To the development of the theory of contact interaction in two-roll modules

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Abstract. The results of the study of the stress-strain state in a two-roll module are presented. The angles that determine the characteristic points of the physical model of the roll contact curves are defined for the case when the strain properties of the material layer and elastic roll coatings are given by power dependences. Formulas are derived for calculating the angles of entering and exit, the angles separating the no-slip zones from the lag and advance slip zones, neutral angles and angles of maximum normal stresses of the two-roll module. It was stated that an increase in the friction coefficient of the roll with the material being processed leads to a decrease in the percentage of slip zones in the contact curve in the driven roll. It was revealed that with an increase in the dynamic coefficient, the slip lag zone decreases, and the advance slip zone increases. It was determined that the faster the feeding rate of the material layer, the greater the percentage of the no-slip zone in the roll contact curve. It was revealed that in the driven roll the neutral angle is inclined towards the entrance of the material layer into the contact zone of the rolls.

1. Introduction
Technological processes in two-roll modules are performed as a result of the contact interaction of the rolls with the processed material.

In the theory of contact interaction of two-roll modules, the following main tasks are solved.
1. Determination and assessment of contact angles (angles of entering and exit) of the lower and upper rolls. These angles are the main quantities that determine the boundary conditions for contact interaction problems.
2. Analytical description of the shape of the curves of the roll contact. These curves are important when simulating contact stresses in two-roll modules with elastic coated rolls.
3. Determination of friction stress models. These models establish a relation between normal and shear contact stresses.
4. Modeling the distribution patterns of normal and tangential contact stresses. The nature of the distribution of these stresses determines the power parameters and technological efficiency of two-roll modules.

On the basis of a comprehensive study of the phenomenon of contact interaction in two-roll modules [1-7], the main problems of the theory of contact interaction of two-roll modules were solved and the following theoretical results were obtained.
1. A generalized model of two-roll modules was developed [1]; by changing its parameters a two-roll module of an arbitrary type was obtained.
2. Analytical expressions for contact angles and conditions for evaluating these angles were constructed for the following cases: when both rolls are driven in a two-roll module; when the upper roll is free in a two-roll module, and when the lower roll is driven [2].
3. Roll contact curves are simulated for the following cases: when the deformation of the contacting bodies is given by empirical formulas or by rheological models [3, 4].

4. Models of friction stresses in two-roll modules were developed, and a relation between the forces acting on each roll of a two-roll module and the stresses distributed under the influence of these forces were established both in the slip and no-slip zones [5].

5. Mathematical models of the distribution pattern of contact stresses in the two-roll module were developed, which take into account all the main parameters of the two-roll modules [6, 7].

In two-roll modules, the contact stresses are distributed along the contact curves of the rolls. The characteristic points of these distributions (for example, the neutral point) are located on the roll contact curves. The roll contact curve containing such characteristic points of the stress-strain state in a two-roll module is called a physical model of the roll contact curve.

To further develop the theory of contact interaction in two-roll modules, we investigate a physical model of a two-roll module.

Consider a two-roll module, in which the rolls are located relative to the vertical line 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 different stiffness and friction coefficients ($f_1 \neq f_2$), both rolls are driven. The layer of material has a uniform thickness $\delta_1$ and is fed downward relative to the line of centers at an angle $\gamma_1$ (Figure 1).

The characteristic points of the physical model are determined by the geometrical, kinematic, and force conditions of the stress-strain state in the two-roll module.

Geometrical conditions in the steady-state interaction mode determine such characteristic points of the physical model as the starting point, the end point and the center line point (the point of the roll contact curve lying on the center line). In this case, a simultaneous compression of the contacting bodies occurs between the starting point and the center line point of the physical model, and their recovery occurs between the center line point and the end point.

Among the kinematic conditions, a phenomenon of slip in the zones of roll contact is the most affecting on the characteristic points of the physical model. In general, in the zone of roll contact, there are three zones that differ in kinematics – the lag slip zone, the no-slip zone, and the advance slip zone [8, 9]. These zones of roll contact curves are separated in the physical model by two characteristic points.

The force conditions define two characteristic points of the physical model: the first is the point at which the tangential contact stresses change signs; the second is the point at which the normal contact stress has a maximum value.

