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Investigation of the distribution of normal contact stresses in deformation zone during hot rolling of strips made of structural low-alloy steels to increase the resistance of working rolls

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ABSTRACT

Introduction. During the operation of the working rolls of the finishing groups of continuous wide-strip hot rolling mills, normal contact stresses have a decisive influence on its resistance and strength, especially when rolling a range of low-alloy structural steels with a minimum thickness range of 5.5–2.0 mm, which does not correspond to the passport characteristics of such mills. **The subject of the study.** Previously performed studies of the stress-strain state of the rolled strip in the deformation zones make it possible to estimate the level of normal contact stresses acting on the working rolls during hot rolling of strips of low-carbon steels. The paper discusses the results of the study of the stressed state of strips of low-alloy structural steels in contact with rolls, taking into account the features of the chemical composition of the metal and changes in its elastic properties during deformation at hot rolling temperatures. The results obtained are applicable to the evaluation of the contact strength of the finishing rolls of the rolling mill. **The purpose of the work** is to investigate the distribution of normal contact stresses in the deformation zones during hot rolling of strips of low-alloy structural steels to ensure high resistance of the working rolls. **Material and methods.** The study is based on the elastic-plastic model and equations for calculating normal contact stresses for each section of the deformation zone. The specificity of variation of *Young's* modulus (modulus of elasticity) of low-alloyed structural steels in accordance with certain hot rolling temperatures is studied in detail, and the contact strength of high-chromium cast iron work rolls is evaluated. **Results and discussion.** A reliable regression equation is obtained for determining the values of the Young's modulus of the rolled strip as a function of changing hot rolling temperatures. The results of a numerical experiment are presented in the form of calculating the maximum normal contact stresses using the elastic-plastic model of the deformation zone and assessing the contact strength of the work rolls based on actual rolling conditions on an operating mill. New improved technological modes of hot rolling of low-alloy structural steels (0.1 *C-Cr-Si-Ni-Cu*, 0.18 *C-Cr-Mn-Ti* and 0.14 *C-2 Mn-N-V*) are proposed, which make it possible to reduce the maximum contact stresses and increase the resistance of the working rolls.

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Introduction

The priority task of the development of modern flat rolled products manufacturing is to develop the technology for hot rolled strip production from structural low-alloyed steels for welded structures with the thickness range of 5.5 to 2.0 mm. Simultaneously with complication of assortment, not corresponding to passport characteristics of continuous wide-strip hot rolling mills and increase of requirements for equipment performance, it is essential to reduce specific consumption of working rolls and increase its lifetime, since the cost of rolls in the expense structure of the rolling production reaches 15–20 % [1].

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The possibility of increasing the lifetime of operated working rolls of hot rolling mills is provided in some studies [2–9] related to direct influence of hot rolling process temperature on the stresses occurring in rolls. However, the materials of the above-presented works practically do not take into account specific features of stress-strain state during strip contact with working rolls [10–12]. At the same time, application of calculation methods for such a stress-strain state based on the elastic-plastic model of the deformation zone [10–12] demonstrated that the calculations require some clarification. The materials of the publication [13] reveal the influence of different ranges of hot rolling temperatures and actual steel chemical compositions with carbon content less than 0.25 % on elastic and plastic properties of strips deformed in the mill. A conclusion is made in the same paper [13] that the length of elastic sections can reach 32 to 40 % of the total length of the deformation zone; this feature was not previously taken into account.

The described changes in the structure of deformation zones when producing rolled products from structural low-alloyed steels with the minimal thickness range of 5.5 to 2.0 mm result in the problem of shortening lifetime of working rolls in last stands of continuous wide-strip hot rolling mills because of increased normal contact stresses in the deformation zone, as further calculations showed, to the dangerous level of 1,068 to 1,245 MPa, typical for cold rolling mills [10]. An effective solution to the problem of increasing the lifetime of operated working rolls at the stage of development hot rolling process modes at modern steel plants should begin with reliable methods for calculating the energy-force parameters and stress-strain state of the strip in the contact with working rolls [11–13].

The purpose of the work is to study the distribution of normal contact stresses in deformation zones during hot rolling of strips from low-alloyed structural steels to achieve high lifetime of working rolls.

