Reliability assessment of cylindrical joints with tensioned roll band of the rolling mill

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Abstract: The work addresses to the problem of ensuring the operability of a composite roll made in the form of a cylindrical joint with the tension of a carbide band and a steel axis. When considering the wear processes, all the characteristics related to the surface microgeometry are combined by a dimensionless complex roughness parameter, which, along with the roughness class, includes the features of the surface treatment technology. To determine the contact pressure associated with the tension, the Lame formula for calculating thick-walled cylinders is used. When a hard-alloy bandage is placed on a steel roll with the tension between the contacting surfaces, a plastic unsaturated or saturated contact is performed, for which a method for calculating the tension values shall be proposed. Formulas are given for determining the maximum permissible torque that does not cause a change in the strength of the joint with tension under conditions of plastic saturated and unsaturated contact. In order to test the strength of the connection elements with tension, the theory of the greatest tangential stresses is applied for two dangerous points located on the inner surfaces of the covered and the covering parts: a formula is obtained for determining the maximum permissible calculated value of tension from the strength condition of the covered part. An example of fitting with the tension of a band made of hard alloy VK8 on a working roll made of improved steel 45 with a diameter of d = 100 mm is considered. The band is installed using a press with an H7/p6 fit to transmit a torque of M = 5 kNm. The minimum tension value is obtained from the condition of fixing the contact surfaces without their relative slippage, and the maximum tension value is obtained from the condition of the strength of the steel axis. As a result of the calculations, it was found that the minimum tolerance for this attachment does not provide the transmission of the specified torque since its value is less than the minimum allowable tension. Therefore, to ensure reliable operation of the connection with tension, it is recommended to use the H7/s6 fit, which provides the transmission of the specified torque without the strength of the connection elements.

1. Introduction
Recently, the reliability of technological machines and equipment has become one of the main engineering problems, which is becoming increasingly important for metallurgical production [1-4]. Insufficient reliability of technological machines and their components and devices not only leads to significant downtime of equipment but also significantly increases the cost of their operation. Increasing requirements for the quality of technological machines and equipment in order to reduce material, labor, and financial costs for maintenance and repair leads to the need for modernizing and reconstructing equipment [5-10]. At the same time, attention shall be paid to equipment for the base metal production [11-14].

2. Setting of a Problem
In the process of rolling workpieces made of refractory metals, the working rolls undergo significant thermal and mechanical pressures. Therefore, for high-temperature rolling of hard-to-deform
materials, carbide rolls are often used. In order to save expensive carbide material, the working roll is often produced composite, consisting of a steel roll and a carbide band [15-16].

The cylindrical connection with the tension of the band with the rolling roll should ensure that the contact surfaces are fixed without their relative slippage. This occurs by assigning the appropriate tightnesses. Due to the spread of the values of the coefficient of friction and tension, when an external (excessive) load and vibration are applied, a relative displacement of the band relative to the roll may occur, which negatively affects the further ability to transmit the full load. Under the action of variable loads, especially at the moment of starting and stopping, micro-displacements and fretting corrosion occur on the mating surfaces at the ends of the connected parts [17-20].

3. Purpose and Objectives of the Study
When considering the wear processes, all the characteristics related to the surface microgeometry can be combined by a complex dimensionless parameter [17-19]

\[
\Delta_\gamma = \frac{R_{\max}}{r_{eq} \sqrt{\beta}}.
\]  

(1)

Here \(r_{eq}\) is the reduced average radius of curvature of the vertices of the projections, equal to

\[
r_{eq} = \frac{r_1 \cdot r_2}{r_1 + r_2},
\]

where \(r_1\) и \(r_2\) are the average values of the radii of curvature of the vertices of the projections in the longitudinal and transverse directions.

It is fundamentally important here that, along with the roughness class, the surface treatment technology also plays a great role, on which the other characteristics included in the formula (1) depend. For the treated surfaces, which are characterized by an equilibrium roughness, the parameters of the reference curve of the profile take fairly stable values of \(b \approx v \approx 2\).

