Distribution of contact voltages in asymmetric two-roll module

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Abstract. Mathematical models of the regularities of the distribution of contact stresses in the generalized two-roll module in the case when the nature of the deformation of the material layer is specified by rheological models are obtained. New data on the regularities of the distribution of contact stresses are revealed: normal contact stresses change from zero at the beginning and at the end of the contact zone of the rolls to a maximum at a point lying to the left of the center line (towards the beginning of the contact of the rolls); the tangential contact stresses change their signs at the neutral point, which in the driven roll is located towards the entrance of the material layer into the contact zone of the rolls, and in the free one - towards the exit; during static interaction of the rolls with the material being processed, the point of maximum normal stresses and the neutral point are located on the center line.

1. Introduction

Twin roll modules are widely used in agricultural and construction machinery. Technological processes in two-roll modules are carried out as a result of contact interaction of the rolls with the processed material. Therefore, the main thing in improving the processing of agricultural and building materials in roller machines is to study the problems of contact interaction in two-roller modules. The theory of contact interaction should predict the shape of the contact area and the patterns of its growth with increasing load, as well as the magnitude and distribution of surface normal and tangential forces transmitted through the contact surfaces [1,2].

In determining the laws of distribution of contact forces, the main factor is the model of friction stresses, which takes into account the effect of friction in the contact zone of the rolls and connects the tangential and normal contact forces [2].

In many twin roll modules, the rolls have an elastic coating. In these twin roll modules, the rolls are immersed in the material to be processed until equilibrium is reached between the forces acting at the point of contact and the forces applied to the axis of the rolls. In this case, the forces applied to the axis of the rolls are transmitted to the workpiece material along curves, called roll contact curves. One of the main tasks in the theory of contact interaction of two-roll modules is mathematical modeling of roll contact curves, that is, obtaining analytical dependences describing the shapes of these curves.

The problems of contact interaction of a two-roll module mainly depend on the contact angles of the lower and upper rolls, since they determine the boundary conditions of these problems. Thus, the main tasks of the theory of contact interaction in two-roll modules are:

- determination of the contact angles of the rolls;
analytical description of the shape of the roll contact curves;
- modeling of friction stresses;
- an analytical description of the distribution patterns of normal and tangential contact forces.

Two-roll modules belong to the main working bodies of the roll machine or perform auxiliary functions. Therefore, in many machines, two-roll modules are asymmetric, that is, an asymmetric process of interaction of the material layer with the pairs of rolls occurs in them. In this case, several types of asymmetry are quite often realized simultaneously, for example, two types of geometric asymmetry (different diameters and inclination of the material layer relative to the horizontal), kinematic asymmetry (one drive roll, the other free) and tribological asymmetry (different coefficients of friction due to different coating material rolls). In this regard, the consideration of the above listed problems of the theory of contact interaction in asymmetric two-roll modules is of scientific interest today in the design and improvement of roll machines.

From the analysis of the literature [3-8], it follows that, despite the availability of extensive material on the study of contact interaction processes in roller machines, the theoretical foundations for solving contact interaction problems in asymmetric two-roll modules have not yet been developed enough. This applies to both plastic and elastic contact, especially when considering the models of friction stresses and deformation of elastic roll coatings.

Previously performed works [9-11] were devoted to the study of the first three of the above problems in the theory of contact interaction in asymmetric two-roll modules. This work is devoted to the study of the last (fourth) problem, that is, to an analytical description of the distribution patterns of normal and tangential contact forces. One of the factors used in the modeling of contact stresses is the deformation properties of the contacting bodies. The deformation properties of materials processed in two-roll modules, and materials used as roll coatings, are described either by empirical stress-relative deformation relationships, or by rheological models consisting of an elastic Hooke body, a viscous Newton body and a Saint-Venant plastic body.

In this work, we consider modeling the regularities of the distribution of contact stresses in the case when the nature of the deformation of the material layer is specified by rheological models.

