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# The longitudinal stability of the rolling process with strip tension at a two-section friction model in the roll pass

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Abstract
The paper proposes a new friction model for determining the shear stresses in the roll pass. With its application a method of estimating of longitudinal strip stability in rolls when rolling with tension is developed. On the basis of the developed method analyses of the tension influence of strips on the kinetic and strength rolling parameters was carried out. It showed that when tension composite longitudinal force increases, the absolute value decreases, and hence the stability of the rolling process is reduced.
Keywords: FRICTIONAL MODEL, TENSION, LONGITUDINAL STABILITY, ROLL PASS

In [1-3] and others the distribution model of specific friction forces in the roll pass is shown, which in a certain range of parameter changes of rolling gives close with respect to the results of tests values. However, they are classified as suitable functions and do not have a physical validation.

In this study, a model of the distribution of specific frictional forces and an attempt to validate its position with the modern theory of rolling and longitudinal stability of the rolling process in the deformation strip under tension has been analyzed.

Let us imagine a rolling process as an upset in the direction of an axis extending at the angle $\alpha/2$ ($\alpha$ – entering angle) to the vertical, with subsequent transportation of metal from the roll pass as the elastic body. Extract the element of metal in the form of a triangular prism (Fig. 1) and consider its balanced state in upset conditions.

Suppose that the deformation is flat and mutually perpendicular faces of the prism are the main platforms. In this case, the principal normal stress $\sigma_1$ and $\sigma_3$, the contact surface being inclined platform - normal pressure $p_x$ and shear stress $\tau_{OC}$ will effect on the faces of the prism.

The equilibrium condition of the element is

$$\begin{cases} \sigma_1 \sin\psi\, dl - p_x \sin\psi\, dl + \tau_{ax} \cos\psi\, dl = 0 \\ \sigma_3 \cos\psi\, dl - p_x \cos\psi\, dl - \tau_{ax} \sin\psi\, dl = 0 \end{cases}$$

Subtracting the second expression from the first and taking into account the equation of plasticity we have

$$\tau_{ax} = \frac{1}{2} 2k \sin 2\psi .$$

When you extract the element from the axis 3-3 from the right the shear stress $\tau_{ax}$ changes its direction as the plastic flow of metal directed in the opposite direction. The final expression for the determining $\tau_{ax}$ the right of the axis 3-3 is a view similar to the equation given above. If we take as the basis of

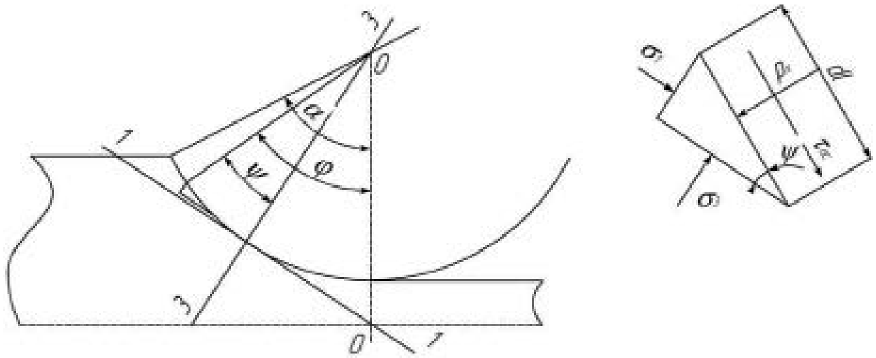

**Figure 1.** Scheme of forces applied to elemental prism

the axis 0-0 (Fig. 1), we obtain an equation describing the variation of the specific friction forces on the contact when the metal rolls upset

$$\tau_{ax} = \frac{1}{2} 2k \sin 2\left(\varphi - \frac{\alpha}{2}\right), \quad (1)$$

where $2k$ is the average deformation resistance of metal; $\varphi$ is current angle in the roll pass.

Select the second component of friction associated with transportation through the roll pass preliminary deformed elements of metal. Let this component depends on the glide process and determined by the function:

$$\tau_{fr} = fp_x. \quad (2)$$

Then the model of friction in the contact zone of the strip with rolls takes the form of

$$t_x = \tau_{fr} + \tau_{ax} = fp_x + \frac{1}{2} 2k \sin 2\left(\varphi - \frac{\alpha}{2}\right). \quad (3)$$

We note that $f$ is conditional coefficient as follows from the expression (3) is not equal to the average coefficient of friction in the roll pass obtained as the ratio of the diagrams' areas of specific friction forces and the normal pressure.

$$f_{av} = \frac{\int_0^\alpha t_x d\varphi}{\int_0^\alpha p_x d\varphi} = \frac{\int_\gamma^\alpha t_x d\varphi + \left|\int_0^\gamma t_x d\varphi\right|}{\int_0^\alpha p_x d\varphi}. \quad (4)$$

It should be noted that the presented model in a certain extent corresponds to the equation of Shevchenko K. N. given in [4]

$$\tau_x = fp_x + t_0\left(v_r - v_x\right), \quad (5)$$

where $t_0$ – a constant; $v_x$ – metal speed (tangential); $v_r$ – linear speed of rotation of the rolls.