The point at which the tangential contact stresses change signs is called a neutral point. The neutral point is in the no-slip zone. The position of the neutral point in the no-slip zone depends on the kinematic relation in the two-roll module. In the driven roll, it is inclined towards the entrance of the material layer into the contact zone of the rolls, that is, to the left of the centerline point [10].

The point at which the normal contact stresses reach its maximum value in the dynamic contact is to the left of this point [7].
Thus, seven characteristic points of the physical model of the i-roll contact curve were identified:

- $A_i$ - a starting point;
- $A_{i2}$ - an end point;
- $A_{i3}$ - a center line point;
- $A_{i4}$ - a point dividing the lag slip and the no-slip zones;
- $A_{i5}$ - a point dividing the no-slip and the advance slip zones;
- $A_{i6}$ - a neutral point;
- $A_{i7}$ - a point of the maximum of normal stresses.

Figure 1 shows a scheme of a two-roll module with an indication of the physical models of the roll contact curves, where $\varphi_{ij}$ is the polar angle defining the point $A_{ij}$, $i = 1, 2, j = 1, 7$.

The angles that determine the characteristic points of the physical model of the roll contact curves are their main indices. The positions of the characteristic points primarily depend on the deformation properties of the contacting bodies. The deformation properties of contacting bodies in two-roll modules are described either by empirical dependencies or by rheological models [3].

The study is devoted to the determination of the main indices (angles that define characteristic points) of the physical model of the roll contact curves when the deformation nature of the contacting bodies is given by empirical power dependencies.

2. Theoretical study of the problem

The first three of the seven indices are defined in [2], based on the analysis of geometrical conditions. For the considered two-roll module (Figure 1) they have the form:

$$\varphi_{11} = \frac{R_2(v_{11} + v_{21}) + \delta_1\gamma_1}{R_1 + R_2}, \quad \varphi_{12} = \frac{R_2(v_{12} + v_{22}) + \delta_2\gamma_2}{R_1 + R_2}, \quad \varphi_{13} = 0,\quad (1)$$

$$\varphi_{21} = \frac{R_2(v_{11} + v_{21}) - \delta_1\gamma_1}{R_1 + R_2}, \quad \varphi_{22} = \frac{R_2(v_{12} + v_{22}) - \delta_2\gamma_2}{R_1 + R_2}, \quad \varphi_{23} = 0,\quad (2)$$

$\varphi_{11}, \varphi_{12}, \varphi_{13}$ - are the angles defining points $A_{11}, A_{12}, A_{13}$, respectively; $\varphi_{21}, \varphi_{22}, \varphi_{23}$ - are the angles defining points $A_{21}, A_{22}, A_{23}$, respectively; $v_{11}, v_{12}$ - are the angles of friction at the starting and ending points of the contact curve of the lower roll in the steady state of interaction; $v_{21}, v_{22}$ - are the angles of friction at the starting and ending points of the contact curve of the upper roll in the steady state of interaction.

To determine angles $\varphi_{14}$ and $\varphi_{15}$ (and, accordingly, $\varphi_{24}$ and $\varphi_{25}$), we use the previously developed models of roll contact curves and friction stresses. For the lower roll of the two-roll module under consideration, they have the form [4, 5]:

1) contact curve equations

$$\begin{align*}
    r_{11} &= \frac{R_1}{1 + k_1\Lambda_{11}} \left(1 + k_1\Lambda_{11} \frac{\cos(\varphi_{11} - \gamma)}{\cos(\theta_{11} + \gamma)}\right), \\
    r_{12} &= \frac{R_1}{1 + k_2\Lambda_{12}} \left(1 + k_2\Lambda_{12} \frac{\cos(\varphi_{12} + \gamma)}{\cos(\theta_{12} + \gamma)}\right).
\end{align*}\quad (3)$$

where $k_{11} = \frac{n_{11}}{m_1}$, $\Lambda_{11} = \frac{dr_{11}}{dh_1}$, $k_{12} = \frac{n_{12}}{m_2}$, $\Lambda_{12} = \frac{dr_{12}}{dh_2}$ - is the strain rate relation of the surface layer of the lower roll and the processed material under compression and recovery;

2) model of friction stress of the lower roll

$$\begin{align*}
    t_{11} &= \tan(\theta_{11} - \psi_{11} + \xi_1)n_{11}, \quad -\varphi_{11} \leq \theta_{11} \leq 0, \\
    t_{12} &= \tan(\theta_{12} - \psi_{12} + \xi_1)n_{12}, \quad 0 \leq \theta_{12} \leq \varphi_{12},
\end{align*}\quad (4)$$
where \( \xi = \arctg C, \quad C = \frac{F}{Q} \) – is the dynamic coefficient of the upper roll [7], \( \dot{Q}, \ddot{F} \) – are the pressure force of the pressing devices and the horizontal reaction of the lower roll supports.