The research objectives are to supplement the method of calculation of normal contact stresses in production of low-alloyed structural carbon steels; to construct a linear regression within the elasticity modulus calculation; to study distribution of normal contact stresses in deformation zones during hot rolling considering special features of its stress-strain state on the basis of the existing process mode; to improve the technology of hot rolled strips production from low-alloyed structural steels in the finishing train of the wide-strip mill to achieve high lifetime of work rolls; to evaluate the efficiency of the developed procedure and new hot rolling modes.

Research methods

Based on the modelling of the stress-strain state of the strip during hot rolling [11–13], Table 1 provides formulas for calculating $p_x(h_x)$ for elastic and plastic sections of the deformation zone. The lengths of such sections are indicated as x_1, x_4 and x_2, x_3 respectively. The formulas help to study and reveal the regularities of changes in the maximum normal contact stresses p_{1max}, p_{4max} and p_{xmax}, distributed along the length of the deformation zone l_c in Fig. 1.

Table 1 shows that the calculation of normal contact stresses $p_x(h_x)$ of strip hot rolling, with known values of reduction in thickness $\Delta h_i = h_{i-1} - h_i$ and specific interstand tensions σ_{i-1} and σ_i, directly depends on the correct definition of the elasticity modulus E_S, the friction factor in the deformation zone μ_i and the actual plastic resistance σ_{pl}. The specifics of μ_i and σ_{pl} values determination depending on deformation-velocity parameters, working rolls material and chemical composition of hot rolled steel are given in [12–14].

Varying strip elasticity modulus E_S at the temperature of 1,050 to 750 °C, which is typical for finishing stands of hot rolling mills, is of particular interest for the study of structural low-carbon steel rolling. For steels *0.14 C-2 Mn-N-V*, *0.18 C-Cr-Mn-Ti* and *0.1 C-Cr-Si-Ni-Cu*, selected for further calculations of normal contact stresses during rolling and for evaluation of lifetime of working rolls in the finishing train of continuous wide-strip *Mill 2000* at PAO Severstal, the dependence of E_S on temperature, according to reference data [15], has the form shown in Fig. 2.

Standard calculation methods intended for all machine parts were used to evaluate the rolls contact strength during rolling. The correction was performed using the formula of allowable stresses for the compression scheme from [16] to apply these conventional methods to cast iron rolls of rolling mills:

$$[\sigma] = 1.5 \cdot \sigma_u, \tag{1}$$

where σ_u is the ultimate compressive strength of the working roll material, MPa.

