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INCREASING THE USE RELIABILITY OF A WORK ROLL ASSEMBLY WITH INTERNAL HEATING BY PREDICTING THE THERMAL STRESS STATE

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Rolling rolls are one of the decisive factors in the formation of flat-rolled product quality indicators. In order to be able to promptly assess the operational reliability of the roll to ensure stable quality indicators, a model of the temperature-stressed state of work rolls with an internal heating source was developed. Considering that during the hot rolling process, the rolls are characterized by high levels of deforming forces and the presence of elevated temperatures in the deformation zone, a complex stressed state arises in them, caused by the joint action of torques, residual stresses, contact forces, bending moments and thermal loads. Contact stresses exert the maximum impact on the stability of work rolls. The model is based on solving the differential equation of heat conductivity and uses elements of the theory of elasticity. The roll is considered a thick-walled pipe with a symmetric temperature distribution along the longitudinal axis, which is loaded by the full rolling force, the reaction from the support rolls and the temperature loads caused by the temperature mismatch of the inner and outer surfaces. The developed mathematical model solves the problem of determining the thermally stressed state of the working roll, which allows for predicting the operational reliability of the rolls during the rolling process. Thus, the result of the numerical implementation of the model showed that at a certain ratio of the outer and inner radii of the roll, the stresses at the upper point of the axial channel change from relatively safe compressive stresses to more dangerous tensile stresses. Also, the analysis of the results showed that an increase in the diameter of the inner hole leads to a relative decrease in the temperature stresses on the surface of the axial hole and a decrease in the temperature stresses on both the outer and inner surfaces of the working roll. In general, the developed mathematical model can be used both for optimizing the design parameters of the roller assembly and for predicting operational use reliability.

Key words: *reliability, warm rolling, roll assembly, internal heating, thermal stress state, temperature field, mathematical model.*

Кулік Тетяна. Підвищення експлуатаційної надійності вузла робочого валка з внутрішнім джерелом нагріву шляхом прогнозування його термонапруженого стану

Прокатні валки є одним із вирішальних факторів формування показників якості плоского прокату. Для можливості оперативної оцінки їх експлуатаційної надійності з погляду отримання стабільних показників якості готової продукції розроблено модель термонапруженого стану робочих валків з внутрішнім джерелом нагрівання. Ураховуючи, що під час процесу теплої прокатки для валків характерні високі рівні деформувальних сил і наявність підвищених температур в осередку деформації, у них виникає складний напружений стан, викликаний спільною дією обертових моментів, залишкових напружень, контактних сил, згинальних моментів та теплових навантажень. Максимальний вплив на стійкість робочих валків мають контактні напруження. Модель ґрунтується на розв’язанні диференціального рівняння теплопровідності та використовує елементи теорії пружності. Валок розглядається як товстостінна труба із симетричним по поздовжній осі розподілом температур, яка навантажена повною силою прокатки, реакцією від опорних валків та температурними навантаженнями, які викликані невідповідністю температури внутрішньої та зовнішньої поверхонь. Розроблена математична модель виконує завдання визначення термонапруженого стану робочого валка, що дає змогу прогнозувати експлуатаційну надійність валків під час процесу прокатки. Так, результат числової реалізації моделі показав, що за певного співвідношення зовнішнього й внутрішнього радіусів валка напруження у верхній точці осьового каналу змінюються з порівняно безпечних напружень стиснення на більш небезпечні напруження розтягування. Також аналіз результатів показав, що збільшення діаметра внутрішнього отвору призводить до відносного зменшення температурних напружень на поверхні осьового каналу та водночас зменшення температурних напружень і на зовнішній, і на внутрішній поверхні робочого валка. Загалом, розроблена математична модель може використовуватися як для оптимізації конструктивних параметрів валкового вузла, так і для прогнозування показників експлуатаційної надійності.