The contact pressure \(p_c\), MPa, is related to the tension \(N\), m, the Lame dependence, which is derived in the course “Resistance of materials” [21]

\[
p_c = \frac{N}{d \cdot C} = \frac{N}{d \cdot \left(\frac{C_1 + C_2}{E_1 + E_2}\right)}.
\]  

(2)

Here \(N\)-tension in the joint, m;  
\(d\)-roll diameter, m;  
\(C\)-coefficient, which is determined by the formula  

\[
C = \frac{C_1}{E_1} + \frac{C_2}{E_2} = \frac{\left(\frac{d_1^2 + d_1^3}{d_2^2 - d_1^2} - \mu_1\right)}{E_1} + \frac{\left(\frac{d_2^2 + d_2^3}{d_2^2 - d_1^2} + \mu_2\right)}{E_2},
\]  

(3)

where \(d_1\) - the diameter of the hole of the covered part (for a solid roll \(d_1 = 0\);  
\(d_2\) – outer diameter of the covering part, m;  
\(E_1\) and \(E_2\) – elastic modulus of the material of the covered (of the roll) and covering (sleeve) surface, MPa;  
\(\mu_1\) and \(\mu_2\) are the Poisson coefficients of the material of the covered (of the roll) and covering (sleeve) surface.
4. Results of the study
When the carbide band is placed on a steel roll with the tension between the contacting surfaces, as a rule, a plastic unsaturated or saturated contact occurs.

Plastic unsaturated contact occurs in the case

\[ N > \frac{14.5 \cdot d \cdot \Theta^4 \cdot HB^5 \cdot C}{\Delta_{\text{ unpl}}^2}. \]  

Here \( \Theta = (1-\mu^2)/E \) - elastic constant for a less rigid body, MPa\(^{-1}\);

\( HB \) – hardness of a less solid body, MPa;

\( \Delta_{\text{ unpl}} \) – a complex characteristic of roughness.

Plastic saturated contact occurs in the case when

\[ N > 0.124 \cdot K_{\text{as}} \cdot HB \cdot d \cdot C, \]  

where \( K_{\text{as}} \) is the assembly coefficient; for thermal assembly \( K_{\text{as}} = 1 \), for press assembly \( -K_{\text{as}} = 0.5 \) [20].

The maximum permissible moment \([M]\), which does not cause a change in the strength of the joint with tension in the conditions of plastic contact, is determined by the formula

\[ [M] = \left[ \frac{f_m \cdot N}{d \cdot C} + K_S \cdot \sqrt{\Delta_{\text{ unpl}} \cdot \frac{N}{HB \cdot C}} \right] \frac{\pi \cdot d^2 \cdot l}{2}, \]  

where \( f_m \) is the molecular component of the coefficient of friction, the value of which for practical calculations can be assumed to be equal to \( f_m = 0.12 \) [17-19];

\( K_S \) – coefficient depending on the type of contact; for unsaturated plastic contact \( K_S = 0.21 \), for saturated \( -K_S = 0.45 \) [20].

Calculations show that for the connection of the band with the roll in the formula (6), the second term can be neglected. Then, for both types of contact, the formula for the permissible moment takes the following form

\[ [M] = \left( \frac{f_m \cdot N}{d \cdot C} \right) \frac{\pi \cdot d^2 \cdot l}{2}. \]  

The minimum allowable design tension value \( N_{\text{min,p}} \) is found when the permissible torque value is equated with the corresponding values of the technological resistance moments \( M \), i.e.

\[ N_{\text{min,p}} \approx \frac{2 \cdot M \cdot C}{f_m \cdot \pi \cdot d \cdot l} + \Delta N, \]  

where \( \Delta N \) is the reduction of tension during press assembly [5];

\( \Delta N = 12 \) \( \mu \)m at the roughness parameter \( Ra = 2.5 \ldots 1.25 \) \( \mu \)m, \( \Delta N = 8 \) \( \mu \)m at \( Ra = 1.25 \ldots 0.63 \) \( \mu \)m, \( \Delta N = \) \( \mu \)m at \( Ra = 0.63 \ldots 0.32 \) \( \mu \)m.

