be applied to determine a stress state of cylinders 0.1 and 0.05 m in radius, when heating up to 400°C. It is showed that changes in a cylinder radius, maintaining the same heating conditions, result in decreasing maximum tension stresses from 4.59 MPa to 2.39 MPa, and compressive stresses from 4.31 MPa to 2.25 MPa. The authors determined principal stresses along a cylindrical rod radius during heating.*

Keywords: *temperature field, cylindrical object, thermal stress state, principal stresses, temperature strains, strength condition.*

Introduction

Metallurgical processes are accompanied by changes in temperature of operating units and parts of equipment. This entails significant thermal stresses resulting in breakdowns of machines and lines in various fields of metallurgy [1-6]. At present, due to development of computer systems it is possible to make a rather correct prediction for a thermal stress state of metallurgical facilities, which can be used to analyze and predict critical states of units and mechanical parts, as well as products in the course of their manufacturing, for example, heat treatment [7, 8].

This type of processing is relevant in the rolling mills production. Heat treatment takes one third part of the roll production cost.

This technological operation determines the main rolls working characteristics, which will be achieved during operation in rolling mills, their durability and reliability. An incorrect heat treatment mode can lead to roll breakage even before it is put into operation, up to rolls destruction in a thermal furnace. Excessively long heat treatment regimes lead to excessive consumption of energy, a decrease in shop productivity and, as a result, an increase in the cost of production of working tools (rolls) for rolling mills.

Prediction of changes in the stress-strain of roll state in the course of heat treatment and the probability of its destruction in a thermal furnace will allow to assess the designated mode suitability. It leads to increased production efficiency along with reduced production costs.

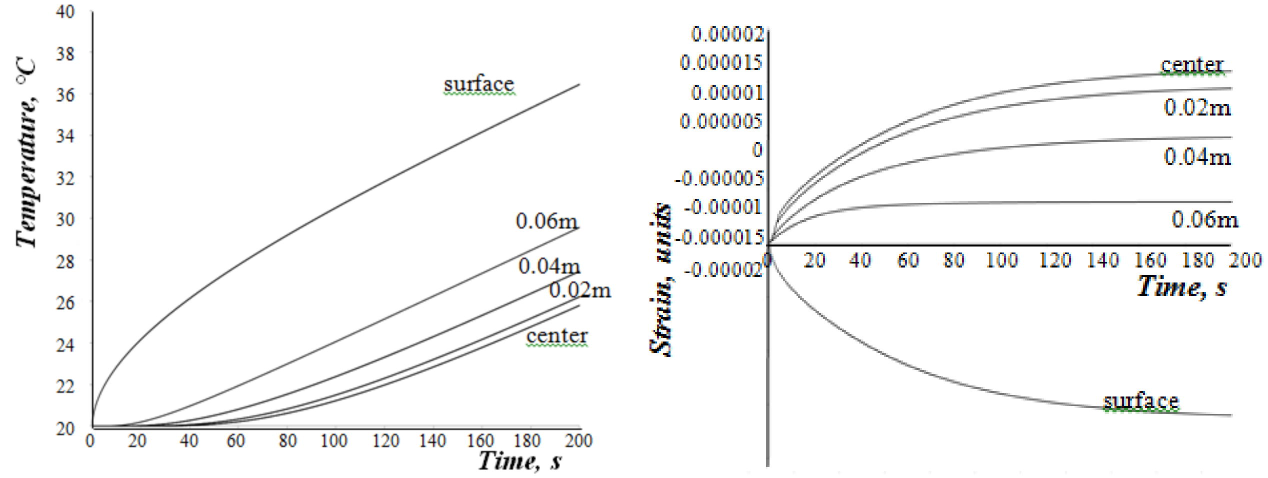
Theory, materials and methods of research, technical and technological development

Let us calculate changes in a stress state, when heating a cylindrical rod in elastic deformation. Let us make calculations of temperature strains in the St3 steel cylindrical rod. Computation time is 200 s, cylinder radius is 0.1 m, the system was broken into 50 layers with the thickness of δ =0.001 m, time increment is 0.1 s, thermal conductivity $\lambda = 50\, W/°C$, heat capacity $c = 502\ J/kg \cdot °C$, density of the object under study $\rho = 7820\ kg/m^3$, Young's modulus $E = 2 \cdot 10^5$ MPa, coefficient of thermal expansion $\alpha = 1.5 \cdot 10^{-6}\, °C^{-1}$, Poisson's ratio $\mu = 0.25$. Initial temperature of the cylinder $T_0 = 20\ °C$, ambient temperature $T_{amb} = 400\ °C$.

