Increase of wear resistance of tribocontact with low-melting metal and porous coating

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Abstract. The paper is devoted to one of the most important problems of increasing wear resistance of tribosystems due to the application of low-melting metal and porous coatings on tribocontact surfaces. The asymptotic and self-similar solution for zero and first approximation was found based on the true viscous fluid flow equation for the “thin layer”, equations of continuity, an equation describing the flow of a lubricant in the body of a porous surface coating of a bearing ring; and an equation describing the profile of the molten surface contour of a bearing ring coated with a low-melting metal alloy, i.e. as a result, excluding the metal coating melt and considering the melt the velocity and pressure fields in the lubricating and porous layers are determined; as well as the load capacity and the friction coefficient, which allows determining the increase of wear resistance – increase of hydrodynamic pattern due to porous and low-melting metal coating of contact surfaces of the tribosystem.

1 Introduction

Currently, low-melting metal and porous coatings are widely used as a lubricant in friction units thus ensuring a hydrodynamic mode.

The use of such materials considerably improves the performance of tribounits. However, existing design methods do not sufficiently take into account the specifics of low-melting metal and porous coatings, their rheological properties, as well as their universal nature [1-17].

One of the peculiarities of the existing calculation methods for the considered structures of a tribounit operating on lubricants and coating melts is the absence of a self-sustaining lubrication [18-22]. To ensure the self-sustained lubrication and increase the duration of the hydrodynamic lubrication mode, one of the options to solve structural and operational problems may be the use of tribounits with low-melting metal and porous coatings of contact surfaces. In turn, the porous coating ensures damping properties.

The proposed study presents a mathematical calculation of the hydrodynamic pattern of lubricant and coating melt flow in the porous coating body and in the working gap taking into account the rheological properties of a lubricant and a coating melt, which allow increasing the wear resistance of tribounits.

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2 Materials and methods

The study considers the steady-state flow of a lubricant and a coating melt in a working gap and a porous body with true viscous rheological properties (Fig. 1).

![Fig. 1. Calculation model.](image)

In the Cartesian coordinate system $x'O'y'$ the equation of the considered bearing structure contours is written as:

$$1 - y' = h_0 + x' \tan \alpha = h_1(x'), 2 - y' = h_0 + x' \tan \alpha + \tilde{H} = h_2(x'), 3 - y' = -\beta \beta(\x' \ell),$$

(1)

The analytical solution of this problem is given under the following assumptions:

1. Lubricant is incompressible fluid.
2. The temperature in the working gap melts the working surface of the coating.
3. Assuming that the value of the angle $\alpha$ is sufficiently small and given the no-slip condition on the porous surface it is considered that:

$$\frac{dP}{dh} \bigg|_{h_0+x'\tan \alpha} \approx \frac{\partial P}{\partial y} \bigg|_{h_0+x'\tan \alpha} \cdot \cos \alpha, $$

where $\frac{dP}{dh}$ – a normal derivative of the hydrodynamic pressure in the porous layer corresponding to the equation of contours 1 and 2.

4. Assuming that the sliding block is stationary, and the guide block moves towards narrowing the gap at a speed $u^*$. The initial basic equations are as follows: the equations of motion of a viscous incompressible fluid for the “thin layer”, the equation of continuity, the Darcy equation, as well as the equation describing the profile of the molten contour of the surface of the guide block taking into account the mechanical energy dissipation.

$$\frac{\mu \partial^2 v_x}{\partial y^2} = \frac{d P'}{dx} + \frac{\partial v_y}{\partial x}, \quad \frac{\partial v_y}{\partial y} = 0; \quad \frac{\partial^2 P'}{\partial x^2} + \frac{\partial^2 P'}{\partial y^2} = 0,$$

$$-L'u^* \frac{d}{dx} \left[ \beta f \left( \frac{x}{l} \right) \right] = 2\mu \int_{-\beta f \left( \frac{x}{l} \right)/y}^{h_{1}(x)} \left( \frac{\partial v_x}{y^2} \right) dy'.$$

(2)

The system of equations (2) is solved under the following boundary conditions:

$$v_x' = -u^*, \quad v_y' = 0 = y' = -\beta f \left( \frac{x}{l} \right),$$

$$v_x' = 0, \quad v_y' = -\frac{k \partial P}{\mu \partial y} \cos \alpha, \quad P' = P' = x_0 + x \tan \alpha,$$