2. Formulation of the problem

![Figure 1. Scheme of force interaction in a two-roll module](image)
The aim of the work is to simulate contact stresses in a symmetrical two-roll module. In this two-roll module the rolls are positioned relative to the vertical with an inclination to the right at an angle \( \beta \), have unequal diameters \( R_1 \neq R_2 \), and elastic coatings made of materials with various fluids and coefficients of friction \( f_1 \neq f_2 \), the lower shaft is driven, the upper one is free. The layer of material has a uniform thickness \( \delta_1 \) and is filed downward inclined relative to the line of centers at an angle \( \gamma_1 \) (figure 1).

Lower contact curve \( (i=1) \) roll (curve \( A_{11}A_{12} \)) consists of two sections \( A_{11}A_{13} \) \( (j=1) \) and \( A_{13}A_{12} \) \( (j=2) \). Location on \( A_{11}A_{13} \) compress interacting bodies, and on \( A_{13}A_{12} \) – recovery, where \( A_{13} \) – the point of the contact curve of the lower roll lying on the line of the roll centers. Point \( B_{11} \) plot \( A_{11}A_{13} \) defined by polar coordinates \( r_{11} \) and \( \theta_{11} \), but point \( B_{12} \) plot \( A_{11}A_{12} \) – \( r_{12} \) and \( \theta_{12} \). Agreeing with figure 1, \(-\phi_1 \leq \theta_1 \leq 0, \ 0 \leq \theta_2 \leq \phi_2 \), the \( \phi_1, \phi_2 \) – bottom roll contact angles.

The main models used in determining the regularities of the distribution of contact stresses are models of roll contact curves and friction stresses. In this work, we use the previously developed new models of roll contact curves and friction stresses in two-roll modules, taking into account their kinematic connections [14]. They look like:

1) bottom roll contact curve equations

\[
\begin{align*}
  r_{11} &= \frac{R_1}{1 + \lambda_{11}} \left( 1 + \lambda_{11} \frac{\cos(\phi_{11} - \gamma)}{\cos(\phi_{11} + \gamma)} \right), \\
  \gamma &= \gamma_1 \phi_{11}, \ -\phi_{11} \leq \theta_{11} \leq 0, \\
  r_{12} &= \frac{R_1}{1 + \lambda_{12}} \left( 1 + \lambda_{12} \frac{\cos(\phi_{12} + \gamma)}{\cos(\phi_{12} + \gamma)} \right), \\
  \gamma &= \gamma_2 \phi_{12}, \ 0 \leq \theta_{12} \leq \phi_{12},
\end{align*}
\]

where \( \lambda_{11} = \frac{d\theta_{11}}{dh}, \lambda_{12} = \frac{d\theta_{12}}{dh} \) – the ratio of the deformation rates, the surface layer of the lower roll and the processed material during compression and recovery;

2) top roll contact curve equations

\[
\begin{align*}
  r_{21} &= \frac{R_2}{1 + \lambda_{21}} \left( 1 + \lambda_{21} \frac{\cos(\phi_{21} + \gamma)}{\cos(\phi_{21} - \gamma)} \right), \\
  \gamma &= \gamma_2 \phi_{21}, \ -\phi_{21} \leq \theta_{21} \leq 0, \\
  r_{22} &= \frac{R_2}{1 + \lambda_{22}} \left( 1 + \lambda_{22} \frac{\cos(\phi_{22} + \gamma)}{\cos(\phi_{22} - \gamma)} \right), \\
  \gamma &= \gamma_2 \phi_{22}, \ 0 \leq \theta_{22} \leq \phi_{22},
\end{align*}
\]

where \( \lambda_{21} = \frac{d\theta_{21}}{dh}, \lambda_{22} = \frac{d\theta_{22}}{dh} \) – the ratio of the rates of deformation, the surface layer of the upper roll and the processed material during compression and recovery;

