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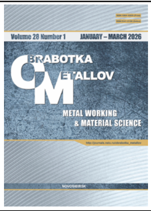

Improving the methodology for calculating temperature stresses in working rolls under non-stationary thermal conditions in a hot rolling mill

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ABSTRACT

Introduction. A significant increase in productivity and intensification of the technological process require taking into account the temperature conditions of the rolls in hot rolling mills. In this regard, the calculation of temperature stresses becomes particularly important for selecting optimal design parameters and technological regimes during the operation of the rolls in modern mills. ***Study object.*** The solution to the problem of calculating the temperature stresses that occur in the working rolls of hot rolling mills can be achieved by improving the existing mathematical model for cold rolling mills, which is based on the analytical solution of the differential heat conduction equation, taking into account that their temperature field is axially symmetric. A special feature of the analytical solution is that it is not possible to set the graph of the change in the surface temperature of the rolls in advance, because it is a complex function of the rolling regimes. In advance, only the graph of the function is known, which is given in the form of a continuous angled line. In this paper, we consider an improved model based on a numerical and analytical solution of the problem of the temperature regime of the working rolls. ***The aim of the work*** is is to develop an improved method for calculating temperature stresses in the working rolls under a non-stationary thermal regime typical of continuous finishing groups of such mills, in order to assess their contact-fatigue strength. **Material and methods of research.** The study is based on the specified improved numerical-analytical model and equations for calculating temperature stresses for a specific layer of the working roll of an operating hot rolling mill in a cross-section, taking into account its design features and the physical and mechanical parameters of its material. **Results and its discussion.** The advantage of the improved method of calculating temperature stresses in terms of their determination at any given time during the roll work is shown. The results of the computational experiment are presented in the form of the calculation of equivalent stresses σ_{eq} using the classical and improved methods, and a comparative assessment of the contact-fatigue strength of the working rolls using the presented methods for the actual operating mode of the finishing group of the current mill is performed. Based on previous studies of the thermal regime of the finishing group of the 2000 hot rolling mill, it is recommended to turn off the cooling collectors during pauses between strips rolling.

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Introduction

Work rolls of four-high (*Quarto*) thin-sheet mills operate under severe stresses caused by the combined influence of contact and thermal loads. Studies and calculations on rolls of the finishing train of a continuous wide-strip hot-rolling mill [1] demonstrate a decisive influence of normal contact stress, which often reaches maximum permissible levels for contact strength, on the strength and durability of such rolls. However, the

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thermal conditions also directly influences the service life of work rolls in state-of-the-art high-performance hot and cold rolling mills [2–4].

Some recent foreign publications [5–14] present studies on thermal stresses occurring in work rolls during hot rolling. Most of the results obtained in these works are based on the methods of statistical, analytical or numerical computer modelling [5–9], as well as on laboratory experiments or on operating hot rolling mills [10–14]. The results of such studies can be used to solve individual problems within a static computer model without indicating the patterns of physical modelling or operating conditions of a mill of a certain design, which prevents them from being universal for the improvement of existing fundamental physical and mathematical models [15–17].

The results of the analysis conducted in the study [15] on improving the accuracy of flat products dimensions based on a dynamic model of the rolls' thermal profile demonstrate that the temperature distribution relative to the roll axis is almost symmetrical at the typical speeds of both hot and cold rolling [16]. The findings of the studies [15–17], based on solving the differential equation of thermal conductivity and on the principle of balanced generation of the thermal conditions model, are universal for hot and cold rolling mills of various designs and have found practical application [2–4]. However, all calculations of thermal stresses performed in [15–17] were simplified for some special cases of linear, parabolic, and logarithmic temperature changes from the work roll surface to its axis, which occur under certain steady heating and cooling conditions.

Another distinctive feature of state-of-the-art hot rolling mills is that in modern four-high roll systems, cast iron work rolls are used. Such rolls differ from steel rolls in their larger diameters and in the physical and mechanical properties of the material [18–20]; furthermore, calculations and studies of thermal stresses according to the existing methods [15–17] have not been conducted for cast iron rolls. The mechanical properties of cast iron are inferior to those of steel; therefore, additional thermal stresses negatively impact the service life (performance) of work rolls.

The purpose of this work is to develop an improved method for calculating the thermal stresses in work rolls under variable thermal conditions typical of continuous finishing trains of such mills in order to evaluate their contact fatigue strength.