Using calculation methods, we determine temperature strains of the St3 steel cylinder. The methods are adapted to cylindrical rod heating conditions. Let us calculate changes of the temperature field in time [9, 10]. The result of the cylinder heating calculation is given in Fig. 1, a. Calculated values of temperature along the cylinder radius were used to determine occurring temperature strains (Fig. 1, b). The figure shows that the highest stretching strain is in the center of the heated object, and the surface is exposed to compression of peripheral layers of the cylinder.

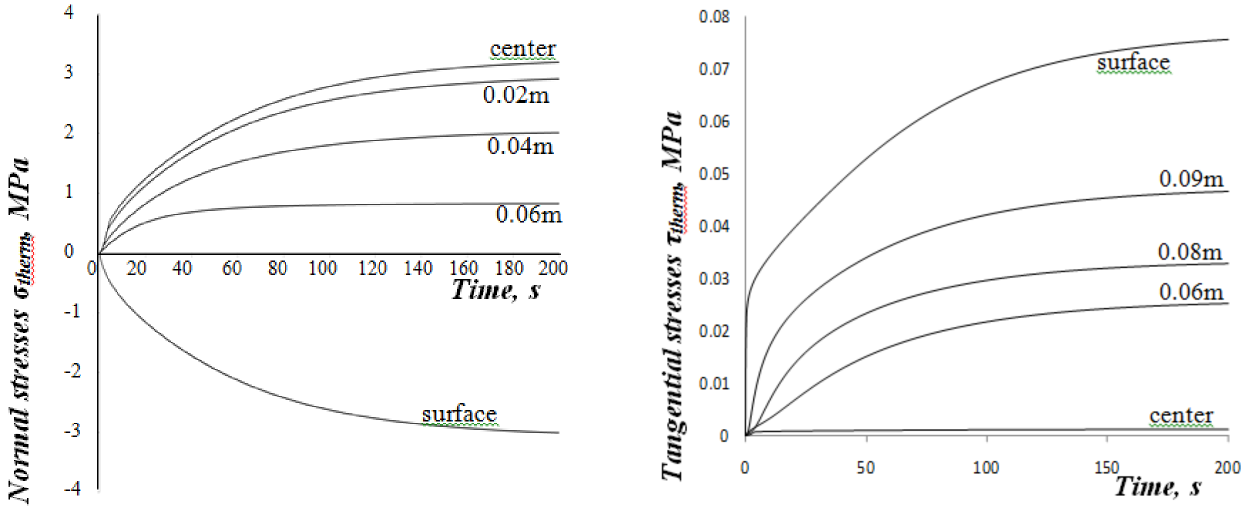
The analysis of the distribution of normal stresses σ_{therm} σ_2 the cylinder radius (Fig. 2, a) shows that the stress state changes from compression stresses on the surface of the object to tension stresses, whose maximum values are found in the center of the object under study. In fact, the object surface, exposed to heating, incurs compression stresses due to its contact with colder layers inside the object under study. Besides, according to Fig. 1, a, the lowest temperature is found in the cylinder center, which contacts more heated layers and is exposed to maximum tension stresses, as shown in Fig. 2, a.

