Friction in roller technological machines

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Abstract. The study is devoted to solving the problem of determining the patterns of friction stress distribution in the symmetric roll module contact zone. A mathematical model was developed that describes the patterns of friction stress distribution in the contact zone of roll modules. It was established that the ratio of friction stress to normal stress in the contact zone of roll modules is not constant and changes at each point of the contact zone. It was revealed that the ratio of friction stress to normal stress depends on external forces acting on the roll supports, geometric and kinematic parameters of the roll module, and deformation properties of the strip and roller coating.

1 Introduction

Roll modules, consisting of a pair of rollers and a processed material, are widely used in various technological machines. The intense impact of the rollers on the strip (of the processed material) in the contact zone helps to increase the efficiency of technological processes.

During the interaction in the roll module, in the contact zone, friction forces arise between the strip and the rollers, which have a great influence on the parameters of the technological process. This indicates the need for an in-depth study of the features and law of friction stress distribution in the contact zone of the roll module.

Quantitative measures of friction force are function $f(x)$ that relates friction stress $t(x)$ to normal stress $n(x)$ distributed in the contact zone (in the zone of strip deformation), according to the following formula [1]:

$$t(x) = f(x)n(x) \tag{1}$$

and the proportionality coefficient f connecting the friction force and the normal force by the Amonton-Coulomb law according to the following formula [2]:

$$T = fN. \tag{2}$$

Function $f(x)$ is called the “Friction Stress Model”, and the proportionality coefficient f is known as the coefficient of sliding friction (or coefficient of friction) [2].

Studies of models of friction stress and friction coefficient were mainly conducted by experimental and experimental-theoretical methods [3-20]. As a result of these studies, empirical formulas for the model of friction stress and friction coefficient were obtained.

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However, the creation of new and improvement of currently used roller technological machines cannot be limited to the use of empirical approaches. The development must be based on a theoretical foundation in the field of processing materials with roller machines, using the methods of Mechanics of Solids and the Theory of Contact Interaction [18].

Friction stresses in the contact zone of the roll module are generally determined using the sliding friction coefficient by Amonton's law (2), depending on the value of normal contact stresses:

$$t(x) = fn(x). \tag{3}$$

Condition (3) does not have sufficient physical substantiation; it is not experimentally confirmed and, naturally, it is not a law [20]. It can only be considered as an assumption, and theoretical solutions obtained using condition (3) are approximate, therefore, it does not provide high accuracy and reliability in predicting the parameters of the roll module [20].

References [21-27] are devoted to the study of friction stresses in roll modules of technological machines. However, the results of these publications do not reveal the patterns of friction stress distribution.

The goal of the work is to develop a friction stress model for roller modules, taking into account the kinematics of the contact zone, which will improve the accuracy of friction determination.

2 Materials and methods

The work is devoted to solving the problem of determining the patterns of friction stress distribution in the contact zone of a symmetrical roller module, consisting of a processed material with a thickness of δ_1 , two drive rolls with radii R .

Since we are considering a symmetrical roller module, we will therefore examine the friction stresses for the upper roller.

We divide the contact zone of the roller module relative to the line of centers into compression and recovery (deformation) zones. Suppose that in the contact zone, according to the kinematics, there are lagging and leading sliding zones, separated by a neutral point. In a two-roll module, the neutral point is located in the compression zone [23]. Then the contact zone consists of compression sections with lag slip 1, compression with leading slip 2 and recovery with leading slip 3 (Figure 1):

$$-\varphi_1 \le \theta_1 \le -\gamma, \quad -\gamma \le \theta_2 \le 0, \quad 0 \le \theta_3 \le \varphi_2, \tag{4}$$

where φ_1, φ_2 – are the contact angles, γ–is the neutral angle (in the zone of deformation of the strip).

When theoretically determining friction stresses in the contact zone, at least the influence of the friction coefficient, normal contact stresses, and sliding velocity must be considered.

Taking into account the above, for the theoretical determination of friction stresses in metal rolling, a friction stress model was proposed in the following form [20]:

- for the lag zone:

$$t_{0x} = -fn_{0x}\frac{h_0}{h_0 - h_\gamma}\left(\frac{h_\gamma}{h_x} - 1\right); \tag{5}$$

- for the advance zone:

$$t_{1x} = -fn_{1x}\frac{h_1}{h\gamma - h_1}\left(\frac{h_\gamma}{h_x} - 1\right), \tag{6}$$

where $t_{0x}, n_{0x}, t_{1x}, n_{1x}$ – are the values of friction stress and normal contact stress in the contact zone section under consideration, in the lag and advance zones, respectively;

h_x, h_γ – are the values of strip thickness in the considered and neutral sections of the contact zone; h_0, h_1 – are the values of the strip thickness in the sections of the entrance and exit from the contact zone, respectively; f – are the values of the friction coefficient.