Ключові слова: *надійність, тепла прокатка, валковий вузол, внутрішній нагрів, термонапружений стан, температурне поле, математична модель.*

Introduction. The quality of flat-rolled products is laid in the deformation zone, i. e. in the area of contact between the strip and the working roll. Therefore, there is no doubt that the rolls are one of the decisive factors in determining the quality indicators of finished products. In order to be able to promptly assess their operational reliability in terms of obtaining stable quality indicators of flat-rolled products, it is necessary to develop a simple and reliable model of the thermal stress state of the working rolls. When developing a model, we take the following factors into account.

The complexity of warm rolling with an internal heating source for the rolls is that in this case the main factors in the state of the rolls are the temperature field, force interaction and geometric relationships. This means that in the general case of technological conditions of the warm rolling process, it is characterized by a high level of deforming forces and elevated temperatures in the zone of plastic deformation of the strip [1].

The process's deforming tool is the rolling mill's working rolls, and during operation, a complex stress state arises in them, caused by the combined actions of torques, residual stresses, contact forces, bending moments and thermal loads [3].

Another aspect is an analysis of different heating schemes which showed that internal heating of the working tool ensures the highest quality of rolled products [2]. However, from the point of view of the reliability of the design, this is another difficulty because it is necessary to make an internal hole to accommodate the heating source. We consider such a hollow working roll as a thick-walled cylinder; in cross-section, we are talking about a thick-walled ring.

Research methods and techniques. Analysis of the force action components showed that the contact stresses have the maximum effect on the durability of the working rolls in the warm rolling process. In some situations, they reach the value of the tensile strength of the working roll material [4]. It must known that the maximum values of contact stresses occur not in the deformation zone, i.e., not in contact with the flat strip, but at the contact of the working and support roll, because despite the almost equivalent magnitude of forces, the contact area between these rolls is much smaller than the area of contact between the working roll and the zone of plastic deformation of the strip.

As already noted, in this case, the cross-section of the working roll is considered a thick-walled ring, which is compressed on one side by the full force $P_{пр}$ from the strip and, on the other side, compressed by the reaction of the support roll. At the same time, thermal stresses arise in the body of the work roll, which happens due to the difference in temperature of the roll on the internal and external surfaces. As a result, we obtain a roll as a thick-walled pipe with a symmetrical temperature distribution along the longitudinal axis (Fig. 1).

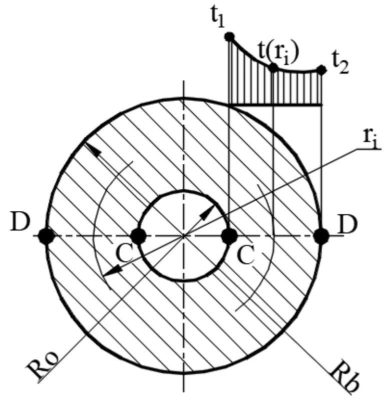


Fig. 1. Calculation scheme and temperature field of the working roll of a warm rolling mill, having an internal axial hole for a heat source

Several other assumptions are made within the model. The main ones are: firstly, the temperature field from the internal heating source is steady over time; secondly, the heat distribution along the roll axis is insignificant and can be neglected.

During mathematical modelling, the stresses that arise under the action of the rolling force $P_{пр}$ were quantitatively determined. As can be seen from the calculation scheme (Fig. 1), the stress distributions along the roll radius in dangerous sections *AB* and *CD* can be determined using a relationship of the following type [5]:

$$\sigma_i = \frac{N}{A} + \frac{M_i}{S}\frac{|r_i - R_N|}{r_i}, , \qquad (1)$$

where σ_i the stress in the dangerous section at radius r_i; N the magnitude of the normal force; $A = (R_b - R_o) \cdot L$ cross-sectional area *AB* or *CD*; $M_i = k_i N R_N (1 + \beta)$ – the magnitude of the bending moment at radius r_i; $\beta = R_o / R_b$; k_i bending moment arm coefficient; $S = A \cdot z_N$ – a statical moment of area A; z_N geometric characteristic of a neutral line, the radius of curvature of which is functionally related to the value of the average radius through the expression: $R_N R_N = R_c - R_b\left(\frac{1+\beta}{2} + \frac{1+\beta}{\ln\beta}\right)$.