Models of changes in the specific forces of friction (3) and (5) are referred to the category of double-sectioned.

Let us carry out the test on conformity of the expression (3) to the limiting conditions of rolling. It is well known from the theory that limiting the ability of gripping the rolls occurs when $\alpha = 2fy$ . In this case roll pass is only a backward slip zone and the specific frictional forces at the output of metal from the rolls equals zero. As a first approximation, taking $\sin 2\left(\varphi - \frac{\alpha}{2}\right) \approx 2\left(\varphi - \frac{\alpha}{2}\right)$ rad and taking into account the limiting conditions at the output of metal from rolls for pressure $\left(p_x = 2k\right)$ and for the specific friction force when the limiting rolling $\left(t_x = 0\right)$ , from the equation (3) we take $\alpha = 2f$ . As shown above the expression (3) represents the limiting condition of rolling at steady state mode.

Introducing into the second term of the expression (3) coefficient $n_1 = \left(\frac{2f}{\alpha}\right)^2$ , the latter can be obtained from well-known in theory equation for determining the angle of the neutral plane

$$\gamma = \frac{\alpha}{2}\left(1 - \frac{\alpha}{2f}\right).$$

The analysis shows that the proposed model of friction corresponds to the limiting and kinematic conditions of rolling.

In [5] A. P.Grudev made a significant remark about the formula of K. N. Shevchenko associated with the fact that the product $fp_x$ is only a part of the total specific friction force in the roll-strip contact.

While in theory is accepted that this product is the total specific friction force. Taking this into account, we introduce into the equation (3) coefficient $n_2$, which is always less than 1and is determined from the limiting conditions when solving differential Karman equation. This is possible because the model (3) describes the change in specific frictional forces along the entire length the roll pass, in the backward slip zone and forward slip zone. Consequently, the limiting condition is that $h_x = h_1$ pressure $p_x = 2k$ can be used for determining $n_2$ .

Moreover, in order that the product $n_2 f$ was close to the ratio of sliding friction in the elastic and the initial part of the roll pass to the second term as a multiplier we introduce the function $\frac{\alpha-\varphi}{\alpha}$.

Finally, the proposed model of the distribution of specific friction forces in the rolling pass when rolling takes the form of

$$\frac{t_x}{2k} = n_2 f \frac{p_x}{2k} + \frac{1}{2}\sin\left[2n_1\left(\varphi - \frac{\alpha}{2}\right)\right]\frac{\alpha-\varphi}{\alpha}. \qquad (6)$$

Let's give some explanations concerning the method of specific frictional forces calculating, according to (6) and the average coefficient of friction in the roll pass.

We note that this ratio should be obtained from the solution of differential Karman equation with taking into account (6) and to be equal to its empirical value for the specified rolling conditions. Therefore, the solution procedure consists of several stages. Previously conditional coefficient *f* should be given.

As a first approximation it may be assumed equals an empirical value of the sliding friction coefficient or calculated by a well-known empirical formulas, for example, the Grudev formula [6]. As the solution of the Karman equation considering friction model (6) we obtain diagrams of contact stress distribution and the average coefficient of friction $f_{av}$. If this coefficient does not satisfy the test data, then varying of the value *f*, we find required value $f_{av}$. In this case, the average calculated pressure of metal on rolls will correspond to empirical value of the friction coefficient and balance of strip in the roll pass.

For calculating $\frac{p_x}{2k}$, $\frac{t_x}{2k}$ and $f_{av}$ by applying ECM a program for numerical determination of these values using the Runge-Kutta method has been developed.

In our opinion, this method of calculation of contact stresses and the average coefficient of friction can be extended to cases of hot and cold sheet rolling, as well as in determining the longitudinal stability of the strip in the roll pass.

The calculation examples of contact stresses in the deformation parameter corresponding to the experimental cold rolling of the steel sheet are given below [7, p.186, Table. 7]. The calculations are made for cases of rolled samples under numbers of figures 92 and 97.