Model (4) establishes a relation between external forces and stresses, both in the slip zones and in the no-slip zone [5]. In addition, refined models of friction stresses for the slip zone were proposed in [9]:

for the lag slip zone:

\[
\tau_{0x} = -f n_{0x} \frac{v_{ck0x}}{|v_{ck0}|};
\]

(5)

for the advance slip zone

\[
\tau_{1x} = -f n_{1x} \frac{v_{ck1x}}{|v_{ck1}|},
\]

(6)

where \( \tau_{0x}, v_{ck0x}, n_{0x}, \tau_{1x}, v_{ck1x}, n_{1x} \) – are the values of the tangential stress, slip speed and normal stress at the considered point of the contact zone of the rolls in the lag slip and advance slip zones, respectively; the sign (−) in models (5) and (6) indicates that the vectors \( \tau_{0x} \) and \( v_{ck0x} \), \( \tau_{1x} \) and \( v_{ck1x} \) are directed in opposite sides.

Formulas (5) and (6) for the lower roll of the considered two-roll module are written as:

\[
\tau_{11} = -f_{11} n_{11} \frac{v_{ck} (\theta_{11})}{|v_{ck} (-\theta_{11})|}, \quad -\phi_{11} \leq \theta_{11} \leq -\phi_{14},
\]

(7)

where \( f_{11} \) – is the coefficient of friction in the lag slip zone of the lower roll, \( \tau_{11}, v_{ck} (\theta_{11}), n_{11} \) – are the values of the shear stress, slip speed and normal stress at the point determined by angle \( \theta_{11} \);

\[
\tau_{12} = -f_{12} n_{12} \frac{v_{ck} (\theta_{12})}{|v_{ck} (\phi_{12})|}, \quad \phi_{13} \leq \theta_{12} \leq \phi_{12},
\]

(8)

where \( f_{12} \) – is the coefficient of friction in the advance zone of the lower roll, \( \tau_{12}, v_{ck} (\theta_{12}), n_{12} \) – are the values of the shear stress, slip speed and normal stress at the point determined by angle \( \theta_{12} \).

Let us select an elementary arc \( dl_{11} \) equal in absolute value to \( dl_{11} = \sqrt{r_{11}^2 + r_{11}^{'2}} \) \( d\theta_{11} \) from the lag zone of the physical model of the lower roll. Let us take an arbitrary point \( B_{11}, \dot{B}_{11}, \ddot{B}_{11} \) on this arc (Figure 1). At this point, two homogeneous points are aligned, from which \( B_{11} \) belongs to the elastic coating of the roll, and \( \dot{B}_{11}, \ddot{B}_{11} \) – belongs to the layer of material. The absolute speed of a point \( \dot{B}_{11} \) is shown as vector \( \dot{v}_{1} \). It is perpendicular to the radius \( OB_{11} = n_{11} \), and is \( v_{1} = \omega_{1} \sqrt{r_{11}^2 + r_{11}^{'2}} \), where \( \omega_{1} \) – is the angular speed of the lower roll.

The value of the relative speed of material lag along the surface of the lower roll \( v_{12} \) is equal to the difference between the absolute speeds \( v_{1} \) and \( v_{2} \), where \( \ddot{v}_{2} \) – is the vector of the absolute speed of point \( \dot{B}_{11} \).