Studies of the changes of normal stresses along the cylinder radius showed that there was a point when tension fibers transferred to compressed ones (a point of intercept with the X-axis) in Fig. 3. In these points there is only pure shear. Later fibers with pure shear shift to the cylinder center.



a b

Fig. 1. Dependence of values in time on the layer thickness for the cylinder 0.1 m in radius:
a – dependence of temperature; b – dependence of the strain value



a b

Fig. 2. Dependence of stresses in time on the layer thickness for the cylinder 0.1 m in radius:
a – normal stresses σ_{therm}; b – tangential stresses τ_{therm}

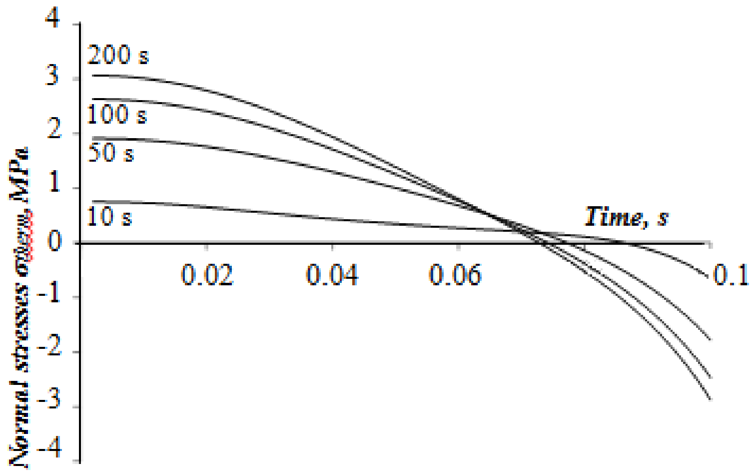


Fig. 3. Distribution of stresses in time along a cylinder rod radius of 0.1 m

The above figure of the stress distribution in longitudinal strains allowed us to determine principal stresses σ_1, σ_2, arising at the temperature difference along the cylinder radius (Fig. 2, a, b). The calculations were made by solving the following equations:

$$\sigma_1 = \sigma_{therm} + \frac{\sqrt{\sigma_{therm} + \tau_{therm}}}{2}, \qquad (1)$$

$$\sigma_2 = \sigma_{therm} - \frac{\sqrt{\sigma_{therm} + \tau_{therm}}}{2}. \qquad (2)$$

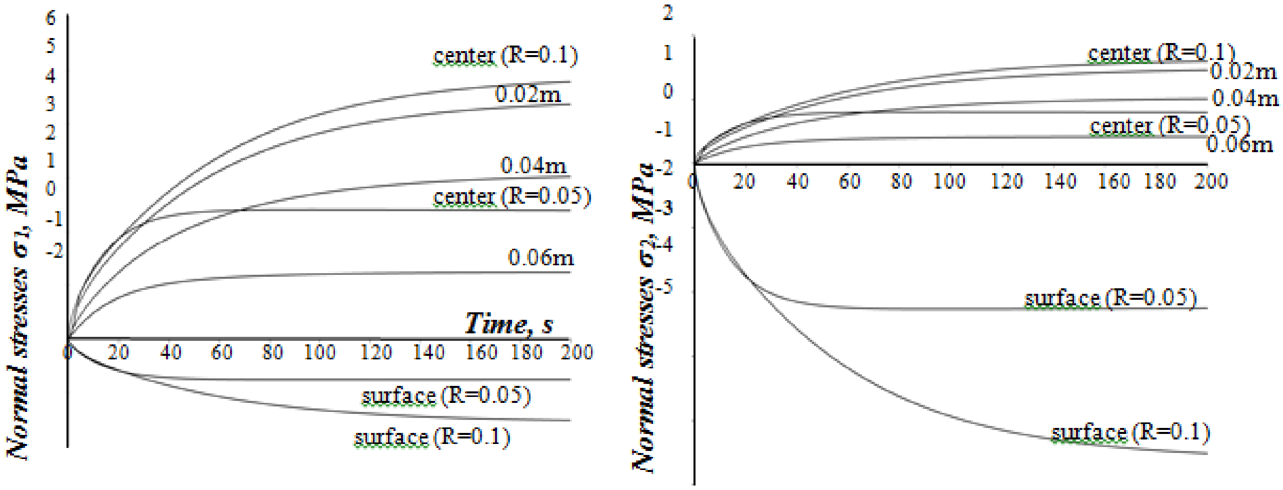
As it is seen from Fig. 4, σ_1 is significantly higher than σ_2, corresponding with existing representations about a stress state of the cylinder wall. However, the analysis of the change of the stress state in fibers under study indicates concordance of signs of principal stresses. This means that the center of the object, fibers on radii of 0.02 and 0.04 are exposed to uniform tension. To find out how the geometrical parameters (the cylinder radius) influence the stress and strain state, we calculated principal stresses σ_1, σ_2 of the St3 steel cylinder rod 0.05 m in radius. The results are given in Fig. 4.

