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Formation of Roll Contact in Four-High Mill Stand

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Reduction of uneven deterioration of roll bodies, broad-strip mill downtime and manufacture of precise transverse section of strip are caused in many respects by application of rational types of grooving of work and back-up rolls in four-high mill stand. Rational roll grooving needs defining the actual length of contact between work and back-up roll. The latter defines sizes of end slopes of back-up rolls and enables to raise accuracy of calculation of work roll natural deflection and values of roll crown out (crown in). The calculation model for determination of rational length of active part of back-up roll body length is suggested in the paper.

Keywords: CALCULATION MODEL, FOUR-HIGH MILL STAND, ROLLS, ROLL CONTACT

Introduction

A convex roll, which generating line is in the form of quadric parabola along the whole length of roll body, is applied together with a cylindrical roll on the broad-strip mills. At such form of roll generating line there are always maximum interroll pressures and, as a result, the maximum wear of rolls in the middle section of roll contact [1-5]. So, it is determined in the experimental research of roll contact conditions [1, 2] that type of interroll pressure q_y is defined by work roll diameter ($D_B = const$), strip thickness and roll grooving. Decrease of roll pressure inhomogeneity (q_y) is provided with increase of work roll diameter as its natural deflection is reduced. The minimum unevenness of q_y is at $B/L_B \approx 0.8$ and $D_W/D_B \approx 0.8$ (B and L_B – strip thickness and length of back-up roll body respectively; L_W - length of work roll body).

Investigations showed that there was a significant non-uniformity of roll pressures as a result of cylindrical roll bending which promoted uneven wear of roll bodies. Application of grooved rolls increases or reduces non-uniformity of roll pressures. When rolling narrow strips ($B/L_B \le 0.6$), elastic approach of axes on the middle of body length and non-uniformity of q_y are less in concave work rolls and more in convex work rolls than in cylindrical ones. When rolling wide strips at $B/L_B \approx 0.8$, q_y distribution pattern decreases on the convex rolls and increases on the concave rolls as compared to cylindrical rolls. As during one working shift strips with different thickness are rolled on the same work rolls, any grooving in the form of quadric parabola is not rational. Such grooved rolls promote uneven wear of roll surface.

Further research of working conditions of shaped rolls [1, 2] with recommendations for industrial strip mills are presented in [3, 5]. The new types of work and back-up rolls grooving are developed and recommended in practice. Authors [5] have considered the theoretical and practical aspects of application of work and back-up rolls with various types of grooving on the broad-strip mills. Much attention was paid to reduction of uneven roll pressure distribution and roll production due to decrease of roll natural deflection.

Results and Discussion

Results of roll grooving types investigation under the terms of their contact are presented below. The experiments are carried out on press in the model of four-stand mill with diameters of cylindrical work roll D_w = 32 mm, back-up roll D_B = 80 mm, length of roll body L_B = 100 mm. An aluminum plate was deformed between the work rolls, and copy paper was put on the roll contact between work and back-up rolls. Data on effect of roll grooving and bending on unevenness of interroll pressure distribution are introduced in **Table 1**.

Table 1. Effect of roll grooving and bending on unevenness of interroll pressure distribution (P = 40 кН, B = 70 mm)

Grooving type of work roll		Roll contact size, mm			Interroll pressure, kN/cm		Interroll pressure q_0 by equation (5), kN/cm	n_q	n
f_b, *mm*	*m*	*2b*	*2a*	*$2a_0$*	*q*	*q_0*			
0	1	100	0.835	1.02	4.0	4.89	4.6	0.82	0.73
0.14	2	74	0.78	1.12	5.42	7.8	8.0	0.7	0.30
0.28	2	51	0.795	1.39	7.8	13.1	14.9	0.58	0.10
0.45	2	27.1	0.77	1.52	14.8	29.3	29.2	0.53	0
0.14	7	96	1.03	1.37	4.16	5.56	5.21	0.75	0.60
0.14	7	96	1.13	1.36	4.43	5.68	5.31	0.78	0.67