In the presence of contact, the absolute speed of point \( \dot{B}_{11} \) can be directed only tangentially to the contact surface of the roll [7]. Therefore, the direction of vector \( \dot{v}_{2} \) is the same as the direction of vector \( \dot{v}_{1} \), and, so, it can be written as \( v_{ck} (\theta_{11}) = v_{2} - v_{1} \). Having determined the absolute speed of point \( \dot{B}_{11} \) through the speed of the material layer \( v_{u} \) and substituting \( v_{1} \) and \( v_{2} \) into this expression,
we obtain

\[ v_{ck}(\theta_{11}) = \omega_1 \sqrt{r_{11}^2 + r_{11}^2} - v_m \cos(\theta_{11} - \psi_{11} + \gamma), \quad \gamma = \frac{\gamma_1}{\phi_{11}}, \quad -\varphi_{11} \leq \theta_{11} \leq -\varphi_{14}. \]  

(9)

Hence

\[ v_{ck}(-\varphi_{11}) = \omega_1 R_1 - v_m \cos(\varphi_{11} - \gamma_1). \]  

(10)

We differentiate the first equation of system (3)

\[ r_{11}' = \frac{k_1 \lambda_{11} R_1}{1 + k_1 \lambda_{11}} \left( \frac{\sin(\varphi_{11} + \theta_{11})}{\cos^2(\theta_{11} + \gamma)} + \frac{\cos(\varphi_{11} - \gamma)}{\cos(\theta_{11} + \gamma)} \right). \]  

Calculations using this formula indicate that the value of the first term in the brackets can be ignored, giving the formula for determining \( r_{11}' \) a simpler form

\[ r_{11}' = \frac{k_1 \lambda_{11} R_1}{1 + k_1 \lambda_{11}} \cos(\varphi_{11} - \gamma) \cos(\theta_{11} + \gamma). \]  

(11)

Let us define \( r_{11}(-\varphi_{14}) \) and \( r_{11}'(-\varphi_{14}) \) by formulas (3) and (11). Assuming that \( \sin \varphi_{14} \approx \varphi_{14}, \cos \varphi_{14} \approx 1 \), we have

\[ r_{11}(-\varphi_{14}) = \frac{R_1}{1 + k_1 \lambda_{11} \cos \varphi_{11}}, \quad r_{11}'(-\varphi_{14}) = -\frac{k_1 \lambda_{11} R_1 \cos \varphi_{11}}{1 + k_1 \lambda_{11}}. \]

Substituting the values of \( r_{11}(-\varphi_{14}) \) and \( r_{11}'(-\varphi_{14}) \) into formula (9), we obtain

\[ v_{ck}(-\varphi_{14}) = \omega_1 R_1(1 + k_1 \lambda_{11} \cos \varphi_{11}) - v_m (1 + k_1 \lambda_{11}). \]  

(12)

From equation (7) we have

\[ \frac{t_{11}(-\varphi_{14})}{n_{11}(-\varphi_{14})} = \frac{f_{11} v_{ck}(-\varphi_{14})}{v_{ck}(-\varphi_{11})}. \]  

(13)

or, taking into account equations (10) and (12)

\[ \frac{t_{11}(-\varphi_{14})}{n_{11}(-\varphi_{14})} = \frac{f_{11} \omega_1 (1 + k_1 \lambda_{11} \cos \varphi_{11}) - v_m (1 + k_1 \lambda_{11})}{(1 + k_1 \lambda_{11})(\omega_1 R_1 - v_m \cos(\varphi_{11} - \gamma_1))}. \]  

(14)

On the other hand, from the first equation of system (4) it follows that

\[ \frac{t_{11}(-\varphi_{14})}{n_{11}(-\varphi_{14})} = \tan(\varphi_{14} - \psi_{11}(-\varphi_{14}) + \xi_{11}). \]  

(15)

Taking into account the values of \( r_{11}(-\varphi_{14}), r_{11}'(-\varphi_{14}) \), and assumptions \( \sin \varphi_{14} \approx \varphi_{14}, \cos \varphi_{14} \approx 1, \varphi_{14} \cdot \xi_{11} \approx 0 \), we obtain the following sequences of expressions

\[ \tan \psi_{11}(-\varphi_{14}) = -\frac{k_1 \lambda_{11} \cos \varphi_{11}}{1 + k_1 \lambda_{11} \cos \varphi_{11}} \varphi_{14}, \]

\[ \tan(-\varphi_{14} - \psi_{11}(-\varphi_{14})) \approx \tan(-\varphi_{14}) - \tan \psi_{11}(-\varphi_{14}) = -\frac{\varphi_{14}}{1 + k_1 \lambda_{11} \cos \varphi_{11}}. \]
\[ \tan(-\varphi_{14} - \psi_{11}(-\varphi_{14}) + \xi_1) \approx \tan(-\varphi_{14} - \psi_{11}(-\varphi_{14})) + \tan \xi_1 = \]
\[ = - \frac{Q_1 \varphi_{14} - F_1 (1 + k_{11} \lambda_{11} \cos \varphi_{11})}{Q_1 (1 + k_{11} \lambda_{11} \cos \varphi_{11})}. \]