3) bottom roll friction stress model

\[
\begin{align*}
  t_{11} &= \left( \frac{Q_1 \cos \theta_{11} + F_1 \cos \theta_{11}}{\cos(\phi_{11} - \gamma)} \right) r_{11} - \left( \frac{Q_1 \cos \theta_{11} - F_1 \sin \theta_{11}}{\sin(\phi_{11} + \gamma)} \right) r_{11}, \ -\phi_{11} \leq \theta_{11} \leq 0, \\
  t_{12} &= \left( \frac{Q_1 \cos \theta_{12} + F_1 \cos \theta_{12}}{\cos(\phi_{12} + \gamma)} \right) r_{12} - \left( \frac{Q_1 \cos \theta_{12} - F_1 \sin \theta_{12}}{\sin(\phi_{12} - \gamma)} \right) r_{12}, \ 0 \leq \theta_{12} \leq \phi_{12},
\end{align*}
\]

where \( Q_1, F_1 \) – pressure force of pressure devices and horizontal reaction of the lower roll supports

4) friction stress model of the free top roll

\[
\begin{align*}
  t_{21} &= \left( \frac{Q_2 \sin \theta_{21} - F_2 \cos \theta_{21}}{\cos(\phi_{21} - \gamma)} \right) r_{21} - \left( \frac{Q_2 \cos \theta_{21} + F_2 \sin \theta_{21}}{\sin(\phi_{21} + \gamma)} \right) r_{21}, \ -\phi_{21} \leq \theta_{21} \leq 0, \\
  t_{22} &= \left( \frac{Q_2 \sin \theta_{22} - F_2 \cos \theta_{22}}{\cos(\phi_{22} + \gamma)} \right) r_{22} - \left( \frac{Q_2 \cos \theta_{22} + F_2 \sin \theta_{22}}{\sin(\phi_{22} - \gamma)} \right) r_{22}, \ 0 \leq \theta_{22} \leq \phi_{22},
\end{align*}
\]
where \( \bar{Q}_2, \bar{F}_2 \) — pressure force of pressure devices and horizontal reaction of the upper roll supports.

3. Analytical solution of the problem

In the compression section of the deformation zone, select an element with a length \( dl_{11} \) and directed along the line \( n - n \), since the deformation of the material layer occurs in this direction (Figure 1).

Elementary normal acts on the selected element of the material layer from the side of the lower roll \( dN_{11} \) and tangent \( dt_{11} \) forces and reactions of the cut off parts of the material layer. We neglect the forces of inertia and gravity of the selected layer element due to their smallness. Force components \( dN_{11} \) and \( dt_{11} \) towards \( n - n \) balanced by force \( \sigma' dl_{11} \) (Figure 1):

\[
\sigma'_{11} dl_{11} - dN_{11} \cos \theta - dt_{11} \sin \theta = 0
\]

or

\[
\sigma'_{11} = n_{11},
\]

where \( \sigma'_{11} \) — compressive stress of the material layer in the direction \( n - n \).

According to Figure 1, we have

\[
\sigma'_{11} = \sigma_{11} \cos \psi_{11},
\]

where \( \sigma_{11} \) — compression stresses of the material layer for the compression section of the lower roll in the radial direction to the roll axis.

Let the nature of the deformation of the material layer be given by the Kelvin-Voigt rheological models. Then we have

\[
\sigma_{11}' = E_i \epsilon_{11}' + \mu_i \frac{d\epsilon_{11}'}{dt}
\]