We also emphasize that if we consider the stresses at point *B*, then the formula for equivalent stresses in the area near the contact will change as $\sigma_e = \sigma_1 - (\sigma_3 + \sigma_B)$. And taking into account thermal stresses, the dependence will be as follows:

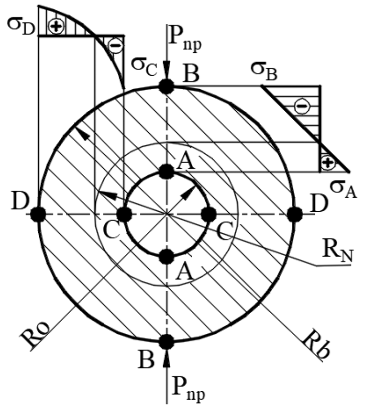


Fig. 2. Calculation scheme for determining tensile-compressive stresses in a working roll of a warm rolling mill, having an internal axial hole for a heat source

$$\sigma_e = \sigma_1 - (\sigma_3 + \sigma_B + \sigma_{ti(r_i = R_b)}). \cdot \qquad (2)$$

The value of the magnitude of radial σ_{ri}, circumferential σ_{ti} and axial $\sigma_{zi} = \sigma_{ri} + \sigma_{ti}$ normal stresses was determined, by analogy with the method of work [5], on the basis of dependencies of the type:

$$\sigma_{ri} = \frac{E \cdot \lambda}{1-\nu}\left[-\frac{1}{r_i^2}\int_{R_o}^{r_i} t(r_i) r_i dr + \frac{r_i^2 - R_o^2}{r_i^2\left(R_b^2 - R_o^2\right)}\int_{R_o}^{R_b} t(r_i) r_i dr\right]; \qquad (3)$$

$$\sigma_{ti} = \frac{E \cdot \lambda}{1-\nu}\left[\frac{1}{r_i^2}\int_{R_o}^{r_i} t(r_i) r_i dr + \frac{r_i^2 - R_o^2}{r_i^2\left(R_b^2 - R_o^2\right)}\int_{R_o}^{R_b} t(r_i) r_i dr\right]; \qquad (4)$$

$$\sigma_{zi} = \frac{E \cdot \lambda}{1-\nu}\left[\frac{2}{R_b^2 - R_o^2}\int_{R_o}^{R_b} t(r_i) r_i dr - t(r_i)\right], \qquad (5)$$

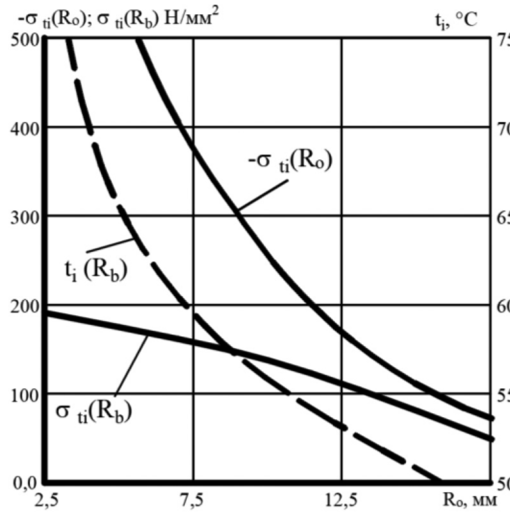
where r_i current value of the radius; E, λ, ν – modulus of elasticity, coefficient of linear expansion and Poisson's ratio of the material of the working roll. The current temperature value at the radius $t(r_i)$ was determined in accordance with the operating procedure [6]. Numerical modelling of the temperature field of the roll was carried out with reversion motion, considering the roll in θ-moment in time (Fig. 1).