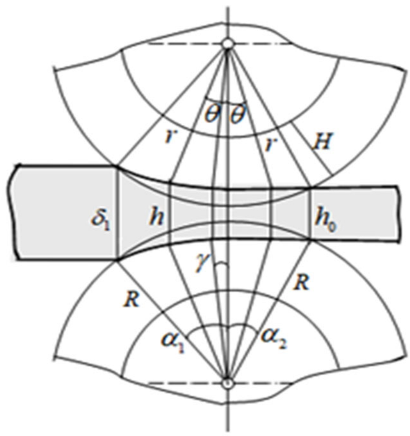

Fig. 1. Scheme of a roll module of technological machines.

3 Results and discussion

We rewrite equalities (5) in polar coordinates:

$$t(\theta) = -fn(\theta)\frac{\delta(-\phi_1)}{\delta(-\phi_1)-\delta(-\gamma)}\left(\frac{\delta(-\gamma)}{\delta(\theta)} - 1\right).$$

Then for section 1, we have

$$t(\theta) = -fn(\theta)\frac{\delta_1}{\delta_1-\delta(-\gamma)}\left(\frac{\delta(-\gamma)-\delta(\theta)}{\delta(\theta)}\right), -\phi_1 \le \theta \le -\gamma. \quad (7)$$

From Figure 1, it follows that

$$\delta(\theta) = K - 2R\cos\theta,\ -\varphi_1 \le \theta \le -\gamma, \quad (8)$$

where K – is the center distance of the rolls.

From here we find

$$\delta(\theta) = K - 2R\cos\gamma. \quad (9)$$

Substituting equalities (8) and (9) into equalities (7), we find

$$t(\theta) = fn(\theta)\frac{\delta_1(\cos\gamma - \cos\theta)}{(\cos\gamma - \cos\phi_1)(K-2R\cos\theta)},\ -\phi_1 \le \theta \le -\gamma. \quad (10)$$

Formula (10) describes the law of friction stress distribution in section 1 of the contact zone.

In section 2, the phenomena of compression and advance slip of the strip occur.

Therefore, first, from dependence (6), we obtain:

$$t(\theta) = -f_1 n(\theta)\frac{\delta(0)}{\delta(-\gamma)-\delta(0)}\left(\frac{\delta(-\gamma)-\delta(\theta)}{\delta(\theta)}\right),\ \ -\gamma \le \theta \le 0, \quad (11)$$

where $f_1 = -f(0)\ \ (0 \le f_1 \le f)$.

From equality (7), we have

$$\delta(\theta) = K - 2R\cos\theta,\ \ -\gamma \le \theta \le 0, \quad (12)$$

$$\delta(0) = K - 2R. \tag{13}$$

Substituting equalities (12) and (13) into equalities (11), we find

$$t(\theta) = -f_1 n(\theta)\frac{(K-2R)(\cos\theta - \cos\gamma)}{(1-\cos\gamma)(K-2R\cos\theta))}, \quad -\gamma \le \theta \le 0. \tag{14}$$

Formula (14) describes the law of friction stress distribution in section 2 of the contact curve zone.

In section 3, the phenomena of compression and advance slip of the strip occur.

Therefore, first, from dependence (6), we obtain:

$$t(\theta) = -n(\theta)\left(f_1 + (f - f_1)\frac{\delta_2}{\delta(0)-\delta_2}\left(\frac{\delta(0)-\delta(\theta)}{\delta(\theta)}\right)\right), \quad 0 \le \theta \le \varphi_2. \tag{15}$$

By analogy with equality (12) and (13), we obtain:

$$\delta(\theta) = K - 2R\cos\theta, \quad 0 \le \theta \le \varphi_2, \tag{16}$$

$$\delta(0) = K - 2R. \tag{17}$$

Substituting equalities (16) and (17) into equalities (15), we find

$$t(\theta) = -n(\theta)\left(f_1 + (f - f_1)\frac{\delta_2(1-\cos\theta)}{(1-\cos\varphi_2)(K-2R\cos\theta)}\right), \quad 0 \le \theta \le \varphi_2. \tag{18}$$

Formula (18) describes the law of friction stress distribution in section 3 of the contact zone.

Generalizing formulas (10), (15), and (18), we obtain

$$t(\theta) = n(\theta)\cdot\begin{cases} f\dfrac{\delta_1(\cos\theta - \cos\gamma)}{(\cos\gamma - \cos\varphi_1)(K-2R\cos\theta)}, & -\varphi_1 \le \theta \le -\gamma, \\ -f_1\dfrac{(K-2R)(\cos\theta) - \cos\gamma)}{(1-\cos\gamma)(K-2R\cos\theta)}, & -\gamma \le \theta \le 0, \\ -f_1 - (f-f_1)\dfrac{\delta_2(1-\cos\theta)}{(1-\cos\varphi_2)(K-2R\cos\theta)}, & 0 \le \theta \le \varphi_2. \end{cases} \tag{19}$$

Thus, a mathematical model was obtained that describes the patterns of friction stress distribution in the contact zone of roll modules of technological machines.