The research objectives are:

– improvement of the methods for thermal stress calculation for a variable process conditions of a hot rolling mill;

– numerical and analytical calculation and graphical plotting of the thermal stress function for a specific work roll of an operating hot rolling mill;

– calculation of thermal stresses in the roll surface layer, considering the specific features of the existing work roll cooling conditions;

– comparative evaluation of the calculated values of thermal stresses and, based on this comparison, recommendations for the efficient utilization of the work roll cooling system.

Research methods

The general arrangement of hot rolling in the finishing train of a continuous wide-strip mill is shown in Fig. 1. Strip **1**, after preheating, with a temperature varying from 950 °C to 1,100 °C depending on the steel grade, enters the specified train. The temperature of work rolls **2** and backup rolls **4** of the four-high system is determined by the balance between the intensity of their heating and cooling. The work rolls and, through them, backup rolls are heated mainly by the heat flow from the strip through contact heat exchange with the work roll, and, to a lesser extent, by the heat released along the length of the elastic plastic deformation zone l_c (Fig. 1) when performing the specific work of rolling for strip deformation from thickness h_{j-1} to thickness h_j [21–24]. The rolls are cooled by water supplied to the entire length of the work roll and backup roll bodies through headers **3**. Wiring-water cutters **5** and **6** are installed at different levels to prevent cooling liquid from contacting the hot steel strip being rolled.

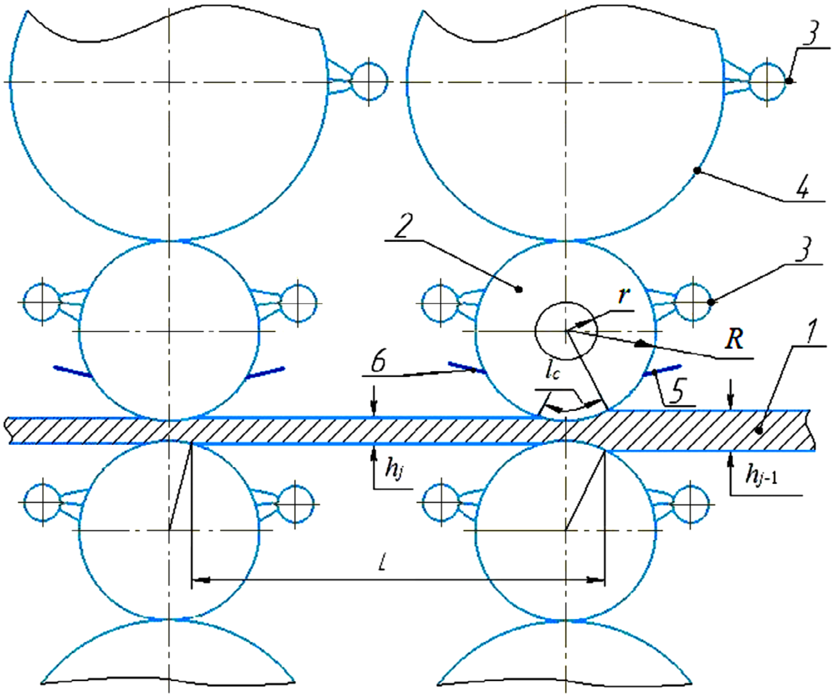

Fig. 1. Scheme of hot rolling and roll cooling in a four-high mill stand:
1 – rolled strip, *2* – working roll; *3* – cooling headers; *4* – back-up roll; *5* and *6* – wiring-water cutters; ***L*** – interstand distance during strip rolling

In order to calculate axi-symmetric thermal stresses in the work roll, taking into account the uniform radius of the roll inner layer ***r*** = const (Fig. 1), well-known formulas from the theory of elasticity are used [17]:

$$\sigma_t = \frac{E \cdot \alpha}{1-\mu}\left[\frac{1}{r^2}\int\limits_r^{\rho \cdot R} tr\,dr + \frac{(\rho \cdot R)^2 - r^2}{(\rho \cdot R)^2 \cdot \left(R^2 - r^2\right)}\int\limits_r^{R} tr\,dr - t\right]; \quad (1)$$

$$\sigma_r = \frac{E \cdot \alpha}{1-\mu}\left[-\frac{1}{r^2}\int\limits_r^{\rho \cdot R} tr\,dr + \frac{(\rho \cdot R)^2 - r^2}{(\rho \cdot R)^2 \cdot \left(R^2 - r^2\right)}\int\limits_r^{R} tr\,dr\right]; \quad (2)$$

$$\sigma_z = \sigma_t + \sigma_r = \frac{E \cdot \alpha}{1-\mu}\left[\frac{2}{R^2 - r^2}\int\limits_r^{R} tr\,dr - t\right], \quad (3)$$