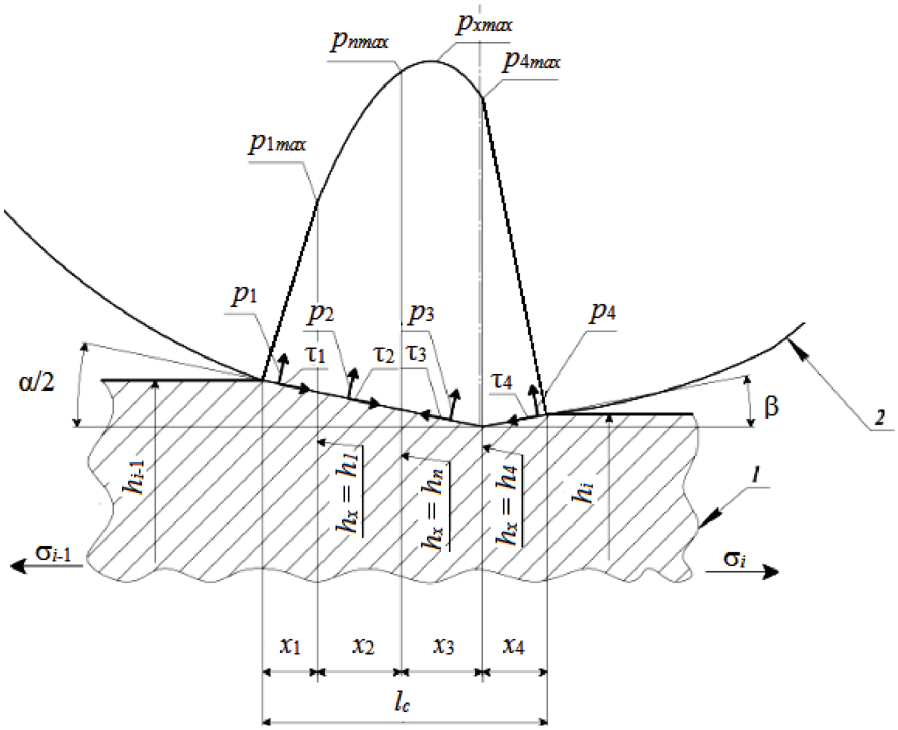

Fig. 1. Distribution pattern of normal contact stresses in the deformation zone during hot rolling:

1 – deformable strip; **2** – working roll; $\boldsymbol{h_{i-1}}$, $\boldsymbol{h_i}$ – thickness of the strip before and after rolling, mm; $\boldsymbol{h_1}$, $\boldsymbol{h_4}$ – thickness of the strip at the boundaries of the first and second elastic sections, mm; $\boldsymbol{h_n}$ – thickness in neutral section, mm; $\boldsymbol{x_1}$, $\boldsymbol{x_4}$ – lengths of elastic sections, mm; $\boldsymbol{x_2}$, $\boldsymbol{x_3}$ – lengths of the plastic sections of lag and advance, mm; $\boldsymbol{\tau_i}$ – contact tangential stresses, MPa; $\boldsymbol{p_i}$ – normal contact stresses, MPa; $\boldsymbol{\alpha}$ – angle of nip of the strip, $\boldsymbol{\beta}$ – angle of inclination of the deformation zone on the second elastic section, deg; $\boldsymbol{\sigma_{i-1}}$, $\boldsymbol{\sigma_i}$ – back and front tensions, MPa

Table 1

Formulas for calculating normal contact stresses $p_x(h_x)$

The first elastic section with a length of x_1	The second elastic section with a length of x_4
$p_x = 1.15 \cdot E_S \cdot \left\{ \frac{1}{\delta_{i-1}} - \frac{2}{\delta_{i-1}+1} \cdot \left(\frac{h_x}{h_{i-1}}\right) + \left(\frac{h_{i-1}}{h_x}\right)^{\delta_{i-1}} \left[\frac{\delta_{i-1}-1}{(\delta_{i-1}+1)\cdot\delta_{i-1}} - \frac{\sigma_{i-1}}{1.15\cdot E_S} \right] \right\},$ where $\delta_{i-1} = \frac{\mu_i}{\mathrm{tg}\left(\frac{\alpha}{2}\right)}$	$p_x = 1.15 \cdot E_S \cdot \left\{ \frac{1}{\delta_i} - \frac{2}{\delta_i+1} \cdot \left(\frac{h_x}{h_i}\right) + \left(\frac{h_i}{h_x}\right)^{\delta_i} \left[\frac{\delta_i-1}{(\delta_i+1)\cdot\delta_i} - \frac{\sigma_i}{1.15\cdot E_S} \right] \right\},$ where $\delta_i = \frac{\mu_i}{\mathrm{tg}(\beta)}$
Plastic section	
$p_x = 1.15 \cdot \sigma_{pl} \cdot \left[\frac{0.5}{\mathrm{tg}\left(\frac{\alpha}{2}\right)} \cdot \frac{(h_1 - h_x)}{(h_1 - h_n)} + \left(1 + \frac{0.5}{\mathrm{tg}\left(\frac{\alpha}{2}\right)} \cdot \frac{h_n}{(h_1 - h_n)} \right) + (\ln(h_x) - \ln(h_1)) + \frac{p_1}{1.15\cdot\sigma_{pl}} \right]$	