Figure 1 implies that

\[
\epsilon_{11}' = \frac{\sin(\varphi_{11} + \varphi_{21})}{2} \left( \frac{R_1 - R_{11} \cos(\varphi_{11} - \varphi)}{\cos(\theta_{11} + \varphi)} \right)
\]

or after substitution of the expression from the system of equations (1), we obtain

\[
\epsilon_{11}' = \frac{R_1 \sin(\varphi_{11} + \varphi_{21})}{(1 + \lambda_{11}) \delta_{11} \sin(\varphi_{21} - \varphi_{11})} \left( 1 - \frac{\cos(\varphi_{11} - \varphi)}{\cos(\theta_{11} + \varphi)} \right),
\]

or

\[
\epsilon_{11}' = A_{11} \left( 1 - \frac{\cos(\varphi_{11} - \varphi)}{\cos(\theta_{11} + \varphi)} \right),
\]

\[
A_{11} = \frac{R_1 \sin(\varphi_{11} + \varphi_{21})}{(1 + \lambda_{11}) \delta_{11} \sin(\varphi_{21} - \varphi_{11})}.
\]

From

\[
\frac{d\epsilon_{11}'}{dt} = -A_{11} \omega \frac{\cos(\varphi_{11} - \varphi)}{\cos(\theta_{11} + \varphi)} \tan(\theta_{11} + \varphi).
\]

From expression (7) taking into account expression (8), (9) and the assumption \( \tan^2 (\theta + \varphi_{11}) \approx 0 \), find

\[
\sigma_{11}' = A_{11} \left( 1 - \frac{\cos(\varphi_{11} - \varphi)}{\cos(\theta_{11} + \varphi)} \right) - \mu_i \omega \frac{\cos(\varphi_{11} - \varphi)}{\cos(\theta_{11} + \varphi)} \tan(\theta_{11} + \varphi).
\]

Expression (10) \( \sigma_{11}' \) reflects the compressive stress of the material layer in experiments. In fact, during contact \( \sigma_{11}' \) it reflects the compressive stress of the material layer in a real process: it is equal to zero at the beginning of the deformation zone, then it increases and reaches a value \( \sigma_{11\text{max}} \) on the center line. Therefore, we will assume that

\[
\sigma_{11}' = a_{11} \sigma_{11} + b_{11}, \quad -\varphi_{11} \leq \theta_{11} \leq 0.
\]

Odds \( a_{11} \) and \( b_{11} \) we find by the initial and boundary conditions:
when $\theta_{1i} = -\phi_{11}$, $\sigma_{1} = 0$; when $\theta_{1i} = 0$, $\sigma_{1i} = \sigma_{1\text{max}}$.

Substituting certain $a_{11}$ and $b_{11}$ coefficients into expressions (11), transforming it, and substituting the resulting expression $\sigma_{1i}'$ into equalities (5), we find the regularities of the distribution of normal stresses $I$ in the lower roll section

$$n_{11} = C_{11} \left( (E_{1} - \mu_{1} \omega_{1} \cos(\phi_{11} + \gamma_{1}))) \frac{\cos(\phi_{11} - \gamma_{1})}{\cos(\theta_{11} + \gamma)} (E_{1} + \mu_{1} \omega_{1} \cos(\theta_{11} + \gamma)) \right),$$

where

$$C_{11} = \frac{\sigma_{1\text{max}}}{E_{1}(1 - \cos \phi_{11}) - \mu_{1} \omega_{1} \cos(\phi_{11} + \gamma_{1})}.$$  

Regularities of the distribution of normal stresses for the site II the bottom roll, as well as in areas $I$ and $II$ the upper roll is determined in the same way.

They look like:

$$n_{12} = C_{12} \left( (E_{1} + \mu_{1} \omega_{1} \cos(\phi_{12} + \gamma_{2}))) \frac{\cos(\phi_{12} + \gamma)}{\cos(\theta_{12} + \gamma)} (E_{1} + \mu_{1} \omega_{1} \cos(\theta_{12} + \gamma)) \right),$$

where

$$C_{12} = \frac{\sigma_{1\text{max}}}{E_{1}(1 - \cos \phi_{12}) + \mu_{1} \omega_{1} \cos(\phi_{12} + \gamma_{2})};$$

$$n_{21} = C_{21} \left( (E_{2} - \mu_{2} \omega_{2} \cos(\phi_{21} + \gamma_{1}))) \frac{\cos(\phi_{21} + \gamma)}{\cos(\theta_{21} - \gamma)} (E_{2} + \mu_{2} \omega_{2} \cos(\theta_{21} - \gamma)) \right),$$