and on the outer and inner surfaces of the roll at **ρ** = 1 and **ρ** = ***r*/*R*** (Fig. 1):

$$\sigma_r = 0, \sigma_t = \sigma_z, \quad (4)$$

where $\boldsymbol{\sigma_t}$, $\boldsymbol{\sigma_r}$ and $\boldsymbol{\sigma_z}$ are respectively circumferential, axial and radial major normal stresses (MPa); ***E*** is the modulus of elasticity of the work roll (MPa); **μ** is the *Poisson* ratio of the work roll material; **α** is the temperature expansion coefficient 1/°C; **ρ** = r_i/R is the dimensionless radius (Fig. 2): $\boldsymbol{r_i}$ is the arbitrary radius of the roll inner layer (mm); ***R*** is the radius of the roll body outer surface (mm).

For a simplified assessment of thermal stresses, it can be assumed that the temperature, according to [16], in the roll cross-section (Fig. 2) changes according to a logarithmic curve. If the approximating expression of the specified temperature distribution curve across the section is substituted into expressions (1)–(3) instead of ***t*** = *t*(*r*), then the value and sign of the thermal stress in such a case are a function, first of all, of the temperature difference in the cross section, i.e., the difference $(t_2 - t_1)$. In this case, the thermal stresses in critical sections, with $\boldsymbol{\rho} = \boldsymbol{k} = r/R$ (Fig. 2), can be calculated using the following simplified formulas from [3]:

– at the outer surface of the work roll body (Fig. 2)

$$\sigma_{r1} = 0; \sigma_{t1} = \sigma_{z1} = (t_2 - t_1) \cdot \frac{E \cdot \alpha}{1-\mu}\left(\frac{1}{2\ln k} + \frac{k^2}{1-k^2}\right); \quad (5)$$

– at the inner layer of the work roll with a dimensionless radius $\boldsymbol{\rho}$ (Fig. 2)

$$\sigma_{r2} = 0; \sigma_{t2} = \sigma_{z2} = (t_2 - t_1) \cdot \frac{E \cdot \alpha}{1-\mu}\left(\frac{1}{2\ln k} + \frac{1}{1-k^2}\right); \quad (6)$$

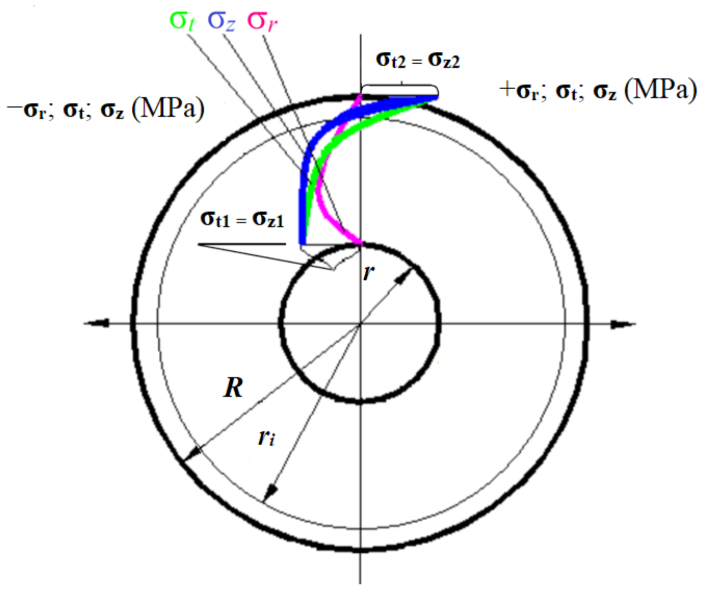

Fig. 2. Schematic distribution of temperature stresses across the roll section for the case $t_2 < t_1$

It should be noted that expressions (5) and (6) provide calculation of thermal stresses only for certain steady-state heating and cooling conditions.

In order to calculate thermal stresses in a work roll at any given time, let us consider a continuous curve $\boldsymbol{\varphi(\tau)}$, in °C, in Fig. 3, representing the graphical variation over time of the surface axi-symmetric temperature of the main roll zone per revolution, which is heated by the temperature on the surface of the work roll body.