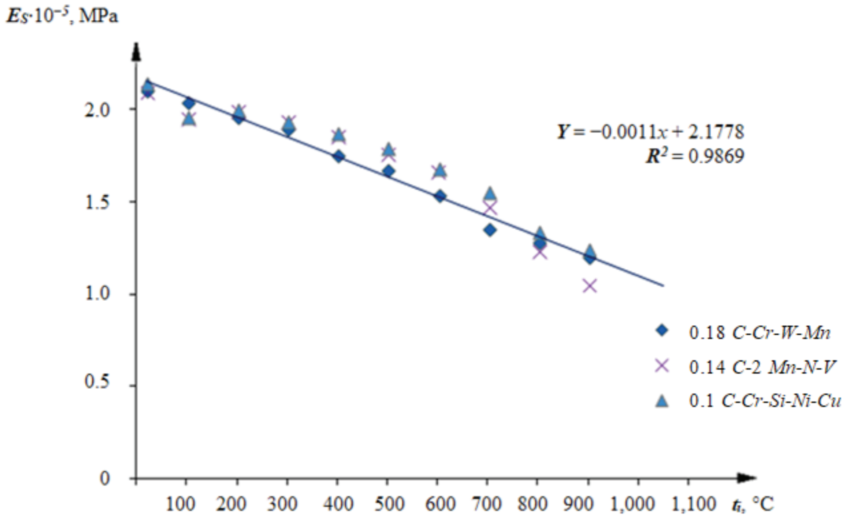

Fig. 2. Change in the modulus of elasticity of low-alloy structural steels depending on the test temperature

Results and discussion

In order to use data shown in Fig. 2 in further calculations of contact stresses in deformation zones, the linear approximation of the elasticity modulus (*Young's* modulus) E_S dependence on temperature was performed for hot rolling of strips and equation (2) was obtained with the determination coefficient R^2 = 0.9869 and the calculated value of the *Fisher* criterion (*F*-test). The *F*-test value is greater than that from the table, so the linear regression equation given below is significant and gives an accurate and reliable prediction.

$$E_S = 2.1778 - 0.0011 \cdot t_i, \qquad (2)$$

where t_i is the temperature of the rolled strip in the *i*-th mill stand, °C.

The actual process mode for rolling a strip from *0.1 C-Cr-Si-Ni-Cu* steel with the thickness of 2.1 mm and the width of 1,270 mm in the finishing seven-stand train of *Mill 2000* of PAO Severstal in stands No.7, No.9 and No.11 respectively, more utilized during hot rolling, was used to study the distribution of normal contact stresses after a strip contact with working rolls. The above-mentioned features of hot rolling of low-alloyed structural steels and calculation formulas from Table 1 were used to study stresses. The target chemical composition of the specified steel grade, its rolling process mode, structural parameters of deformation zones and calculated values of normal contact stresses in the above-mentioned stands are provided in Table 2.

The Fig. 3 schematically represents the distribution of maximum normal stresses on the plastic section in stands No.7, No.9 and No.11 during strip hot rolling according to the mode specified in Table 2. This plastic section completely consists of the stick area [11–13]. The estimated values from Table 2 and Table 3 demonstrate that maximum values of contact stresses p_{xmax} influence the plastic section of the deformation zone in the lag section with the length of x_2 (Fig. 1) near the neutral section, also one can see slight decrease of such stresses to maximum values p_{4max} on the border of the plastic and second elastic section. Taking into account the above, when determining the stress-strain state of the strip in the contact with working rolls, particularly when calculating x_4 and p_{4max}, it is necessary to take into account the peculiarity of the change in the modulus of elasticity of the steel in Fig. 2.

Calculation using formula (1), taking into account the tests of the ultimate strength of high chromium cast iron working rolls σ_u = 700–800 MPa [17] used in finishing train stands of *Mill 2000*, indicates that permissible contact stresses are in the range of [σ] = 1,050–1,200 MPa. Comparing the maximum normal contact stresses p_{xmax} from Table 2 and the above permissible stresses [σ] we can conclude that these stresses are the most dangerous for the working rolls in stand No.11, because the stresses fall in the range of

Table 2

Chemical composition of *0.1 C-Cr-Si-Ni-Cu* steel, rolling process condition and the results of calculating the structural parameters of the deformation zone and normal contact stresses