The maximum design tension \( N_{\text{max,p}} \) is determined from the solution of the problem of calculating thick-walled cylinders [22] and is reduced to testing for strength at dangerous points where the greatest tensile and compressive stresses act (Figure 1):

- on the inner surface of the enclosing part

\[ \sigma_1 = \sigma_{12} = p_{\text{max}} \cdot \frac{d_2^2 + d_1^2}{2d_1^2 - d_2^2}; \quad \sigma_3 = \sigma_2 = -p_{\text{max}}, \]  

- on the inner surface of the covered part
\[
\sigma_1 = \sigma_{r2} = P_{max} \cdot \frac{d_2^2 + d^2}{d_2^2 - d^2}; \quad \sigma_3 = \sigma_r = -P_{max}.
\] (10)

**Figure 1.** Stresses in parts connected with tension.

According to the theory of the greatest tangential stresses, the strength condition has the form [21]

\[
\sigma_{\text{m宾客}} = \sigma_1 - \sigma_3 \leq \sigma_1.
\] (11)

Given this expression from formulas (9) and (10), we shall obtain

\[
P_{max,2} \leq \sigma_{r2} \cdot \frac{d_2^2 - d^2}{2 \cdot d_2^2}; \quad P_{max,1} \leq \sigma_{r1} \cdot \frac{d^2 - d_1^2}{2 \cdot d_1^2}.
\] (12)

Of the two values \( P_{max} \), the lower value limits the amount of allowable pressure determined by the formula (2). The dangerous element, as a rule, is the covered part [21], and therefore from (12) for a solid roll \( (d_1 = 0) \), we get \( p_{max} = \sigma_{r1}/2 \). Then the maximum permissible calculated value of the tension \( N_{max, p} \) according to formula (2) will be equal to

\[
N_{max, p} = P_{max} \cdot d \cdot \left( \frac{C_1}{E_1} + \frac{C_2}{E_2} \right) = \frac{d \cdot \sigma_{r1}}{2} \left( \frac{C_1}{E_1} + \frac{C_2}{E_2} \right).
\] (13)

Because building connections smooths roughness, the maximum actual tension \( N_{max} \) take more received by the formula (16), at the height of the roughness of the mating surfaces, i.e.

\[
N_{max} = N_{max, p} + 1.2(R_{Z_1} + R_{Z_2}).
\] (14)

Usually, the surfaces of the covered parts (rolls) are treated with a roughness of \( R_{Z_1} = 0.4 \ldots 3.2 \) \( \mu m \), and the covering (holes) - with a roughness of \( R_{Z_2} = 0.8 \ldots 6.3 \) \( \mu m \). Therefore,

\[
N_{max} = N_{max, p} + (2 \ldots 10) \mu m.
\] (15)
According to the calculated values of the tension $N_{\text{max}}$ и $N_{\text{min}}$, the corresponding standard fit is selected; most often, H7/p6, H7/r6, H7/s6, H7/t7, H7/z6, H7u7 landings are used.

5. Discussion of the research results
An example of fitting with the tension of a band made of hard alloy VK8 [23] on a working roll made of improved steel 45 [23] with a diameter of $d = 100$ mm is considered. The band is installed using a press with a H7/p6 fit to transmit a torque of $M = 5$ kN·m. The outer diameter of the band $d_2 = 170$ mm, the length of the landing surface $l = 145$ mm. The landing surface is treated according to the 6th class of cleanliness, for which the complex roughness characteristic of the $\Delta_r = 0.5$. The surface hardness of the roll HB = 2500 MPa. Check whether the specified torque can be transmitted.

For the H7/p6 landing [24], we find the lower and upper limit deviations of the roll and the hole, and then the lower $N_{\text{low}} = 2 \mu$m and the upper $N_{\text{high}} = 59 \mu$m limit values of the tightness (Figure 2).

![Figure 2](image-url)

**Figure 2** Roll tolerance fields and holes with a diameter of 100 mm for tight fit H7/p6, H7/r6, H7/s6.

Substituting the corresponding values of the diameters and mechanical characteristics of the materials in the formula (3), we obtained the value of the coefficient $C = 0.7 \cdot 10^{-5}$ MPa$^{-1}$.