After substituting the expression for the temperature field $\boldsymbol{F_l(\rho,\tau)}$ from study [17] instead of $\boldsymbol{t}$ into formulas (1)–(3), we obtain:

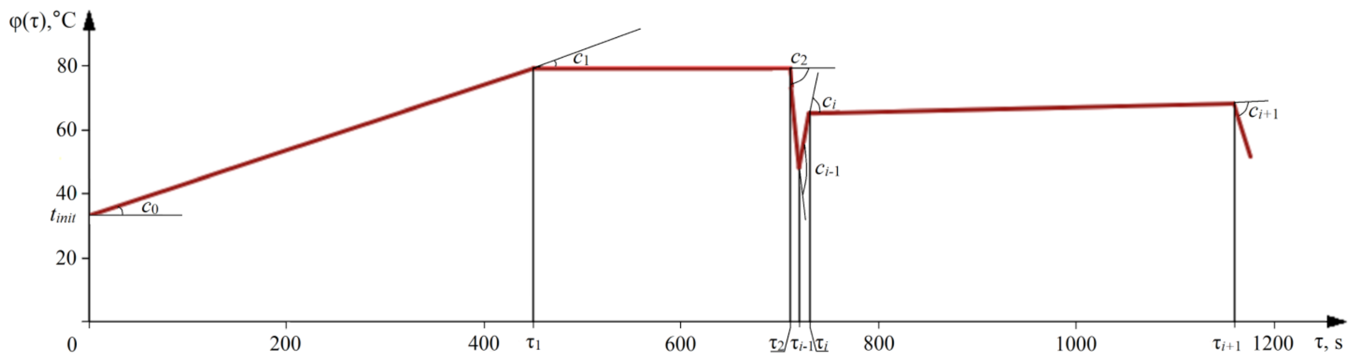

Fig. 3. Temperature curve on the surface of the working roll during hot rolling, represented as a polygonal line: $\boldsymbol{c_0}$ is the heating rate at the initial time $\boldsymbol{\tau_0}$, °C/s; $\boldsymbol{c_i}$ is the change in heating rate from the i-th polygon leg to the adjacent (i+1)-th polygon leg, °C/s; τ_i is the specific time corresponding to the transition from heating at the rate of $\boldsymbol{c_0} + \boldsymbol{c_1} + \ldots + \boldsymbol{c_{i-1}}$ to heating at the rate of $\boldsymbol{c_0} + \boldsymbol{c_1} + \ldots + \boldsymbol{c_{i-1}} + \boldsymbol{c_i}$

– for the first time interval 0–**τ₁** (heating at rate c_0 in Fig. 3):

$$t_1(\rho,\tau) = c_0 \cdot F_1(\rho,\tau); \tag{7}$$

– for any time interval ($\tau_{i-1} - \tau_i$):

$$t_i(\rho,\tau) = c_0 \cdot F_1(\rho,\tau) + c_1 \cdot F_2(\rho,\tau-\tau_1) + \ldots + c_{i-1} \cdot F_1(\rho,\tau-\tau_{i-1}); \tag{8}$$

– after integration and simple transformations, we obtain:

$$\sigma_{t1} = \frac{E\cdot\alpha}{1-\mu}\cdot c_0 \cdot F_2(\rho,\tau) = \frac{E\cdot\alpha}{1-\mu}\cdot c_0 \cdot \left[\frac{1}{f_2}\cdot\left(f_3 + e^{-f_2\cdot\nu_1^2\cdot\tau\cdot f_4} + e^{-f_2\cdot\nu_2^2\cdot\tau\cdot f_5}\right)\right]; \tag{9}$$

$$\sigma_{r1} = \frac{E\cdot\alpha}{1-\mu}\cdot c_0 \cdot F_2(\rho,\tau) = \frac{E\cdot\alpha}{1-\mu}\cdot c_0 \cdot \left[\frac{1}{f_2}\cdot\left(f_6 + e^{-f_2\cdot\nu_1^2\cdot\tau\cdot f_7} + e^{-f_2\cdot\nu_2^2\cdot\tau\cdot f_8}\right)\right]; \tag{10}$$

$$\sigma_{t(r)i} = \frac{E\cdot\alpha}{1-\mu}\cdot\left[c_0 \cdot F_{2(4)}(\rho,\tau) + c_1\cdot F_{2(4)}(\rho,\tau-\tau_1) + \ldots + c_{i-1}\cdot F_{2(4)}(\rho,\tau-\tau_{i-1})\right], \tag{11}$$

where $F_2(\rho,\tau)$ and $F_4(\rho,\tau)$ are the functions of circumferential (tangential) and radial thermal stresses (s);