Chemical composition, %										
C	*Si*	*Mn*	*Cr*	*Mo*	*Ni*	*Al*	*Cu*	*Nb*	*Ti*	*V*
0.102	0.87	0.55	0.63	0.05	0.53	0.016	0.46	0.001	0.003	0.002
Rolling stand No.								7	9	11
Outgoing thickness h_i, mm								10.43	3.99	2.33
Percentage reduction ε_i, %								48.16	34.27	19.09
Back tension σ_{i-1}, MPa								20	30	40
Front tension σ_i, MPa								30	30	40
Rolling speed υ_i, m/s								2.3	5.76	10.36
Strip temperature t_i, °C								1,024	984	939
Coefficient of friction μ_i								0.418	0.295	0.24
Plastic resistance σ_{pl}, MPa								167	239.9	315.1
Young's modulus for work rolls E_R, MPa								205,000	185,000	185,000
Young's modulus for a strip E_S, MPa								105,165	109,497	114,494
Rolling force P_i, MN								33.46	23.13	19.97
Length of deformation zone l_c, mm								63.8	29.56	26.76
Elastic section length x_4, mm								4.85	6.31	8.18
Maximum normal contact stresses p_{1max}, MPa								172.6	247.1	327.7
Maximum normal contact stresses on the plastic section p_{xmax}, MPa								332.5	645.9	1,067.7
Normal contact stresses in the neutral section p_{nmax}, MPa								328.5	643.3	1,066.9
Maximum normal contact stresses p_{4max}, MPa								190.5	378.9	798.3

permissible values [σ] in several estimated points of the deformation zone p_{xmax} and p_{nmax} (Fig. 3). The fact of the maximum loading of the roll system of the four-high stand No.11 according to the existing production technology in the finishing train of the *Mill 2000* is also confirmed by studies in [18].

The risk of further growth of maximum contact stresses p_{xmax} increases significantly during hot rolling of strip sections with higher longitudinal thickness variation due to fluctuations in the force P_i as a function of all crucial process factors [19, 20], therefore the risks of surface damage, reduced lifetime, or destruction of working rolls and the risk of emergency roll change increase due to repetitive loading and heavy thermal stresses [21–23]. It should also be noted that rolling of low-alloyed structural steels in the conditions of real production of the finishing train is performed before scheduled rolls change in all stands of *Mill 2000*, therefore the calculated values of maximum contact stresses p_{xmax} and p_{nmax} (Fig. 3) really affect the working roll lifetime.

The studies [19, 20] can be used as a potential for improving the technology of hot-rolled high-strength steel strips production in the finishing train of a wide-strip mill to ensure high durability of working rolls. The essence of the proposed improvement in rolling strips of high-strength steels is that the increase of percentage reductions ε_i in the first three stands of the *Mill 2000* finishing train in the rolling direction to maximum permissible values of reductions $\varepsilon_{i.max}$ or $P_{i.max}$ force, as specified in the mill technical passport data, have no significant impact on growth of maximum normal contact stresses p_{xmax} because of high