where

$$C_{21} = \frac{\sigma_{2\text{max}}}{E_{2}(1 - \cos \phi_{21}) - \mu_{2} \omega_{2} \cos(\phi_{21} + \gamma_{1})};$$

$$n_{22} = C_{22} \left( (E_{2} + \mu_{2} \omega_{2} \cos(\phi_{22} + \gamma_{2}))) \frac{\cos(\phi_{22} + \gamma)}{\cos(\theta_{22} - \gamma)} (E_{2} + \mu_{2} \omega_{2} \cos(\theta_{22} - \gamma)) \right),$$

where

$$C_{22} = \frac{\sigma_{2\text{max}}}{E_{2}(1 - \cos \phi_{22}) + \mu_{2} \omega_{2} \cos(\phi_{22} + \gamma_{2})}.$$  

From the system of equations (1) we have

$$r_{11} = \frac{R_{i}}{1 + \lambda_{11}} \left[ 1 + \lambda_{11} \frac{\cos(\phi_{11} - \gamma)}{\cos(\theta_{11} + \gamma)} \right], \quad \gamma = \frac{\gamma_{i}}{\phi_{11}}, \quad -\phi_{11} \leq \theta_{11} \leq 0.$$  

$$r_{11}' = \frac{\lambda_{11} R_{i}}{1 + \lambda_{11}} \left( \frac{\sin(\phi_{11} + \theta_{11})}{\cos^{2}(\theta_{11} + \gamma)} + \frac{\cos(\phi_{11} - \gamma)}{\cos(\theta_{11} + \gamma)} \frac{\cos(\phi_{11} - \gamma)}{\cos(\theta_{11} + \gamma)} \right).$$  

Calculations using this formula indicate that the value of the first term of the bracket can be neglected, giving the formula for determining a simpler form

$$r_{11}' = \frac{\lambda_{11} R_{i}}{1 + \lambda_{11}} \frac{\cos(\phi_{11} - \gamma)}{\cos(\theta_{11} + \gamma)} \frac{\cos(\phi_{11} - \gamma)}{\cos(\theta_{11} + \gamma)} \frac{\cos(\phi_{11} - \gamma)}{\cos(\theta_{11} + \gamma)} \frac{\cos(\phi_{11} - \gamma)}{\cos(\theta_{11} + \gamma)}.$$

We transform the first formula of system (1) taking into account the expression $tg \psi_{11} = \frac{R_{i}}{1 + \lambda_{11}}$ and

$$tg \xi_{1} = \frac{F_{i}}{Q_{1}}$$

$$t_{11} = tg(\theta_{11} - \psi_{11} + \xi_{1})n_{11}.$$  

Similarly, we transform the models of friction stresses $t_{12}$, $t_{21}$, $t_{22}$. Generalizing them, we have

$$t_{11} = tg(\theta_{11} - \psi_{11} + \xi_{1})n_{11}, \quad \phi_{11} \leq \theta_{11} \leq 0,$$

$$t_{12} = tg(\theta_{12} - \psi_{12} + \xi_{1})n_{12}, \quad 0 \leq \theta_{12} \leq \phi_{12},$$  

$$t_{21} = tg(\theta_{21} - \psi_{21} + \xi_{1})n_{21},$$  

$$t_{22} = tg(\theta_{22} - \psi_{22} + \xi_{1})n_{22}.$$  

$$t_{12} = tg(\theta_{12} - \psi_{12} + \xi_{1})n_{12},$$  

$$t_{22} = tg(\theta_{22} - \psi_{22} + \xi_{1})n_{22}.$$
\[
\begin{aligned}
  t_{21} &= -\tan(\theta_{21} - \psi_{21} - \xi_2)n_{21}, \quad -\varphi_{21} \leq \theta_{21} \leq 0, \\
  t_{22} &= -\tan(\theta_{22} - \psi_{22} - \xi_2)n_{22}, \quad 0 \leq \theta_{22} \leq \varphi_{22},
\end{aligned}
\]

where \( \xi_2 = \arctg \frac{F_2}{Q_2} \).