The problem of heat exchange between the rolls and the environment was considered, assuming that the heat exchange is stationary:

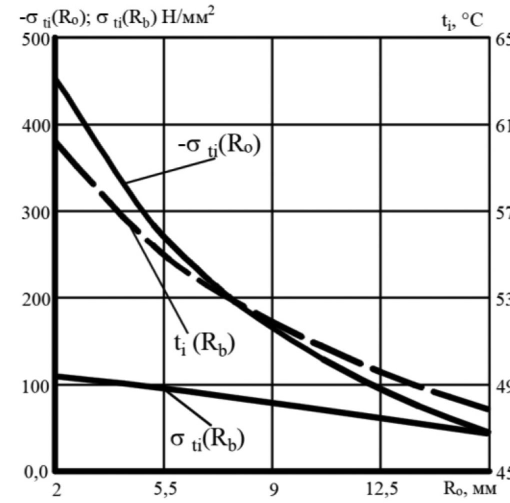
$$t(r_i;\, \theta) = t_u(r_i) + t_{ox}(r_i;\, \theta) + t_{od}(r_i;\, \theta), \qquad (6)$$

where $t_u(r_i)$, $r_{ox}(r_i;\, \theta)$, $r_{od}(r_i;\, \theta)$ temperature determined by: the internal heat source, losses into the environment, and heat generation in the plastic deformation zone.

Results. As a result of the numerical implementation of this mathematical model, the calculated distributions and the stress distributions depending on the rolling force and depending on the difference in temperature of the outer surface and the axial hole were obtained. (Fig. 3).



а



б

Fig. 3. Calculated distributions of stresses and temperatures depending on the radius of the axial hole a) $R_b = 45$ мм; b) $R_b = 25$ мм

Analysis of the results showed that an increase in the diameter of the inner hole leads to a relative decrease in thermal stresses on the surface of the axial hole $t_i(R_o)$ and, along with this, to a decrease in thermal stresses on both the outer surface and the inner surface of the working roll. Interestingly, the circumferential $\sigma_{ti}(r_i = R_b)$ and axial $\sigma_{zi}(r_i = R_b)$ thermal stresses on the outer surface, because a temperature difference, are tensile stresses, and similar circumferential $\sigma_{ti}(r_i = R_o)$ and axial $\sigma_{zi}(r_i = R_o)$ stresses on the inner surface are compressive stresses.

It also becomes clear that an increase in the radius of the axial hole and, consequently, in the compression-tensile stresses and temperature stresses, leads to a decrease in the equivalent stresses in the contact zone. At the same time, the total circumferential stresses at points $D(\sigma_{D\Sigma} = \sigma_D + \sigma_{ti}(r_i = R_b))$ and $C(\sigma_{C\Sigma} = \sigma_C + \sigma_{ti}(r_i = R_o))$ increase in absolute value. At point *A* the bending and temperature difference stresses have the opposite sign. Moreover, with an increase in the radius of the inner hole, they pass from compression stresses, because the dominance of the temperature difference, to tensile stresses, because the dominance of bending.

Conclusions. A mathematical model of the working roll's thermal stress state was obtained for the process conditions of warm rolling in preheated working rolls, inside which the heating source is located. The model is based on the solution of the differential equation of heat conductivity and uses elements of the theory of elasticity. The developed mathematical model solves the problem of determining the thermo stress state of the working roll, which allows for predicting the operational reliability of the rolls during the rolling process. For example, based on the results of the numerical implementation of the model, it was possible to determine the ratio of the outer radius and the inner radius of the roll, at which the stresses at point *A*, that is, at the top point of the axial hole, change from compression stresses to more dangerous tensile stresses.