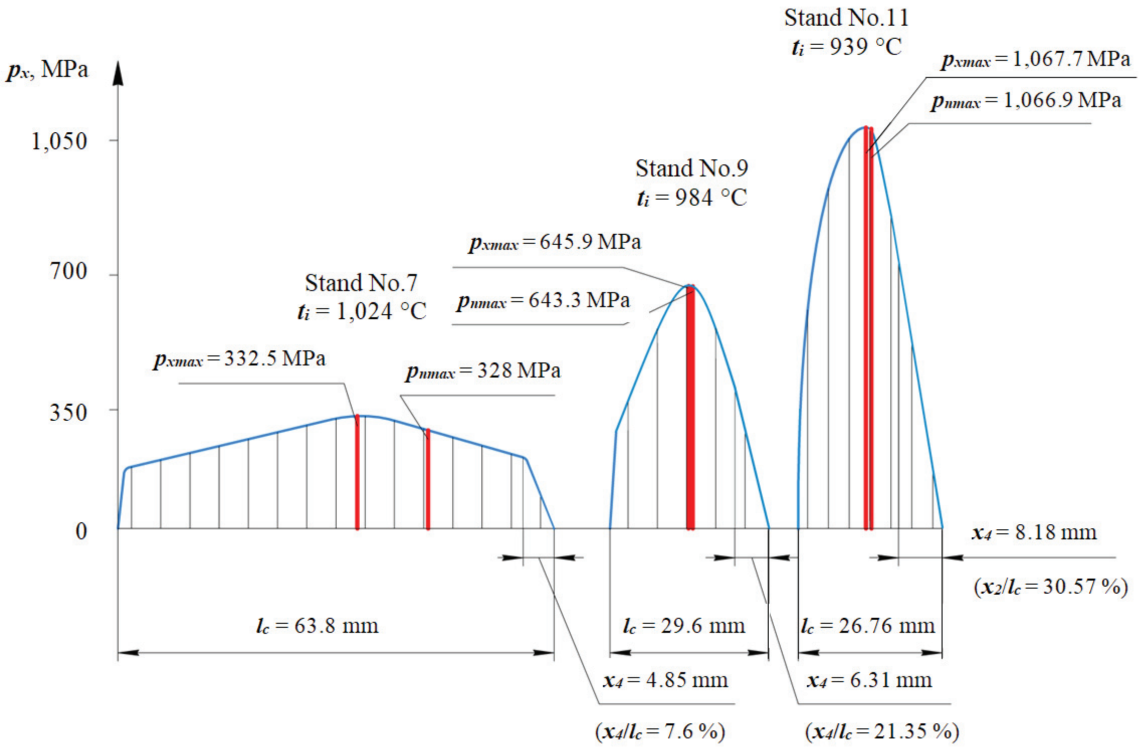

Fig. 3. Distribution pattern of normal contact stresses along the length of the deformation zone in rolling stands No.7, No.9 and No.11

rolling temperature (Table 2). The decrease of reductions and increase of specific interstand tensions $\boldsymbol{\sigma}_{i-1}$ and $\boldsymbol{\sigma}_i$ to maximal possible values ≤ 60 MPa, as shown by successful experience of implementation at various hot rolling mills in [19, 20], in the rolling direction in the last stands greatly reduce fluctuations of forces $\boldsymbol{P}_i$ and strip thickness in it.

Table 3 presents the process restrictions, new design modes and values of normal contact stresses in the above-mentioned stands No.7, No.9 and No.11. Table 3 is an illustrative example of the efficiency of the developed method related to redistributing reductions and increasing interstand tensions in the area of contact stresses decrease during hot rolling of 2.1×1,270 mm strip made of *0.1 C-Cr-Si-Ni-Cu* steel.

The efficiency of the initial adjustment of hot rolling process modes for low-alloyed structural steel *0.1 C-Cr-Si-Ni-Cu* according to the above principle demonstrates the decrease of maximum normal contact stresses in the stand No.11 and up to the safe range of calculated values $\boldsymbol{p}_{xmax}$ = 837.5–838.0 MPa (Table 3). The lifetime of the working rolls of stand No.7 with the increase of reduction to the maximum value $\boldsymbol{\varepsilon}_{i.max}$, as shown by calculation of stresses $\boldsymbol{p}_{xmax}$ (Table 3), does not depend on normal contact stresses from the strip contact with the working roll; the decisive factors of the technology are the high temperature of rolling $\boldsymbol{t}_i$, which greatly affects thermal deformations and effective cooling of working roll bodies [24].

Similar calculations of the maximum contact stresses $\boldsymbol{p}_{xmax}$ and $\boldsymbol{p}_{nmax}$ were done for steels *0.18 C-Cr-Mn-Ti* and *0.14 C-2 Mn-N-V* (Table 4) during hot rolling in stands of the finishing train from the thickness of 35.5 mm to the thickness of 2.1 mm, to demonstrate the feasibility of using new improved modes compared to the existing ones to increase contact strength of working rolls. Table 4 shows that hot rolling, according to operating modes, of structural steels *0.18 C-Cr-Mn-Ti* and *0.14 C-2 Mn-N-V* with higher content of carbon and alloying elements, results in increase of maximal contact stresses to the values $\boldsymbol{p}_{xmax}$ = 1,095.7–1,245 MPa, which exceed the permissible values **[σ]** = 1,200 MPa. The results of calculations given in Table 3 and Table 4 lead us to a conclusion that the algorithm of optimization of hot rolling process modes from [19, 20] can be applied to improve the strip rolling technology to ensure high durability of working rolls by reducing of maximum contact stresses to the range of 838–1,023 MPa.