(3)
By integrally averaging the expression under integral sign of the fourth equation of the system (2), and substituting the obtained expression into the equation, we get the following equation for the profile of the molten contour of the low-melting metal coating surface:

$$\beta f \left( \frac{x'}{l} \right) = h_0' + K \int_0^{x'} \frac{dx'}{1 + x' \tan \alpha + \tilde{H}} \left( \frac{x'}{l} \right)$$

(4)

To find the values of the molten coating contour profile the equation (4) is solved by the method of successive approximations:

for zero approximation

$$\beta f \left( \frac{x'}{l} \right) = h_0'$$

(5)

for the first approximation

$$\beta f \left( \frac{x'}{l} \right) = h_0' + K \int_0^{x'} \frac{dx'}{1 + x' \tan \alpha + \tilde{H}'} \left( \frac{x'}{l} \right)$$

(6)

In the lubricating layer let us turn to dimensionless variables according to the formulas:

$$v = u \xi, \quad v_x = u \nu, \quad p = \rho \nu, \quad p = \frac{\mu u 't}{h_0}, \quad y = h_0 y, \quad x' = l x, \quad e = \frac{h_0}{l}.$$

(7)

In the porous layer let us turn to dimensionless variables according to the formulas:

$$y' = ly, \quad p' = P \rho, \quad x' = lx'.$$

(8)

Taking into account (7) and (8), we get the following system of dimensionless equations and their boundary conditions:

$$\frac{\partial^2 u}{\partial y^2} + \frac{dp}{dx'} \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = 0, \quad \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial x^2} = 0.$$  

(9)

$$v = -1, \quad u = 0, \quad y = -\frac{\alpha}{h_0}, \quad v = 0, \quad y = 1 + \eta x,$$

$$u|_{y=1+\eta x} = -\frac{\beta \rho \frac{\partial P}{\partial y}}{\mu l} \left. \left[ \cos \frac{\alpha}{h_0} \right] y = \frac{h_0}{l} + x ' \tan \alpha \right], \quad P = P \left| y = \frac{h_0}{l} + x ' \tan \alpha \right|^{'}, \quad P(0) = p(1) = \frac{p_2}{p}, \quad \eta = \frac{\tan \alpha}{h_0}.$$  

(10)

The exact self-similar solution of the problem (9) – (10) will be found as follows:

$$v = \frac{\partial \psi}{\partial y} + V(x, y), \quad u = -\frac{\partial \psi}{\partial x} + U(x, y), \quad \psi = \tilde{\psi}(\xi),$$

$$V(x, y) = \tilde{V}(\xi), \quad U(x, y) = -\tilde{U}(\xi) \eta,$$

$$\xi = \frac{y + \alpha x}{h_0}, \quad \frac{dp}{dx} = \tilde{c}_1 \left( 1 + \eta x + \alpha^2 \frac{h_0}{h_0} \right)^2 + \tilde{c}_2 \left( 1 + \eta x + \alpha^2 \frac{h_0}{h_0} \right)^3.$$
\[ P = C_1(x) \left( y^* - \frac{h_0}{l} + x^* \tan \alpha \right) + C_2(x) \left( y^* - \left( \frac{h_0 + \tilde{H}}{l} + x^* \tan \alpha \right) \right) \left( y^* - \left( \frac{h_0 + \tilde{H}}{l} + x^* \tan \alpha \right) \right) + C_3(x) \left( y^* - \left( \frac{h_0}{l} + x^* \tan \alpha \right) \right)^2 \left( y^* - \left( \frac{h_0 + \tilde{H}}{l} + x^* \tan \alpha \right) \right). \] (11)

Substituting (11) into (9) and (10) we come to the following system of equations:

\[ \frac{d^3 \psi}{d \xi^3} = \tilde{C}_2, \quad \frac{d^2 \psi}{d \xi^2} = \tilde{C}_1, \quad \frac{d \psi}{d \xi} + \xi \frac{d \psi}{d \xi} = 0. \] (12)

The system of equations (12) is solved under the following boundary conditions:

\[ \psi' = 0, \quad \psi = 0, \quad \xi = 1, \quad \psi = 0, \quad \psi(1) = 0, \quad \psi(1) = 0, \quad \psi(1) = -\frac{K \tilde{C}_1}{h_0} \cos \alpha = N. \] (13)