The above figure shows that a growth rate of the stress state slightly changes with changes of the radius; however, principal stresses stop growing earlier, about 40 s. The reason is the quicker heating of the object, and, consequently, less difference of temperature around the cylinder radius. This entails a significant drop of occurring maximum tension stresses from 4.59 MPa to 2.39 MPa and compressive stresses from 4.31 MPa to 2.25 MPa, which are relevant to physics of a thermal stress state of the object.

The obtained values of principal stresses may be used to assess the strength of products. As St3 steel grade is considered to be a ductile material, to generalize the stresses, we apply the fourth theory of strength [11] (the Huber-Mises criterion), which will be presented for the flat stress state studied in the paper as follows:

$$\sigma_{eq}^{IV} = \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2} \le [\sigma]. \qquad (3)$$

Values of equivalent stresses at t = 200 s calculated by the above equation are given in Fig. 5



a b

Fig.4. Distribution of principal stresses in time along the layer thickness for cylinders 0.1 m and 0.05 m in radius

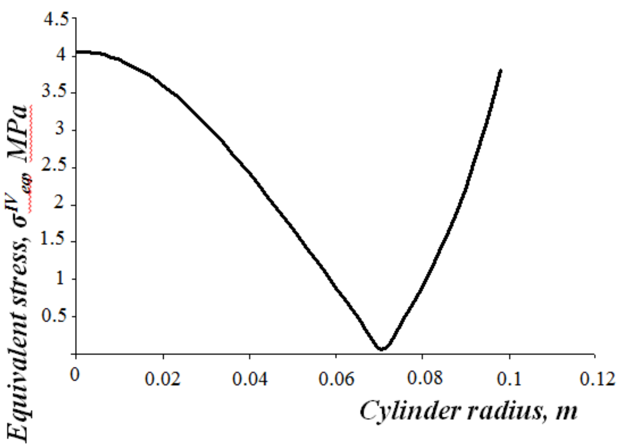


Fig. 5. Distribution of equivalent stress σ^{IV}_{eq} along the cylinder radius

Regarding ductile materials, a dangerous state arises in case of exceeding yield stress at compression strain, as well as tensile deformation, as shown in Fig. 5. The extremum of the function is located in an area of a neutral fiber, transferring from tensile fibers to compressed ones (Fig. 5). Having compared by equation (3) the calculated values of σ^{IV}_{eq} with allowable stresses [12], it is possible to assess strength of the cylindrical rod under study.

Summary

Thus, the research performed allows us to simulate the stress state as a result of longitudinal strains occurring during the temperature difference along a radius of cylindrical objects. The obtained solution is used to compare the current stress state with the critical state to assess the strength of materials. At a stage of designing the heat treatment process cycle this ensures revealing critical thermal strains and stresses, entailing breakdowns of the object wall, and, consequently, providing the possibility to control the stress and strain state to prevent discontinuity of the material.

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ИДЕНТИФИКАЦИЯ ТЕРМИЧЕСКИХ НАПРЯЖЕНИЙ В СТАЛЬНОМ ЦИЛИНДРИЧЕСКОМ СТЕРЖНЕ

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Аннотация. В работе рассмотрен вопрос возникновения продольных деформаций по высоте объекта циindрической формы, возникающих вследствие температурного перепада по радиусу цилиндра. Получены математические зависимости, обеспечивающие в динамике расчет нормальных, касательных и эквивалентного напряжений. Рассмотрено применение данной методики для определения напряженного состояния цилиндров радиусами 0,1 и 0,05 м при нагреве до 400°С. Показано, что изменение радиуса цилиндра при одинаковых условиях нагрева приводит к уменьшению максимальных растягивающих напряжений с 4,59 до 2,39 МПа, а сжимающих – с 4,31 до 2,25 МПа. Определены главные напряжения по радиусу цилиндрического стержня при нагреве.

***Ключевые слова*:** тепловое поле, цилиндрический объект, термонапряженное состояние, главные напряжения, температурные деформации, условие прочности

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