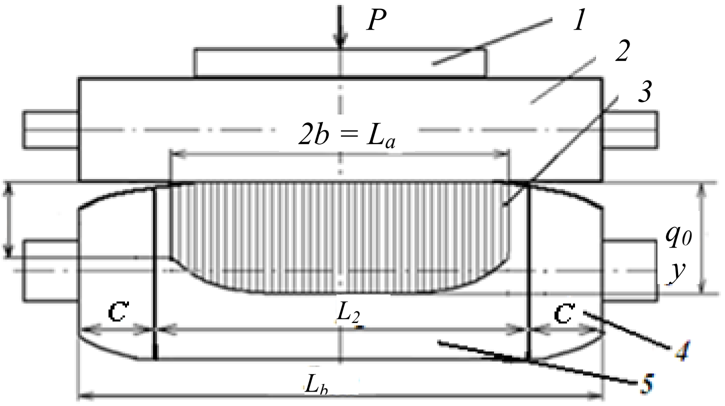

Figure 1. Work and back-up rolls interaction pattern: *1* - strip; *2* - work roll; *3* - interroll pressure distribution diagram; *4* - slope; *5* - back-up roll

Roll force is P = 10 - 42 kN and convexity of back-up roll is $f_b = 0 – 0.45$ mm at the exponent of generating line m = 2 and 7 [3] in the experiments. Conditions in the contact between rolls were estimated by the following parameters (**Figure 1**):

$$\left.\begin{aligned} q &= P / 2b; \\ q_0 &= 2a_0 \cdot q / 2a; \\ q_y &= 2a_y \end{aligned}\right\} \quad \text{(Eq. 1)}$$

$$\left.\begin{aligned} n_q &= q / q_0; \\ n &= q_1 / q_0 \end{aligned}\right\} \quad \text{(Eq. 2)}$$

where q, q_0, q_1, q_y - interroll pressures: average, on the roll axis, on the boundary line of roll contact, current; n and n_q - irregularity coefficients on the boundary of roll contact; b - half of roll contact length; a and a_0 - half of roll contact width: average and on the roll axis respectively.

As follows from **Table 1**, at deformation in cylindrical rolls ($f_b = 0$) the roll contact length is equal to length of roll body ($2b = L_B$), but interroll pressure q_y changes on the length $2b$ and coefficient n = 0.73 (m = *1*). The increase of back-up roll convexity to f_b = 0.45 mm (m = 2) reduces the active contact length to $2b$ = 27.1 mm and coefficient n = 0, i.e. on the contact boundary q_1 = 0. Change of generating line into parabola with m = 7 (f_b = 0.14 mm) provides increase of contact length and decrease of roll contact irregularity to n_q = 0.75-0.78 and n = 0.60-0.67. These data are close to those obtained in cylindrical rolls. Thus, reduction of generating line arch in the back-up roll (increase of m) at P = const provides decrease of interroll pressure unevenness and, as a result, wear of back-up rolls.

Effect of shape and grooving of roll body generating line on unevenness of roll contact is characterized by following equations [3]:

$$\begin{aligned} n_m &= 1.03 - 0.03m \\ n_f &= 0.5 + 0.5(1 - 1000 f_{\sum} / L_B)^2 \end{aligned} \quad \text{(Eq. 3)}$$

where f_{Σ} - total convexity of work and back-up rolls for diameters. Factor n is defined by experimental data [1, 2]:

$$n = n_f n_m \left\{ 0.86 + 0.97 \frac{B}{L_a} (2.44 \frac{B}{L_a} - 1) - 5.9 \frac{D_W}{D_B} (1 - 1.56 \frac{D_W}{D_B}) \right\} \quad \text{(Eq. 4)}$$

Distribution of interroll pressure along the length of roll body can be defined as follows [3, 4]:

$$q_y = \frac{P(1+m)}{L_a(m+n)} \left[1 + (n-1) \frac{2 \cdot y^m}{L_a{}^m} \right] \quad \text{(Eq. 5)}$$

Equation (5) gives a good correlation with empirical data from **Table 1** and data in [1, 2].

Unknown parameter "L_a" in equation (5) is defined from a condition that curvatures of bending lines of work and back-up rolls are equal in a certain point of the contact. Thus the total bending of the work roll is:

$$W_W = W_1 + W_B \quad \text{(Eq. 6)}$$

where W_1 and W_B - natural bending of work roll and back-up rolls respectively.

Curvature of roll bending line according to [7, 8] is:

$$\frac{1}{R_i} = \frac{d^2 Z_i}{dy^2} / \left[1 + (\frac{dZ_i}{dy})^2 \right]^{3/2} \quad \text{(Eq. 7)}$$

where z_i - current altitude from a horizontal to roll bending line in the cross-section on length y.