$$f_2 = \frac{a}{R^2}; \tag{12}$$

$$f_3 = \frac{1}{8}\cdot\left[\frac{1}{2}\cdot\left(1+\frac{k^2}{\rho^2} - 3\cdot\rho^2 + 5\cdot k^2\right) + 2\cdot k^2\cdot\left(\ln\rho + \left(\frac{k^2}{\rho^2}\right)\cdot\left(\frac{1+\rho^2}{1-k^2}\right)\cdot\ln k\right)\right]; \tag{13}$$

$$f_6 = \frac{1}{8}\cdot\left[\frac{1-\rho^2}{2}\cdot\left(1-\frac{k^2}{\rho^2}\right) + 2\cdot k^2\cdot\left(\ln\rho - \left(\frac{k^2}{\rho^2}\right)\cdot\left(\frac{1-\rho^2}{1-k^2}\right)\cdot\ln k\right)\right]; \tag{14}$$

$$f_4 = \frac{2}{\rho\cdot(1-k^2)}\cdot\frac{(1-k^2)\cdot\{6\}_{\nu_1} + \frac{\rho^2-k^2}{\rho}\cdot\{2\}_{\nu_1} + \rho\cdot(1-k^2)\cdot\nu_1\cdot\{4\}_{\nu_1}}{\nu_1^4\cdot\left(\{2\}_{\nu_1} + k\cdot\{3\}_{\nu_1}\right)}; \tag{15}$$

$$f_5 = \frac{2}{\rho\cdot(1-k^2)}\cdot\frac{(1-k^2)\cdot\{5\}_{\nu_2} + \frac{\rho^2-k^2}{\rho}\cdot\{2\}_{\nu_2} + \rho\cdot(1-k^2)\cdot\nu_2\cdot\{4\}_{\nu_2}}{\nu_2^4\cdot\left(\{2\}_{\nu_2} + k\cdot\{3\}_{\nu_2}\right)}; \tag{16}$$

$$f_7 = \frac{2\cdot\frac{1-\frac{k^2}{\rho^2}}{1-k^2}\cdot\{2\}_{\nu_1} - \frac{1}{\rho^2}\cdot\{5\}_{\nu_1}}{\nu_1^4\cdot\left(\{2\}_{\nu_1} + k\cdot\{3\}_{\nu_1}\right)}; \tag{17}$$

$$f_8 = \frac{2\cdot\frac{1-\frac{k^2}{\rho^2}}{1-k^2}\cdot\{2\}_{\nu_2} - \frac{1}{\rho^2}\cdot\{5\}_{\nu_2}}{\nu_2^4\cdot\left(\{2\}_{\nu_2} + k\cdot\{3\}_{\nu_2}\right)}; \tag{18}$$

$$\{1\} = J_0(\lambda)\cdot Y_1(\lambda\cdot k) - J_1(\lambda\cdot k)\cdot Y_0(\lambda); \qquad \{2\} = J_1(\lambda\cdot k)\cdot Y_1(\lambda) - J_1(\lambda)\cdot Y_1(\lambda\cdot k); \tag{19}$$

$$\{3\} = J_0(\lambda)\cdot Y_0(\lambda\cdot k) - J_0(\lambda\cdot k)\cdot Y_0(\lambda); \quad (20)$$

$$\{4\} = J_0(\lambda\cdot\rho)\cdot Y_1(\lambda\cdot k) - J_1(\lambda\cdot k)\cdot Y_0(\lambda\cdot\rho); \quad (21)$$

$$\{5\} = J_1(\lambda\cdot k)\cdot Y_1(\lambda\cdot\rho) - J_1(\lambda\cdot\rho)\cdot Y_1(\lambda\cdot k), \quad (22)$$

where $\boldsymbol{a}$ is a roll thermal diffusivity coefficient (mm^2/s); $\boldsymbol{J_0(x)}$ and $\boldsymbol{J_1(x)}$ are *Bessel* functions of the first kind of zero and first orders; $\boldsymbol{Y_0(x)}$ and $\boldsymbol{Y_1(x)}$ are *Bessel* functions of the second kind of zero and first orders; $\boldsymbol{\nu_1}$ and $\boldsymbol{\nu_2}$ are two first roots of the function {1}, i.e. two first values of $\boldsymbol{\lambda}$, for which {1} = 0.

The indices $\boldsymbol{\nu_1}$ and $\boldsymbol{\nu_2}$ in the expressions {2}, {3}, {4} and {5} in formulas (15) – (18) demonstrate that the values $\boldsymbol{\nu_1} = 2.40482$ and $\boldsymbol{\nu_2} = 5.52007$ are substituted instead of the variable $\boldsymbol{\lambda}$ in these expressions [25].