From the system of equations (16) and (17), taking into account expressions (12) - (15), we find the regularities of the distribution of shear stresses.

They look like

\[
t_{11} = C_{11} \left( (E_1 - \mu_1 \omega_1 \tan(\varphi_{11} + \gamma_1)) - \frac{\cos(\varphi_{11} - \gamma)}{\cos(\theta_{11} + \gamma)} (E_1 + \mu_1 \omega_1 \tan(\theta_{11} + \gamma)) \right) \times \tan(\theta_{11} - \psi_{11} + \xi_1),
\]

where

\[
C_{11} = \frac{\sigma_{11}}{E_1(1 - \cos(\varphi_{11})) - \mu_1 \omega_1 \tan(\varphi_{11} + \gamma_1)}; \quad \psi_{11} = \arctg \frac{\lambda_{11} \cos(\varphi_{11} - \gamma) \tan(\theta_{11} + \gamma)}{\cos(\theta_{11} + \gamma) + \lambda_{11} \cos(\varphi_{11} - \gamma)};
\]

\[
t_{12} = C_{12} \left( (E_1 + \mu_1 \omega_1 \tan(\varphi_{21} + \gamma_2)) - \frac{\cos(\varphi_{21} + \gamma)}{\cos(\theta_{21} + \gamma)} (E_1 + \mu_1 \omega_1 \tan(\theta_{21} + \gamma)) \right) \times \tan(\theta_{12} - \psi_{12} + \xi_1),
\]

where

\[
C_{12} = \frac{\sigma_{12}}{E_1(1 - \cos(\varphi_{21})) + \mu_1 \omega_1 \tan(\varphi_{21} + \gamma_2)}; \quad \psi_{12} = \arctg \frac{\lambda_{12} \cos(\varphi_{21} + \gamma) \tan(\theta_{21} + \gamma)}{\cos(\theta_{21} + \gamma) + \lambda_{12} \cos(\varphi_{21} + \gamma)};
\]

\[
t_{21} = -C_{21} \left( (E_2 - \mu_2 \omega_2 \tan(\varphi_{21} + \gamma_1)) - \frac{\cos(\varphi_{21} + \gamma)}{\cos(\theta_{21} - \gamma)} (E_2 + \mu_2 \omega_2 \tan(\theta_{21} - \gamma)) \right) \times \tan(\theta_{21} - \psi_{21} - \xi_2),
\]

where

\[
C_{21} = \frac{\sigma_{21}}{E_2(1 - \cos(\varphi_{21})) - \mu_2 \omega_2 \tan(\varphi_{21} + \gamma_1)}; \quad \psi_{21} = \arctg \frac{\lambda_{21} \cos(\varphi_{21} + \gamma) \tan(\theta_{21} - \gamma)}{\cos(\theta_{21} - \gamma) + \lambda_{21} \cos(\varphi_{21} + \gamma)};
\]

\[
t_{22} = -C_{22} \left( (E_2 + \mu_2 \omega_2 \tan(\varphi_{22} - \gamma_2)) - \frac{\cos(\varphi_{22} - \gamma)}{\cos(\theta_{22} - \gamma)} (E_2 + \mu_2 \omega_2 \tan(\theta_{22} - \gamma)) \right) \times \tan(\theta_{22} - \psi_{22} + \xi_2),
\]

where

\[
C_{22} = \frac{\sigma_{22}}{E_2(1 - \cos(\varphi_{22})) + \mu_2 \omega_2 \tan(\varphi_{22} - \gamma_2)}; \quad \psi_{22} = \arctg \frac{\lambda_{22} \cos(\varphi_{22} - \gamma) \tan(\theta_{22} - \gamma)}{\cos(\theta_{22} - \gamma) + \lambda_{22} \cos(\varphi_{22} - \gamma)}.
\]