Parameter z_i is defined from the following expression for original roll grooving:

$$Z_i = \frac{f_i}{2} (\frac{2y}{L_i})^m \quad \text{(Eq. 8)}$$

where f_i - value of original crown for the diameter; L_i - length of roll body. Solving equations (7) and (8) we will obtain the equation for definition of generating line curvature of shaped roll in the point:

$$\frac{1}{R_i} = \frac{0.5 \cdot f_i \cdot m(m-1)(\frac{2y}{L_i})^{m-2}}{\left\{ 1 + \left[\frac{f_i}{2} m (\frac{2y}{L_i})^{m-1} \right]^2 \right\}^{3/2}} \quad \text{(Eq. 9)}$$

According to equations (7) - (9), curvature of roll bending lines is as follows:

$$\frac{1}{R'_i} = \frac{w_i \cdot m(m-1)(\frac{2y}{L_i})^{m-2}}{\left\{ 1 + \left[w_i \cdot m (\frac{2y}{L_i})^{m-1} \right]^2 \right\}^{3/2}} \quad \text{(Eq. 10)}$$

where w_i - bending of work or back-up roll; R_W (R'_W) and R_B (R'_B) - curvature radiuses of work and back-up rolls respectively along the length of roll body.

The second summands of denominators are close to zero so they can be neglected in equations (9) and (10):

$$\frac{1}{R_i} = 0.5 \cdot f_i \cdot m_i (m_i - 1)(\frac{2y}{L_i})^{m_i - 2} \quad \text{(Eq. 11)}$$

$$\frac{1}{R_i} = w_i \cdot m_i (m_i - 1)(\frac{2y}{L_i})^{m_i - 2} \quad \text{(Eq. 12)}$$

For roll bending lines we accept the generating line in the form of quadric parabola and will obtain:

$$\frac{1}{R_i} = 2 w_i \quad \text{(Eq. 13)}$$

These equations enable to define the length of actual contact of work and back-up rolls by their bodies. Indeed, when rolling a strip the back-up roll has a bending W_B in the middle of body roll length (**Figure 2**). Under the action of rolling force P the convex work roll is bended as well following the bending of back-up roll (without taking into account wear of rolls). However, the work roll is maximum naturally bended as a result of elastic flattening of roll surfaces in the middle part of roll body length [1-3]. As a consequence, curvature of bending of work and back-up rolls will be various and at certain parameters of roll grooving the absence of contact on the end sections of rolls is possible (**Figure 2**).

The length of roll contact can be defined from a condition that curvatures of roll bending lines will be equal in the line intersection point "A":

$$\frac{1}{R'_W}+\frac{1}{R'_W}=\frac{1}{R'_B}+\frac{1}{R'_B} \quad \text{(Eq. 14)}$$

Then it follows from equations (10) and (11) that:

$$0.5f_W\cdot m_W(m_W-1)\cdot\left(\frac{2y}{L_W}\right)^{m_W-2}-2W_W=$$
$$=-0.5f_B\cdot m_B(m_B-1)\cdot\left(\frac{2y}{L_B}\right)^{m_B-2}+2W_B \quad \text{(Eq. 15)}$$

where m_W and m_B - exponents of bending curve of work and back-up rolls respectively; L_W and L_B - lengths of work and back-up roll bodies respectively ($L_W = L_B$).

Usually, roll bending curves have a form of parabola, but exponent m_i of these parabolas is various. In most cases, work rolls are manufactured with cylindrical or convex barrel shape ($m_W = 2$). Taking this into account we will solve equation (15) in relation to parameter $2y/L_B$. After transformation we will obtain:

$$\frac{L_a}{L_B}=\sqrt[m_B-2]{\frac{2(W_W+W_B)-B}{A}} \quad \text{(Eq. 16)}$$

$$\left.\begin{aligned}A&=0.5f_B\cdot m_B(m_B-1)\\B&=0.5f_W\cdot m_W(m_W-1)\end{aligned}\right\} \quad \text{(Eq. 17)}$$

As at $m_W = 2$ parameter $B = f_W$, we will obtain ($2y = L_a$)

$$\frac{L_a}{L_B}=\sqrt[m_B-2]{\frac{2(W_W+W_B)-f_W}{A}} \quad \text{(Eq. 18)}$$

where f_W and f_B - actual (during rolling) diametrical convexities of work and back-up rolls respectively.

Parameter L_a/L_b is defined by iterative method at the joint solution of equations (4) and (18).