Parameters of power, as well as the value of the specific backward tension in the dimensionless form $\frac{\sigma_0}{2k}$ and forward creep $S$ are given in the table. The value of the average pressure $\frac{p_{av}}{2k}$ and forward creep are calculated and shown in the denominator of the table. When determining the forward creep the angle of the neutral plane was found directly from the distribution diagrams of specific friction forces.

Analysis of these data shows that in cold rolling steel samples under numbers 92 and 97 calculated and empirical values of the average pressure and forward creep are quite close. The distribution of specific frictional forces qualitatively corresponds to well-known empirical diagrams. With increasing of back tension the corner of the neutral plane and the average pressure in the roll pass decreases (Fig. 2).

The theoretical estimate of the longitudinal stability of the rolling process with the tension of metal was performed according to the procedure set out in [8]. The resultant of longitudinal forces $Q^{*t}_{av.long.}$ was calculated in accordance with the experimental parameters of rolling steel strip tension [7].

The amount of tension was evaluated with average index [9]

$$\xi_{av} = \xi_0\left(1,05 + 0,1\frac{\xi_1}{\xi_0} - 0,15\frac{\xi_0}{\xi_1}\right),$$

where

$$\xi_0 = 1 - \frac{\sigma_0}{2k};\ \xi_1 = 1 - \frac{\sigma_1}{2k}.$$

The comparative results of experiments and calculations of resultant of longitudinal forces are given in Fig. 3. As shown, with the increase in the average tension the resultant $Q^{*t}_{av.long.}$ in absolute value decreases, therefore longitudinal stability of the rolling process decreases also. This conclusion is supported

**Table.** Deformation modes and force parameters in cold steel sheet rolling [7]

| Figure No | Strip thickness, mm | | $\frac{\sigma_0}{2k}$ | $S$, % | $\frac{p_{av}}{2k}$ | $\alpha_{alloy}$ | $l_{alloy}$, mm | $v_r$, $\frac{mm}{s}$ | $f_{av}$ | $f$ | $n_2$ | $Q^{*t}_{av.long.}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $h_0$ | $h_1$ | | | | | | | | | | |
| 92 | 1,95 | 1,3 | 0,688 | 3,5 / 3,6 | 1,09 / 1,01 | 0,067 | 9,68 | 43 | 0,17 | 0,21 | 0,91 | 0,00011 |
| 97 | 1,95 | 1,32 | 0 | 5,7 / 5,9 | 1,55 / 1,52 | 0,061 | 9,82 | 42 | 0,12 | 0,21 | 0,41 | 0,00492 |

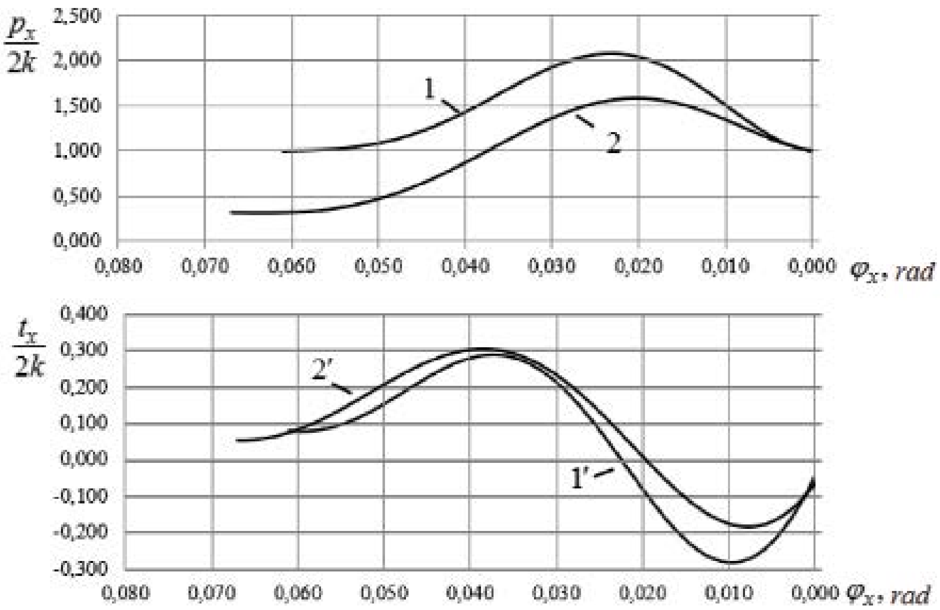


**Figure 2.** The distribution contact stresses in accordance with the results of experiments [7]:
1 and 1'contact stresses when rolling the sample 97; 2 and 2 '- contact stresses when rolling the sample 92