In formula (19), stresses $t(\theta)$ and $n(\theta)$ reflect the stresses acting on the strip at the points of the contact zone. At these points of the contact zone, there are also stresses $t_1(\theta)$ and $n_1(\theta)$, acting on the roller coating. According to Newton's law, stresses $t(\theta)$, $n(\theta)$ and $t_1(\theta)$, $n_1(\theta)$ are equal in magnitude and opposite in direction.

Previously, a mathematical model was obtained that describes the patterns of friction stress distribution $t_1(\theta)$ in the contact zone of roll modules of technological machines, which has the following form [24]:

$$t_1(\theta) = n_1(\theta)\begin{cases} tg(\theta + \xi), & -\varphi_1 \le \theta \le 0, \\ tg(\theta + \xi), & 0 \le \theta \le \varphi_2, \end{cases} \tag{20}$$

where $\xi = arctg\frac{F}{Q}$, $F-$ is the horizontal reaction of the roll supports, $Q-$is the pressure force of the roll clamping device.

At the neutral point, we have $t_1(-\gamma) = 0$, therefore, $tg(-\gamma+\xi) = 0$ or $tg(-\gamma) + tg\xi = 0$, since the values of $(-\gamma)$ and ξ are close to zero.

Then, we have

$$\gamma = tg\xi \ . \tag{21}$$

From equalities (19) and (20), we have

$$f_1 = \frac{t(0)}{n(0)} = \frac{t_1(0)}{n_1(0)}$$

or

$$f_1 = \frac{F}{Q}. \tag{22}$$

From equality (1) considering equalities (23) and (28), we find

$$f(\theta) = \begin{cases} f\dfrac{\delta_1(\cos\theta - \cos\gamma)}{(\cos\gamma - \cos\varphi_1)(K - 2R\cos\theta)}, & -\varphi_1 \le \theta \le -\gamma, \\ -\dfrac{F}{Q}\dfrac{(K-2R)(\cos\theta) - \cos\gamma)}{(1-\cos\gamma)(K-2R\cos\theta)}, & -\gamma \le \theta \le 0, \\ -\dfrac{F}{Q} - \left(f - \dfrac{F}{Q}\right)\dfrac{\delta_2(1-\cos\theta)}{(1-\cos\varphi_2)(K-2R\cos\theta)}, & 0 \le \theta \le \varphi_2 \end{cases} \tag{23}$$

From equality (23), it follows that the ratio of friction stress to normal stress in the contact zone of the roll modules of technological machines is not constant and changes at each point (angle) of the contact zone (Figure 2, therefore, in the roll modules of technological machines condition (4) is not fulfilled.

Analysis of formula (23) shows that the ratio of friction stress to normal stress depends on external forces acting on the roll supports, geometric and kinematic parameters of the roll module, and deformation properties of the strip and roller coating.

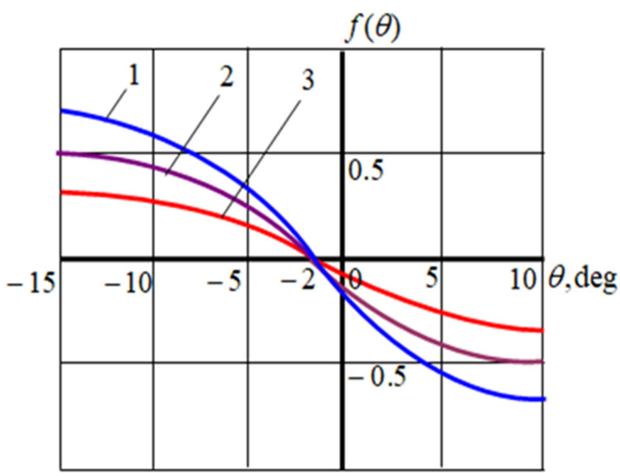

Fig. 2. Change in the ratio of friction stress to normal stress in the zone of contact: $1 - f = 0.74; -f = 0.5; 3 - f = 0.3$.

4 Conclusion

A mathematical model was developed that describes the patterns of friction stress distribution in the contact zone of roll modules of technological machines.

It was determined that the ratio of friction stress to normal stress in the contact zone of roll modules of technological machines is not constant, and changes at each point of the contact zone.

It was revealed that the ratio of friction stress to normal stress depends on external forces acting on the roll supports, geometric and kinematic parameters of the roll module, and deformation properties of the strip and roller coating.

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