Shapes of roll body lines as a result of their bending are shown in **Figure 2**. If bending of work and back-up rolls are equal ($W_1 = 0$), the roll contact length will be equal to L_B ($L_a = L_B$). In case of non-uniform distribution of interroll pressures ($q_0 > q_1$) there is an additional bending of work roll (W_1) in the middle part of roll body length and increase of contact length with the back-up roll. The values of initial convexities decrease and become equal due to specified deformations.

$$\left.\begin{aligned}f_b&=f_{bu}+\Delta R_{bt}+\delta_{Bu}\\f_w&=f_{wu}+\Delta R_{wt}+W_1+\delta_{wu}\end{aligned}\right\} \quad \text{(Eq. 19)}$$

where f_{bu} and f_{wu} - initial convexities of back-up and work rolls; ΔR_{bt}, ΔR_{wt} - thermal convexities of

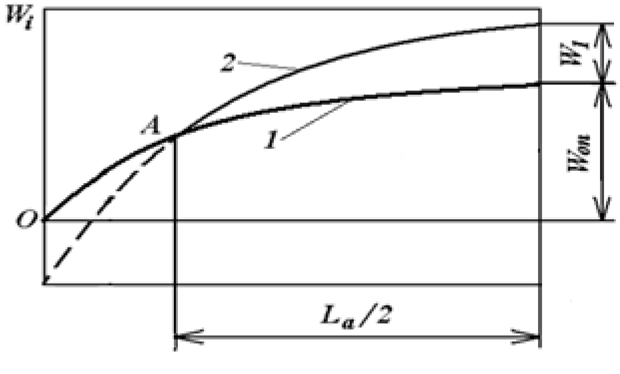

Figure 2. Bending pattern of back-up (*1*) and work (*2*) rolls

rolls on radius; δ_{bu}, δ_{wu} - nonuniformity of roll production on radius.

Parameters $\delta_{b.u}$ and $\delta_{w.u}$ have a positive sign in formulas (19) as it promotes the bending of work rolls and increase of roll contact length. When the back-up roll is worn out on convexity, parameter $\delta_{b.u}$ has a minus sign.

Bending of work and back-up rolls is defined by formulas from works [3, 6] taking into account parameters n and m_i.

The back-up roll body line is a curve in the initial state that is caused by shape coefficient m_b and value of machine-tool and thermal crown. Possible back-up roll body lines are presented in **Figure 3**. In the first case, there are end slopes in the cylindrical back-up roll. In this case, $f_b = 0$ on cold rolls. However, as a result of heating and temperature gradient along the roll length there is a convexity within the limits f_b = 0.05-0.10 mm. Besides, the end slopes give the generating line of rolls a form of higher order parabola (**Figure 1**) with factor m ≥ 4-6 and slope value "c". And the more slope value "c", the more factor m.

The generating lines of back-up roll surface are reasonable to make in the form of higher order parabola with m ≥ 4-6 (curve 3) [3]. At such form there is no need in the end slopes. Work rolls are usually fabricated with cylindrical profile of the body or with profile in the form of quadric parabola at $m_w = 2$. While in service the profile of work convex roll is produced non-uniformly [3, 7] and the exponent m_w decreases which calls reduction of length L_a and nonuniform distribution of interroll pressures. Cylindrical work rolls are worn out on crown providing increase of contact length L_a, but with higher interroll pressures at the ends of roll bodies.

The natural bending of work roll (W_1) and back-up roll bending (W_b) is calculated by formulas [3, 6] in relation to back-up roll length L_b.

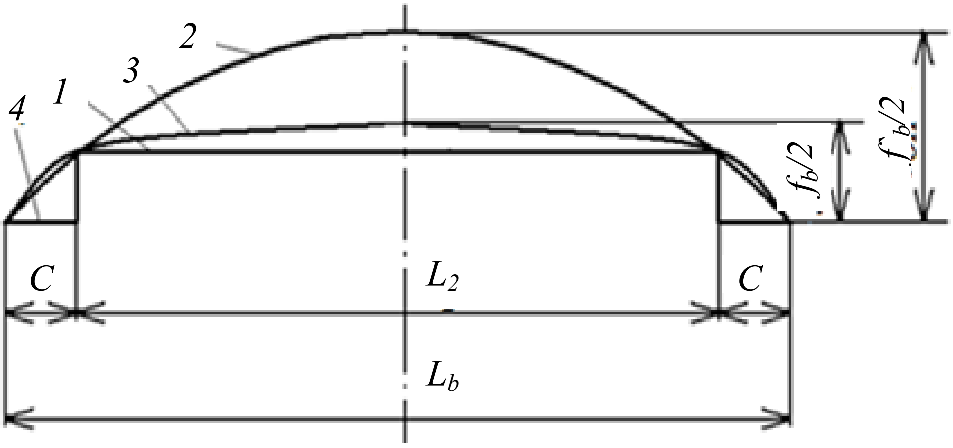

Figure 3. Types of back-up roll body grooving: *1* - cylindrical profile; *2* - convex parabolic profile (m = 2); *3* - parabolic profile with m> 2; *4* – end slopes