We now consider a two-roll module with two driven rolls. In this two-roll module, the distribution patterns of the shear stresses of the upper rolls are defined as the bottom roll, that is, they have the form

\[
t_{21} = C_{21} \left( (E_2 - \mu_2 \omega_2 \tan(\varphi_{21} + \gamma_1)) - \frac{\cos(\varphi_{21} + \gamma)}{\cos(\theta_{21} - \gamma)} (E_2 + \mu_2 \omega_2 \tan(\theta_{21} - \gamma)) \right) \times \tan(\theta_{21} - \psi_{21} + \xi_2); (24)
\]

\[
t_{22} = C_{22} \left( (E_2 + \mu_2 \omega_2 \tan(\varphi_{22} - \gamma_2)) - \frac{\cos(\varphi_{22} - \gamma)}{\cos(\theta_{22} - \gamma)} (E_2 + \mu_2 \omega_2 \tan(\theta_{22} - \gamma)) \right) \times \tan(\theta_{22} - \psi_{22} - \xi_2). (25)
\]

Thus, formulas have been obtained that determine the regularities of the distribution of contact stresses in a two-roll module, when the deformation of the material layer is given by empirical formulas:

- (12) - (15) - patterns of distribution of normal stresses;
- (18), (19), (24) and (25) - regularities in the distribution of shear stresses when both rolls of the two-roll module are driven;
- (18), (19), (22) and (23) - the regularities of the distribution of shear stresses, when in the two-roll module the upper roll is free and the lower one is driven.
The analysis of the obtained mathematical models shows that the regularities of the distribution of contact stresses in the two-roll module depend on the coefficients of friction of the material layer on the contact surface of the rolls, the geometric, kinematic and deformation parameters of the contacting bodies, as well as on the forces acting on the roll supports.

For a visual representation of the nature of the influence of these factors on normal and tangential contact stresses, Figures 2-5 show their diagrams with some changing parameters.

4. Conclusion

1. The analysis of the calculated data on the obtained models indicates that the normal and tangential contact stresses over the contact surface of the rolls are distributed unevenly:
   - normal contact stresses change from zero at the beginning and at the end of the contact zone of the rolls to a maximum at a point lying to the left of the center line (towards the beginning of the contact of the rolls);
   - the tangential contact stresses change their signs at the neutral point, which in the driven roll is located towards the entrance of the material layer into the contact zone of the rolls, and in the free one - towards the exit.
2. Based on the analysis of the distribution diagrams of contact stresses, the following were revealed:

- with an increase in the hardening factor of the material being processed, the maximum value of the normal stress increases. The larger this coefficient, the more the point of maximum normal stresses is removed from the center line towards the entrance of the material layer into the contact zone of the rolls;

- the maximum value and the maximum point of the diagram of the distribution of normal stresses at different values of the angle of inclination of the processed material relative to the line of centers has different meanings: for example $\gamma = 5^\circ$, in their values less than $\gamma = 0^\circ$, and in $\gamma = 10^\circ$ - more;

- the coefficient $C = \frac{F}{Q}$ has a significant effect on the shear stress distribution diagram. The larger this coefficient, the more to the left (to the right) in the driven (free) roll from the center line the neutral point. An increase in the coefficient $C$ will lead to an increase in positive shear stresses;

- the coefficient $C$ does not affect the diagrams of the distribution of normal stresses both in the driven roll and in the free roll;

- with a decrease in the radii of the rolls, with other parameters being the same, the maximum normal and shear stresses increase;

- at lower initial thicknesses of the material layer, an increase in normal stresses from zero to a maximum value and a decrease from a maximum value to zero occurs faster than with large initial thicknesses of the material layer;

- with static interaction of the rolls with the material being processed, the point of maximum normal stresses and the neutral point are located on the center line.

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