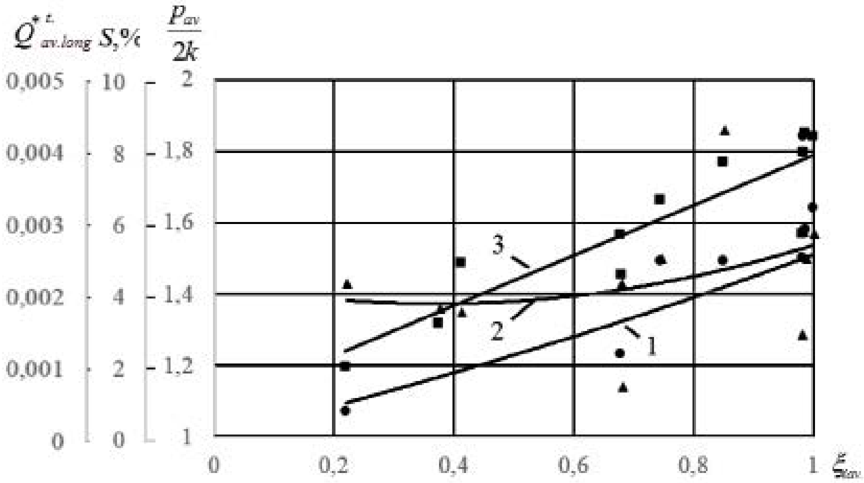


**Figure 3.** Effect of the tension on the strip on the kinetic and power parameters of rolling

● — average pressure $\frac{p_x}{2k}$, curve 1;

▲ — forward creep $S$, curve 2;

■ — average horizontal longitudinal forces resultant $Q^{*t.}_{av.long.}$, curve 3

by empirical value of forward creep $S$. Some scatter of the experimental points associated with different rolls flattening when changing tension of the strip.

In conclusion, we note that longitudinal stability of the metal in the rolls can be one of the restrictions on the strip tension when rolling. This circumstance must be especially taken into account in the continuous rolling of sheet steel.

**Conclusion**

We propose a three-section distribution model of specific frictional forces in the roll pass that takes into account famous principles of the theory of rolling. The method of calculation of these stresses was developed. There is a certain correspondence between the calculated and empirical diagrams of specific frictional forces, as well as the values of average pressure, forward creep and friction coefficient. It is shown that when tension increasing the resultant of longitudinal forces in an absolute value decreases and therefore, the stability of the rolling process reduces.

**References**


1. Levanov A. N. , Kolmogorov V. L., Burkin S. P. *Kontaktnoe trenie v protsessah obrabotki metallov davleniem* [Contact friction in processes of metal treatment under the pressure], Moscow, Metallurgy, 1976, 416 p.
2. Semenyuta A. Ya. *Opredelenie udelnyih davleniy pri prokatke shirokih polos sredney tolschinyi* [Determination of specific pressures when broad strips rolling of average thickness], Moscow, Metallurgy, 1967, Vol. 52, p.p. 118-123.
3. Vasilev Ya. D., Dementnenko A. V. The model of stress friction when sheet rolling(2002), Universities publisher. Ferrous metallurgy, No 1, p.p. 29-33.
4. Shevchenko K. N. *Zakon treniya pri prokatke i drugie zamechaniya. Teoriya prokatki . Materialyi konferentsii po teoreticheskim voprosam prokatki* [Law of friction when rolling and other comments. Theory of rolling. Proceedings of the conference on theoretical questions of rolling], Moscow, Metallurgy Press, 1962, p. p. 459-461.
5. Grudev A. P. *Vneshnee trenie pri prokatke* [External friction when rolling], Moscow, Metallurgy, 1973, 288 p.
6. Grudev A. P. *Teoriya prokatki* [Theory of rolling], Moscow, Metallurgy, 1988, 240 p.
7. Korolev A. A. *Novyie issledovaniya deformatsii metalla pri prokatke* [New study of metal deformation when rolling], Moscow, Mashgiz, 1953, 267 p.
8. Maksimenko O. P., Izmailov M. K., Loboyko D. I. Analysis of longitudinal stability of the rolling process considering the internal forces and the strip tension mode(2015), *Metallurgical and mining industry*, No 1, p.p. 59-62.
9. Vassilev Ya. D., Konovodov D. V., Dementienko A. V., Samokish D. N., Zavgorodniy M. I. Refinement of methods of calculating energy-power parameters of cold strip rolling with a large gradient of specific tensions(2010), Metals t*reatment under the pressure*, No 2(23), p.p. 190-194.