$$W_1 = \frac{PL_b^3}{384E_1J_1}\left(\frac{3}{2+n}\{3-1.7(1-n)\} - \frac{B^3}{L_b^3}\frac{3}{2+n_1} \times \left\{1 - 4\frac{L_b}{B} + \frac{L_b^2}{B^2} - 8(1-n_1) \times \left[0.5\frac{L_b^4}{B^4} - 0.167\frac{L_b^3}{B^3} - 0.12\right]\right\}\right) + \frac{PL_b k}{4\pi R_1^2 G_1} \times \frac{3}{2+n}\left[0.5 - \frac{n-1}{4} - \frac{B}{L_b}\frac{3}{2+n_1}\left(0.5 - \frac{1-n_1}{4}\right)\right] \quad \text{(Eq. 20)}$$

$$W_b = \frac{PL_b^3(1+m)}{384E_2J_2(m+n)}\left(1 + \frac{n-1}{1+m/4}\right)\left(1 + 4\frac{1 + \frac{n-1}{1+m/3}}{1 + \frac{n-1}{1+m/3}}\right) + \frac{PL_b^3}{48E_2J_2} + \frac{P}{4\pi R_2^2 G_2}\left(L_b - \frac{L_b}{2}\right), \quad \text{(Eq. 21)}$$

where B - plate strip width; L_b - length of back-up roll body; n_1 - pressure nonuniformity coefficient under the strip; D_w and D_b - diameters of work and back-up rolls; P – rolling force; E_1 and E_2 - modulus of work and back-up rolls respectively; J_1 and J_2 - inertia moment of work and back-up roll respectively; k - cross-section factor (k = 1); G_1 and G_2 - shear modulus of work and back-up roll respectively. The factor n_1 from work [3] is:

$$n_1 = 0.87 + 3.15(B / L_W - 0.39)^4 \quad \text{(Eq. 22)}$$

We used an iterative process when calculating parameters n, L_a/L_b, W_1 and W_2.

Calculation of elastic deformation parameters as applied to stand of cold mill 1700 with D_w = 500 mm and D_b = 1300 mm, L_2 = 1550 mm. We accepted f_b = 0.1 and 0.3 mm, m_b = 8 as constants for the back-up roll and B = 1000 - 1500mm and convexity of work roll f_w = -0.3 - (+0.4) mm as variables. Rolling force P = 20 MH.

Computation data are presented in **Figures 4, 5**.

At the accepted rolling parameters, bending of back-up rolls slightly depends on plate strip width and their bodies grooving which correlates with known data [1, 2]. The natural bending of work roll W_1 (**Figure 4b**, **5b**) decreases with increase of plate strip width and almost does not depend on its crown. However, bending W_1 increases with increase of back-up roll crown [2, 3] due to increase of interroll pressure (equation (5)) at simultaneous reduction of roll contact length L_a/L_b (**Figure 4c**, **5c**).

Calculations show that in all cases at m = 8 and f_b = 0.1 and 0.3 the relative length of roll contact L_a/L_b <1. On the one hand, it is caused by shape of roll generating line, when $L_2 \approx 1350$ and 1450 (at f_b = 0.3 and 0.1 respectively) (**Figure 3**, curve 3), and on the other hand - by work roll grooving. The roll contact length $L_a/L_b \rightarrow 0.9$ (f_b = 0.1 mm) at the concave grooving.

The increase in convexity of back-up roll to f_b = 0.3 mm (**Figure 5a**) reduces the roll contact length to L_a/L_b = 0.76 as a result of increase of interroll pressures in the middle part of roll length. The increase of natural bending of the work roll is indicative of this (**Figure 4b, 5b**). It is seen in **Figure 4c** and **5c** that the minimum values of parameter L_a/L_b decrease with increase of plate strip width at f_w = *const*. However, convexity of work rolls reduces with increase of plate strip width which promotes the increase of roll contact length in the real rolling practice.

Obtained relations enable to determine the rational grooving types of back-up rolls (values m, L_2, f_b) together with convexity values of work roll defined earlier.