To determine the type of contact, we use the formula (5) to determine the amount of tension that characterizes the transition condition to plastic contact, taking into account that when pressing $C_{\text{as}} = 0.5$.

Therefore, in connection with the tension, both unsaturated ($N_{\text{low}} = 2 \mu$m) and saturated ($N_{\text{high}} = 59 \mu$m) plastic contact can be performed. For the maximum amount of tension, according to the formula (7), we obtain the maximum permissible moment $[M]$

$$[M] = \left( \frac{f_{\text{in}} \cdot N}{d \cdot C} \right) \frac{\pi \cdot d^2 \cdot l}{2} = \left( \frac{0.12 \cdot 59 \cdot 10^{-6}}{0.1 \cdot 0.7 \cdot 10^{-5}} \right) \frac{\pi \cdot 0.1^2 \cdot 0.145}{2} \approx 0.026 \text{ MN} \cdot \text{m} = 26 \text{ kN} \cdot \text{m}.$$  

For the minimum amount of tension, using the formula (7), we obtain the minimum allowable moment $[M]$

$$[M] = \left( \frac{f_{\text{in}} \cdot N}{d \cdot C} \right) \frac{\pi \cdot d^2 \cdot l}{2} = \left( \frac{0.12 \cdot 2 \cdot 10^{-6}}{0.1 \cdot 0.7 \cdot 10^{-5}} \right) \frac{\pi \cdot 0.1^2 \cdot 0.145}{2} \approx 0.001 \text{ MN} \cdot \text{m} = 1 \text{ kN} \cdot \text{m}.$$  

Since $[M]_{\text{min}} = 1 \text{ kH} \cdot \text{m} < M = 5 \text{ kH}$, the minimum tolerance for this fit does not provide the transmission of the specified torque.

During the press assembly, it is necessary to switch to a different type of fit to ensure the minimum allowable tension, which can be estimated using the formula (8)
The value of the tension reduction $\Delta N = 12 \mu m$ is taken for the 6th class of surface treatment purity, i.e. for $Ra = 2.5...1.25 \mu m$.

For the H7/r6 landing, we find [8] the lower $N_{low} = 51 \mu m$ and the upper $N_{high} = 73 \mu m$ values of the limit deviations (see Figure 2), and we determine the lower $N_{low} = 16 \mu m$ and the upper $N_{high} = 73 \mu m$ of the tension values, which is also not enough to transmit the specified torque.

For the H7/s6 landing, we find [24] the lower $N_{low} = 71 \mu m$ and the upper $N_{high} = 93 \mu m$ values of the limit deviations (see Figure 2), and we determine the lower $N_{low} = 136 \mu m$ and the upper $N_{high} = 93 \mu m$ of the tension values. This landing ensures the transmission of the specified torque.

Tight joints are used in various technological machines [25-29]. The proposed method can be useful in continuing the work [30-36].

6. Conclusions
When considering the wear processes, all the characteristics related to the surface microgeometry are combined by a dimensionless complex roughness parameter, which, along with the roughness class, includes the features of the surface treatment technology. To determine tensed contact pressure, the Lame formula for calculating thick-walled cylinders is used. Formulas are given for determining the maximum permissible torque that does not cause a change in the strength of the joint with tension under conditions of plastic saturated and unsaturated contact. In order to test the strength of the connection elements with tension, the theory of the greatest tangential stresses is applied for two dangerous points located on the inner surfaces of the covered and the covering parts: a formula is obtained for determining the maximum permissible calculated value of tension from the strength condition of the covered part. An example of fitting with the tension of a band made of hard alloy VK8 on a working roll is considered. The band is installed using a press with an H7/p6 fit to transmit a torque of $M = 5 \text{kN} \cdot \text{m}$. Calculations have shown that the minimum tolerance for this landing does not provide the transmission of the specified torque. Therefore, to ensure reliable operation of the connection with tension, it is recommended to use the H7/s6 fit, which provides the transmission of the specified torque without the strength of the connection elements.

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