Taking into account the last expression from equation (15) we have
\[ \frac{t_{11}(-\varphi_{14})}{n_{11}(-\varphi_{14})} = - \frac{Q_1 \varphi_{14} - F_1 (1 + k_{11} \lambda_{11} \cos \varphi_{11})}{Q_1 (1 + k_{11} \lambda_{11} \cos \varphi_{11})}. \] (16)

Equating the right-hand sides of equations (14) and (16) and considering expressions (10) and (12), we have
\[ \varphi_{14} = \frac{(1 + k_{11} \lambda_{11} \cos \varphi_{11}) f_{11} Q_1 (\omega_1 R_1 (1 + k_{11} \lambda_{11} \cos \varphi_{11}) - v_m (1 + k_{11} \lambda_{11}))}{Q_1 (1 + k_{11} \lambda_{11})(\omega_1 R_1 - v_m \cos(\varphi_{11} - \gamma_1))}
+ \frac{F_1 (1 + k_{11} \lambda_{11} \cos \varphi_{11})(1 + k_{11} \lambda_{11})(\omega_1 R_1 - v_m \cos(\varphi_{11} - \gamma_1))}{Q_1 (1 + k_{11} \lambda_{11})(\omega_1 R_1 - v_m \cos(\varphi_{11} - \gamma_1))}. \] (17)

Angle \( \varphi_{15} \) is determined in a similar way:
\[ \varphi_{15} = \frac{(1 + k_{12} \lambda_{12} \cos \varphi_{12}) f_{11} Q_1 (\omega_1 R_1 (1 + k_{12} \lambda_{12} \cos \varphi_{12}) - v_m (1 + k_{12} \lambda_{12}))}{Q_1 (1 + k_{12} \lambda_{12})(\omega_1 R_1 - v_m \cos(\varphi_{12} + \gamma_2))}
- \frac{F_1 (1 + k_{12} \lambda_{12} \cos \varphi_{12})(1 + k_{12} \lambda_{12})(\omega_1 R_1 - v_m \cos(\varphi_{12} + \gamma_2))}{Q_1 (1 + k_{12} \lambda_{12})(\omega_1 R_1 - v_m \cos(\varphi_{12} + \gamma_2))}. \] (18)

Angles \( (-\varphi_{14}) \) and \( \varphi_{15} \), defined by expressions (17) and (18), make it possible to determine the position of the characteristic points \( A_{14} \) and \( A_{15} \), which separate the no-slip zones from the lag slip and advance slip zones.

The remaining two angles \( \varphi_{16} \) and \( \varphi_{17} \) of seven angles of the physical model of the lower roll contact curve are determined by the force conditions. They have the form [7]:
\[ \varphi_{16} = \frac{F_1 (1 + k_{12} \lambda_{11} \cos \varphi_{11})}{Q_1}, \] (19)
\[ \varphi_{17} = \frac{\gamma_1 \varphi_{11}}{\gamma_1 + (\gamma_1 + \varphi_{11}) \cos \varphi_{11}}. \] (20)

Thus, expressions (1), (17), (18), (19), and (20) are obtained, which determine the indices of the physical model of the contact curves of the lower roll.