Table 3

Technological constrains, the new rolling mode and results of normal contact stresses calculation

Rolling stand No.	7	9	11
Maximum percentage reduction $\boldsymbol{\varepsilon}_{i.max}$, %	50	30	25
Maximum rolling force $\boldsymbol{P}_{i.max}$, MN	35	28	20
Maximum back tension $\boldsymbol{\sigma}_{i.max}$, MPa	22	35	47
Maximum front tension $\boldsymbol{\sigma}_{i.max}$, MPa	31	42	55
Estimated rolling speed $\boldsymbol{\upsilon}_i$, m/s	1.97	6.08	11.41
Design strip temperature $\boldsymbol{t}_i$, °C	1,016	975	935
Estimated percentage reduction $\boldsymbol{\varepsilon}_i$, %	50	20.45	10
Plastic resistance $\boldsymbol{\sigma}_{pl}$, MPa	174	247	313
Young's modulus for a strip $\boldsymbol{E}_S$, MPa	105,981	110,479	114,922
Rolling force $\boldsymbol{P}_i$, MN	33.81	14.93	12.4
Maximum estimated normal contact stresses on the plastic section $\boldsymbol{p}_{xmax}$, MPa	350.1	634.73	837.5
Estimated normal contact stresses in the neutral section $\boldsymbol{p}_{nmax}$, MPa	341.7	633.85	838

Table 4

Operating and new rolling schedule and calculation results of maximum normal contact stresses

Steel	Rolling mode	Rolling stand No.	ε_i, %	σ_{i-1}/σ_i, MPa	p_{xmax}, MPa	p_{xmax}, MPa
0.18 C-Cr-Mn-Ti	Operating schedule	7	48.5	20/30	337	329.6
		9	34.3	30/30	685	682.5
		11	21.3	40/40	1,096.5	1,095.7
	New schedule	7	50	24/32	393.5	386
		9	30	37/43	664	663
		11	18.9	49/58	939	938
0.14 C-2 Mn-N-V	Operating schedule	7	47.9	20/30	378	370
		9	33.8	30/30	750.2	748
		11	22.1	40/0	1,245	1,243.4
	New schedule	7	50	30/35	441	433
		9	30	40/48	732.6	731
		11	19.1	50/60	1,023	1,021.9

Conclusions

1. The method of calculation for normal contact stresses in elastic sections of the deformation zone during rolling of low-alloyed structural carbon steels is supplemented by the dependence of the change in the elasticity modulus of the strips on temperature.

2. A regression equation is obtained for predicting the calculated values of the elasticity modulus of such steels as a function of the change in hot rolling temperature.

3. A study is carried out of the distribution of normal contact stresses along the length of the deformation zone taking into account the specific features of the stress-strain state of the strip contacting with working rolls based on the existing hot rolling process mode in the most utilized stands of the finishing train of *Mill 2000*. According to the study results it is noted that the existing rolling process modes lead to growth of maximum contact stresses in the stand No.11 of the finishing train of the hot rolling *Mill 2000* of PAO Severstal to dangerous range of values of 1,068–1,245 MPa in the plastic section of the deformation zone. The working rolls resistance to early emergency destruction under conditions of the above stated maximum stresses falling within and exceeding the range of permissible contact stresses **[σ]** = 1,050–1,200 MPa can be explained by the fact that the material of the working rolls in the contact area is in favourable conditions of all-round elastic compression.

4. Improved modes of reduction and specific interstand tensions, which can reduce and maintain maximum normal contact stresses in the stand No.11 of the finishing train in a safe range of 838–1,023 MPa, are calculated and suggested based on the previously developed principles of hot rolling process modes optimization to reduce fluctuations in thickness and force.

It is concluded that the developed approach to evaluation of lifetime of work rolls in hot rolling mill finishing trains when exposed to normal contact stresses and a new advanced method of the modes initial adjustment can be applied for designing the efficient rolling technology for low-alloyed structural steels with the minimal thickness range of 5.5–2.0 mm.

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Conflicts of Interest

The author declare no conflict of interest.