Since the stress state of the work roll material in the area of contact stress influence is three-dimensional compression [1], the equivalent stress $\boldsymbol{\sigma_{eq}}$, characterizing the risk of the stress state, can approximately be determined as the difference between the maximum and minimum contact stresses [3]:

$$\sigma_{eq} = \sigma_{1c} - \sigma_{3c}, \quad (23)$$

where $\boldsymbol{\sigma_{1c}}$ is the maximal (taking the sign into account) contact stress (usually $\sigma_{1c} = \sigma_\varphi + \sigma_t$, where $\boldsymbol{\sigma_\varphi}$ is the circumferential or tangential contact stress) (MPa); $\boldsymbol{\sigma_{3c}}$ is the minimal contact stress (provided that $\boldsymbol{\sigma_r} = 0$ (Fig. 2) $\boldsymbol{\sigma_{3c}}$ is the maximal value in modulus, but, considering the sign, is the minimal value) (MPa).

A special feature of such a stress state is that the risk of its occurrence depends heavily on the value and sign of additional, in particular – circumferential thermal stress $\boldsymbol{\sigma_t}$, even if such stress is not high compared to the contact stress.

Based on expression (23), the expected critical section of the roll inner layer at the dimensionless radius $\boldsymbol{\rho} = \boldsymbol{k} = r/R$ (Fig. 2) should be excluded when evaluating the critical stress state, as the circumferential stress is absent in this layer, and the contact stress decreases sharply and practically disappears when approaching the roll axis [3]. Therefore, the most critical stresses $\boldsymbol{\sigma_{t2}} = \boldsymbol{\sigma_{z2}}$ act in the area of direct contact of the strip surface being rolled with the surface of the work roll (Fig. 2).

The value of the permissible equivalent stress $[\boldsymbol{\sigma_{eq}}]$, in MPa, can be taken considering the method for calculating the contact fatigue strength of rolls for cold rolling mills [3], depending on the hardness of the work roll body surface:

$$\left[\sigma_{eq}\right] = 10\cdot HSh, \quad (24)$$

where *HSh* is the hardness of the work roll body according to the *Shore* scale.

Contact and circumferential stresses acting on the roll outer surface were calculated according to the methods described in [1, 23], and the temperature in the inner layers was determined according to the research findings [27].

The study of thermal stresses according to the existing simplified and improved methods, as well as their influence on durability, was conducted for the bottom work roll of the most heavily loaded stand No. 10 [26] of the finishing train of the wide-strip rolling Mill 2000 at *PJSC Severstal* when rolling strips of *0.3-Cr-Mn-Si* high-strength steel with a reduction of $\boldsymbol{\varepsilon} = 21.3\%$ at a strip temperature of $\boldsymbol{t} = 834$ °C; the process parameters and physical and mechanical properties are given in Table 1.

The graphical change in temperature on the surface of the specified roll, recorded by the automated control system of the continuous hot rolling mill, is shown in Fig. 3.

Results and Discussion

The calculated values $\boldsymbol{t_1}$, $\boldsymbol{t_2}$, $\boldsymbol{\sigma_{t2}} = \boldsymbol{\sigma_{t2}}$ and $\boldsymbol{\sigma_{t1}} = \boldsymbol{\sigma_{z1}}$ for the dimensionless radii $\boldsymbol{\rho} = 1.0$ and $\boldsymbol{\rho} = 0.25$ in the case of the pause between rolling of two strips at time $\boldsymbol{\tau_{i-1}} = \boldsymbol{\tau_3} = 720$ s (Fig. 3) are given in Table 2 to determine thermal stresses according to formulas (5) and (6) as an example of the conventional method [3], successfully applied in modern production at hot and cold rolling mills [2, 4].

Table 1

Technological and physical-mechanical characteristics of the working roll

Material of the working roll	Hi–*Cr*-cast iron
Barrel radius $\boldsymbol{R}$, mm	400
Initial barrel temperature t_{init}, °C	35
Thermal diffusivity coefficient $\boldsymbol{a}$, mm²/s	13.050
Modulus of elasticity $\boldsymbol{E}$, MPa	175000
Poisson's ratio $\boldsymbol{\mu}$	0.28
Coefficient of thermal expansion $\boldsymbol{\alpha}$, 1/°C	$11.6 \cdot 10^{-6}$
Shore hardness	81.3–83.9
Permissible equivalent compression stress $[\sigma_{eqv}]$, MPa	813–839