In the two-roll module under consideration, both rolls are driven. Therefore, angles \( \varphi_{24} \), \( \varphi_{25} \), \( \varphi_{26} \) and \( \varphi_{27} \) are defined similar to angles \( \varphi_{14} \), \( \varphi_{15} \), \( \varphi_{16} \) and \( \varphi_{17} \):
\[ \varphi_{24} = \frac{(1 + k_{21} \lambda_{21} \cos \varphi_{21}) f_{21} Q_2 (\omega_2 R_2 (1 + k_{21} \lambda_{21} \cos \varphi_{21}) - v_m (1 + k_{21} \lambda_{21}))}{Q_2 (1 + k_{21} \lambda_{21})(\omega_2 R_2 - v_m \cos(\varphi_{21} - \gamma_1))}
+ \frac{F_2 (1 + k_{21} \lambda_{21} \cos \varphi_{21})(1 + k_{21} \lambda_{21})(\omega_2 R_2 - v_m \cos(\varphi_{21} - \gamma_2))}{Q_2 (1 + k_{21} \lambda_{21})(\omega_2 R_2 - v_m \cos(\varphi_{21} - \gamma_2))}; \]
\[ \varphi_{25} = \frac{(1 + k_{22} \lambda_{22} \cos \varphi_{22}) f_{22} Q_2 (\omega_2 R_2 (1 + k_{22} \lambda_{22} \cos \varphi_{22}) - v_m (1 + k_{22} \lambda_{22}))}{Q_1 (1 + k_{12} \lambda_{12})(\omega_1 R_1 - v_m \cos(\varphi_{12} + \gamma_2))}. \] (21)
\[
\varphi_{26} = \frac{F_2 (1 + k_{21} \lambda_{21} \cos \varphi_{21})}{Q_2}, \quad \varphi_{23} = \frac{\varphi_{21}}{\gamma_{1} - (\gamma_{1} - \varphi_{21}) \cos \varphi_{21}}.
\]

3. Results and conclusions

1. The indices of the physical model of the roll contact curves of the two-roll module shown in Fig. 1 are determined.

2. Based on the analysis of the obtained indices of the physical model of the contact curves, the following aspects were revealed:
   - with an increase in the radius of the upper roll and the angle of inclination of the material layer relative to the centerline, the contact angle of the lower roll increases, and the contact angle of the upper roll decreases;
   - with an increase in the friction coefficient of the roll with the material being processed, the absolute values of the angles separating the no-slip zones from the slip zones increase. This leads to a decrease in the percentage of slip zones in the contact curve and in the drive roll;
   - with an increase in the dynamic coefficient in the drive roll, the angle dividing the lag slip zone and the no-slip zone increases, and the angle dividing the advance slip zone and the no-slip zone decreases. This means that with an increase in the dynamic coefficient, the lag slip zone decreases, and the advance slip zone increases;
   - with an increase in the speed of the material, the values of the angles separating the no-slip zones from the lag slip zones and the advance slip zones, decrease. In this case, the angle separating the lag slip zones and the no-slip zones increases faster than the angle separating the advance slip zones and the no-slip zones. The faster the speed of the material layer, the higher the percentage of the no-slip zone in the roll contact curve;
   - an increase in the coefficient of friction of the driven roll on the material layer leads to a decrease in the percentage of slip zones in the contact curve in the driven roll. With an increase in the dynamic coefficient in the drive roll, the lag slip zone decreases, and the advance slip zone increases. The faster the speed of the material, the greater the percentage of the no-slip zone in the roll contact curve;
   - the neutral angle increases with an increase in the dynamic coefficient and the angle of initial contact. In the drive roll, the neutral angle is inclined towards the entrance of the material layer into the contact zone of the rolls;
   - with increasing angles of initial contact, the angle of maximum normal stresses in the drive roll increases. With an increase in the angle of inclination of the processed material relative to the line of centers, the angle of the maximum of normal stresses increases and asymptotically approaches a certain value.

References
[1] Khurramov Sh R, Abdukarimov A 2016 Reports of Kirgiz GTU 1 109–112
[2] Bahadirov G A, Khurramov Sh R, Abdukarimov A 2018 Reports of the Academy of Sciences of the Republic of Uzbekistan 5 40–44
[3] Khurramov Sh R 2020 Journal of Physics: Conf. Series 1546 012132
[4] Khurramov Sh R 2020 IOP Conf. Series: Earth and Environmental Science. 614 012096
[5] Khurramov S R, Abdukarimov A, Khalturayev F S, Kurbanova F Z 2020 IOP Conference Series: Materials Science and Engineering 916 012051
[6] Khurramov Sh R, Kurbanova F Z 2020 IOP Conf. Series: Earth and Environmental Science. 614 012098
[7] Khurramov Sh R, Khalturayev F S 2020 IOP Conf. Series: Earth and Environmental
Science. 614 012097
[8] Grudev A P 1998 Gripping capacity of milling rolls (Moskow, Intermet Engineering)
[9] Vasiliev Ya.D. 2001 Reports of Higher Educational Institutions. Ferrous metallurgy 5 19–23
[10] Kuznetsov G K, Kislitsky P I, Mametyev T Kh, Malin A S 1987 Reports of Higher Educational Institutions. Textile Industry Technology 3 104–105