So, the length of active part of the back-up roll is sufficient within the limits $L_2 = L_a \approx 0.83L_b$ for B = 1000 mm at computed convexity of work roll f_w = 0.2 mm. At roll body length L_b = 1700 mm the length of active part L_2 = 1410 mm. At L_2> 1410 mm a part of back-up roll length does not contact with the work roll which enhances nonuniformity of its roll wear.

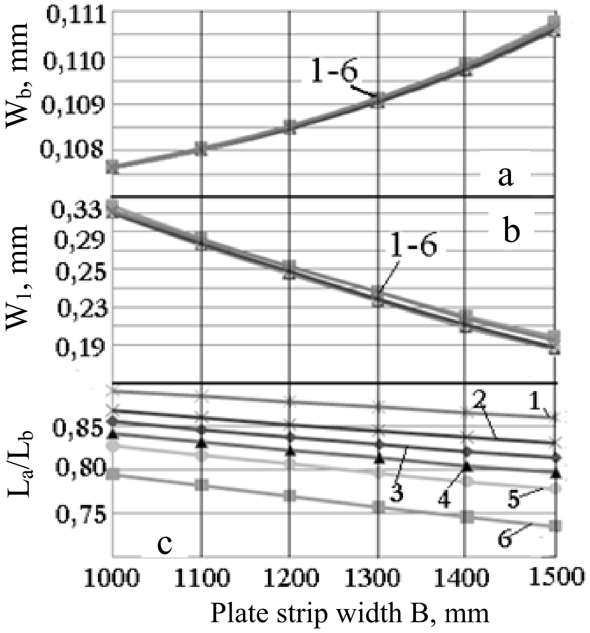

Figure 4. Parameters of elastic deformations of work and back-up rolls of mill 1700 depending on plate strip width at m_b = 0.8, f_b = 0.1 for f_w of work roll, mm: *1* - 0.3; *2* - 0.1; *3* - 0; *4* - 0.1; *5* - 0.2; *6* - 0.4

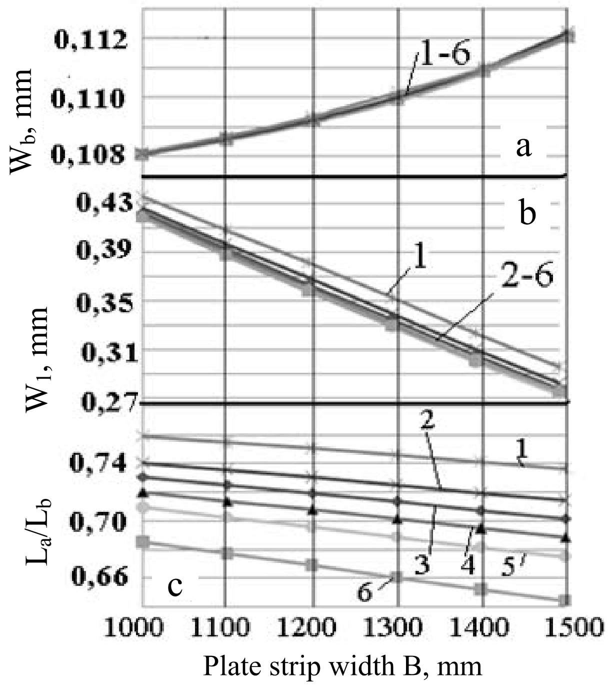

Figure 5. Parameters of elastic deformations of work and back-up rolls of mill 1700 depending on plate strip width at m_b = 0.8; f_b = 0.3 for f_w *of* work roll, mm: *1* - –0.3, *2* - 0.1, *3* - 0, *4* - 0.1, *5* - 0.2, *6* - 0.4

Conclusions

Rational grooving of rolls needs defining the actual length of contact between work and back-up roll. The model for determination of active length of roll contact is suggested. The roll contact length is computed for stand 1700 under various conditions of rolling. Suggested model of calculation enables to determine the rational length of active part of back-up roll length.

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Формирование межвалкового контакта в клети кварто

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На сегодняшний день снижение неравномерности износа бочек валков, простоев широкополосных станов и получение точного поперечного профиля полосы во многом обусловлены применением рациональных типов профилировок рабочих и опорных валков клетей кварто. Создание рациональной профилировки валков предусматривает необходимость определения фактической длины контакта между рабочим и опорным валком, а это в свою очередь определяет размеры концевых скосов (врезов) опорных валков и позволяет повысить точность расчета собственного прогиба рабочего валка и величин выпуклостей (вогнутостей) валков. В статье предложена модель расчета, позволяющая установить рациональную длину активной части длины бочки опорного валка.