In order to confirm the results of the calculations given in Table 2, we obtain the expression to determine stresses $\boldsymbol{\sigma}_{t2} = \boldsymbol{\sigma}_{t2}$ and $\boldsymbol{\sigma}_{t1} = \boldsymbol{\sigma}_{z1}$ at any specific time $\boldsymbol{\tau}_n$. Formula (11) demonstrates that the method for calculating thermal stresses $\boldsymbol{\sigma}_{ri}$ and $\boldsymbol{\sigma}_{ti}$ is the same as for the calculation of temperature fields according to formulas **(5)** and **(6)** from [17]. It should be noted that according to (4), radial stresses $\boldsymbol{\sigma}_{ri}$ at $\boldsymbol{\rho} = 1$ and $\boldsymbol{\rho} = \boldsymbol{r/R}$ (Fig. 1) are equal to zero; therefore, further calculation of the above-mentioned stresses is simplified, and it is sufficient to apply only the function $\boldsymbol{F_2(\rho,\tau)}$, which is the thermal stress function. The curve of this function $\boldsymbol{F_2(\rho,\tau)}$ for different values of $\boldsymbol{\rho}$ is plotted on the basis of formulas (9)–(19) for the work roll under consideration from Table 1 and is shown in Fig. 4.

The computational experiment was conducted for the case with the pause between rolling of two strips at time $\boldsymbol{\tau}_{i-1} = \boldsymbol{\tau}_3 = 720$ s (Fig. 3) in order to check the reliability and feasibility of the graphical constructions from Fig. 4 for the improved method and in order to substantiate the risk of the case $\boldsymbol{t_2 < t_1}$ (Fig. 2) of the existing processing conditions of work roll cooling with respect to contact fatigue strength. In order to

Table 2

Calculated values of t_1, t_2, $\sigma_{t2} = \sigma_{t2}$ and $\sigma_{t1} = \sigma_{z1}$ for ρ = 1.0 and ρ = 0.25 at time $\tau_{i-1} = \tau_3 = 720$ s

t_1, °C	t_2, °C	$\sigma_{t2} = \sigma_{z2}$, MPa	$\sigma_{t1} = \sigma_{z1}$, MPa
41	47	7.44	–6.91

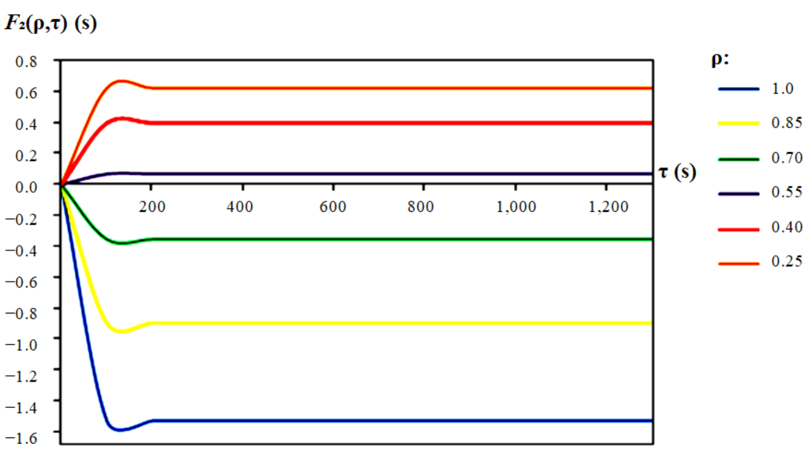

Fig. 4. Graph of the $\boldsymbol{F_2(\rho, \tau)}$ function of the working roll under consideration

confirm this assumption, the values $\Delta\tau_i$, c_i, $F_2(\rho,\tau)$, $\sigma_{t1} = \sigma_{z1}$ and $\sigma_{t2} = \sigma_{t2}$ at $\rho = 1.0$ and $\rho = 0.25$, provided in Table 3, were calculated for the case of a change in the measured temperatures t_i on the work roll surface at time $\tau_3 = 720$ s (Fig. 2).