BIBLIOGRAPHY:

1. Effect of Temperature Field and Stress Field of Different Crack Behavior on Twins and Dislocations under Mg Alloy Rolling / J. Tian et al. *Materials*. 2021. Vol. 14, no. 19. P. 56–68. URL: https://doi.org/10.3390/ma14195668

2. Novel online prediction model for thermal convexity of work rolls during hot steel rolling based on machine learning algorithms / J. Lu et al. *Expert Systems with Applications*. 2024. P. 124–384. URL: https://doi.org/10.1016/j.eswa.2024. 124384

3. On the Evolution of Temperature and Combined Stress in a Work Roll under Cyclic Thermo-Mechanical Loadings during Hot Strip Rolling and Idling / K. Hu et al. *Materials*, 2020. Vol. 13, no. 21, P. 50–54. https://doi.org/10.3390/ ma13215054

4. Thermal stress analysis in hot rolling process / T. Hazeezet et al. *Engineering Today*. 2023. Vol. 2(4). P. 41–58. https://doi.org/10.5937/ engtoday2300017H

5. Кулік Т. О. Виробництво листового металопрокату з використанням режимів теплого деформування. Перспективи розвитку, розширення сфери використання та удосконалення технологій і обладнання : монографія. Краматорськ : ДДМА, 2020. 180 с.

6. Кулік Т. О. Математичне моделювання температурного поля валків станів теплої прокатки з внутрішнім джерелом нагріву. *Збірник наукових праць дніпровського державного технічного університету (технічні науки).* 2020. Т. 2 (37).С. 53–57. https://doi.org/10.31319/2519-2884.tm.2020.11

REFERENCES:

1. Tian, J., Deng, J., Shi, Q., Chang, Y., Liang, W., & Zhang, W. (2021). Effect of Temperature Field and Stress Field of Different Crack Behavior on Twins and Dislocations under Mg Alloy Rolling. Materials, 14(19), 5668. https://doi.org/10.3390/ma14195668

2. Lu, J., Wang, P., Huang, H., Hao, L., Li, X., Peng, Q., Su, L., Deng, G. (2024). Novel online prediction model for thermal convexity of work rolls during hot steel rolling based on machine learning algorithms. *Expert Systems with Applications*, 254. P. 124–384. https://doi.org/10.1016/j.eswa.2024.124384

3. Hu, K., Shi, Q., Han, W., Zhu, F., & Chen, J. (2020). On the Evolution of Temperature and Combined Stress in a Work Roll under Cyclic Thermo-Mechanical Loadings during Hot Strip Rolling and Idling. *Materials*, 13(21), P. 50–54. https://doi.org/10.3390/ma13215054

4. Hazeez, T., Sobamowo, G., Fetuga, I., Modebelu, U., Adeleke, S., Aderemi, K. (2023). Thermal stress analysis in hot rolling process. *Engineering Today*, 2(4). P. 41–58. https://doi.org/10.5937/ engtoday2300017H [in English].

5. Kulik, T. (2020). Vyrobnytstvo lystovoho metaloprokatu z vykorystanniam rezhymiv teploho deformuvannia. Perspektyvy rozvytku, rozshyrennia sfery vykorystannia ta udoskonalennia tekhnolohii i obladnannia : monohrafiia [Production of sheet metal using warm deformation modes. Prospects for development, expansion of the scope of use and improvement of technologies and equipment: monograph]. 2020. 180. https://doi.org/10.31319/2519-2884.tm.2020.11. [in Ukrainian].

6. Kulik, T. (2020). Matematychne modeliuvannia temperaturnoho polia valkiv staniv teploi prokatky z vnutrishnim dzherelom nahrivu [Mathematical modeling of the temperature field of rolls of warm rolling mills with an internal heating source]. *Zbirnyk naukovykh prats dniprovskoho derzhavnoho tekhnichnoho universytetu (tekhnichni nauky) Collection of scientific works of the Dnipro State Technical University (technical sciences),* 2(37), 53–57. [in Ukrainian].