Table 3

Calculated values of $\Delta\tau_i$, c_i, $F_2(\rho,\tau)$, $\sigma_{t1} = \sigma_{z1}$ and $\sigma_{t2} = \sigma_{t2}$ for $\rho = 1.0$ and $\rho = 0.25$

τ_i, s	t_i, °C	$\Delta\tau_i$, s	c_i, °C/s	$F_2(0.25,\tau)$, s	$F_2(1.0,\tau)$, s	$\sigma_{t2} = \sigma_{z2}$, MPa	$\sigma_{t1} = \sigma_{z1}$, MPa
0	33	720	0.155	0	0	0	0
450	70	270	–0.155	0.62	–1.5	0.32	–0.13
710	70	10	–2.9	0.62	–1.5	0.32	–0.13
720	41	0	2.4	0.62	–1.5	12.42	–5.13

As can be seen from the data given in Table 3, minor positive tensile stresses $\sigma_{t2} = \sigma_{z2} < 1$ MPa occur on the outer surface during hot rolling in the time interval $\tau_i = 450$–710 s (Fig. 3), and such stresses increase significantly to $\sigma_{t2} = \sigma_{z2} > 12$ MPa at the pause time $\tau_{i-1} = \tau_3 = 720$ s. Thereafter, with the cooling method used, such variations are repeated, which negatively affects the durability of the work roll surface. The reason for such stress variations is the intensive heating of the work roll inner zones [27].

The maximum normal contact stress σ_{3c}, the circumferential contact stress $\sigma_{1c} = \sigma_{\varphi} + \sigma_{t2}$, and the equivalent stress σ_{eq} (Table 4) were determined according to the procedures described in [19, 23] for both the conventional and improved methods of thermal stress calculation $\sigma_{t2} = \sigma_{z2}$ in order to confirm the negative impact of tensile stresses $\sigma_{t2} = \sigma_{z2}$ on the contact fatigue strength in the roll surface layer at the dimensionless radius $\rho = 1$. A comparison of the results obtained with the permissible stresses $[\sigma_{eq}]$ leads to the conclusion that the most critical are the equivalent stresses in work rolls during rolling of high-strength steel grades [1], because they are closer to the upper limit of the acceptable range of $[\sigma_{eq}]$ (Table 1).

Table 4

Calculated values of σ_{3c}, σ_{φ}, σ_{t2}, $\sigma_{1к}$ and σ_{eqv} on the roll surface at $\rho = 1.0$

Methodology	σ_r, MPa	σ_{3c}, MPa	σ_{φ}, MPa	σ_{t2}, MPa	σ_{1c}, MPa	σ_{eqv}, MPa
Classical	0	–1,168.3	350.54	7.44	–343.1	825.2
Improved	0	–1,168.3	350.54	12.42	–338.12	830.2

The risk of a further increase in σ_{eq} and of exceeding the permissible range of $[\sigma_{eq}]$ increases significantly during hot rolling of strips with greater longitudinal gauge variation. Such an increase is related to variations in forces and temperatures along the entire strip length [1]; therefore, such loads on work rolls and the occurrence of significant tensile thermal stresses result in higher risks of damage or fracture of the work roll surface layer, leading to unscheduled roll changes.

The issues of optimizing the thermal conditions of rolls in wide-strip hot rolling mills, including changes in the supply of cooling fluid to the roll system of four-high stands with pauses in time, are addressed in detail in [3, 4, 20, 24, 27]. Based on the results of the present study on the evaluation of thermal stresses at various points in time τ_i for the finishing train of *Mill 2000* (Table 3), it is recommended to shut off the external cooling headers during pauses in hot rolling of strips, because in this case the occurrence of critical tensile stresses $\sigma_{t2} = \sigma_{z2}$ in the surface layer of work rolls is almost completely eliminated.

Conclusions

1. The procedure for calculating thermal stresses in work rolls for a variable thermal conditions of hot rolling has been improved and adapted to the finishing train of a continuous wide-strip rolling mill.

2. The curves of the thermal stress functions $\boldsymbol{F_2(\rho,\tau)}$ have been plotted for different values of the dimensionless radius ρ of the work roll.

3. It has been demonstrated that the functional dependence $\boldsymbol{F_2(\rho,\tau)}$ possesses the important property of universality, which makes it possible to calculate thermal stresses at any point on the curve **φ(τ)**, represented as a piecewise linear function of the surface temperature variation of the work roll during hot rolling of strips.

4. Thermal stresses were calculated according to conventional and improved methods, taking into account the actual variable thermal conditions of hot rolling mill operation. 5. The comparative analysis demonstrates the higher accuracy of the improved method for thermal stress calculation.

5. Based on the results of the data analysis from the computational experiment aimed at increasing the contact fatigue strength of rolls, a recommendation was developed to implement a more efficient method of work roll cooling. In particular, it is recommended to shut off the external cooling headers during pauses in hot rolling of strips.

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Conflicts of Interest

The authors declare no conflict of interest.