For the field of velocity and pressure in the lubricating layer and the porous layer we have:

\[ \tilde{C}_2 = \frac{C_2}{2} \left( \xi^2 - \xi \right), \quad \tilde{C}_1 = \frac{C_1}{2} \left( \xi^2 - \xi \right). \]

\[ p = \frac{\tilde{C}_1}{\left( 1 + \frac{\alpha}{h_0} \right)} \left( \frac{\tilde{\eta} x^2}{2} - \frac{\tilde{\eta} x}{2} - \frac{3}{4} \frac{\tilde{\eta}^2 x^2}{2} + \frac{\tilde{\eta}^2 x^2}{4} \right). \]

\[ \tilde{C}_1 = -6 - 12N, \quad N = -\frac{K \tilde{C}_1}{h_0} \cos \alpha. \] (14)

Taking into account (14) for the bearing capacity and the friction force, the following analytical expressions are obtained:

\[ R_y = \frac{\mu u^* l^2}{h_0^2} \left( \frac{-6 - 12N}{1 + \frac{\alpha}{h_0}} - \frac{\tilde{\eta}^2}{12} + \frac{\tilde{\eta}^2}{24} \right), \]

\[ L_{f,\tau} = \mu \left( \frac{30 + 60N}{24(1 + \frac{\alpha}{h_0})} + \frac{\eta^2}{1 + \frac{\alpha^2}{h_0}} \right). \] (15)

### 3 Results and discussion

The final stage of theoretical calculation methods is numerical analysis. The analysis of its results showed that the design of tribounits with low-melting metal and porous coating of contact surfaces has the bearing capacity exceeding 9-12% of standard structures in the studied range of load-speed modes. The friction coefficient is thus reduced by 8-11%.

The experimental studies were carried out to verify and confirm the effectiveness of the obtained theoretical models. In the first case, the standard tribounit structure was studied; in the second – a low-melting metal coating; in the third – a porous coating. The studies were carried out on a modernized II5018 friction machine. The results are shown in Table 1.
Table 1. Experimental study of a thrust bearing.

<table>
<thead>
<tr>
<th>Replicate tests</th>
<th>Friction coefficient for different coating types</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standard</td>
<td>Low-melting metal coating</td>
</tr>
<tr>
<td>1</td>
<td>0.0054</td>
<td>0.0042</td>
</tr>
<tr>
<td>2</td>
<td>0.0056</td>
<td>0.0044</td>
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<tr>
<td>4</td>
<td>0.0061</td>
<td>0.0048</td>
</tr>
<tr>
<td>5</td>
<td>0.0065</td>
<td>0.0052</td>
</tr>
<tr>
<td>Average</td>
<td>0.0059</td>
<td>0.0046</td>
</tr>
</tbody>
</table>

The analysis of the obtained experimental results confirms the effectiveness of theoretical studies and proves the advantage of the studied tribounits with a low-melting metal and porous coating of contact surfaces, which provide increased wear resistance, load-bearing capacity and reduced friction coefficient.

4 Conclusion

The study proposes new models describing the motion of a lubricant and a coating melt having viscous properties in a laminar friction mode. As a result, the main performance characteristics were determined, which make it possible to establish the effectiveness of the study, proving the advantage of the studied tribounits with low-melting metal and porous coatings. The experimental study was carried out to verify and confirm the effectiveness of the obtained models, as well as to conduct the comparative analysis of new and existing results.

1. New multiparametric models for engineering calculations of tribounits with low-melting metal and porous coatings were developed, which ensure increased wear resistance, increased hydrodynamic friction mode, increased load capacity and reduced friction coefficient.

2. Design models take into account the use of a low-melting metal coating and a porous coating for additional lubrication of the melt. Original expressions are obtained for the calculation of load capacity and friction force of tribounits at the following loading modes $\nu = 0.5 \div 3 \text{ m/s}, \sigma = 2 \div 7 \text{ MPa}$.

3. According to the results of the experimental study, the obtained stable hydrodynamic mode is characterized by fluctuations of the friction coefficient in the range of 0.002-0.004 regardless of the step-like load increase by 5 times to 8.76 MPa and $\nu = 0.5 \text{ m/s}$. Besides, the wear rate does not exceed 0.0063 (Fig. 2).
Fig. 2. Type of coating under the microscope.

5 Designations

\( v'_x, v'_y \) – components of the velocity vector in the lubricating layer; \( \mu \) – dynamic viscosity coefficient; \( p' \) – hydrodynamic pressure in the lubricating layer; \( P' \) – hydrodynamic pressure in the porous layer; \( l \) – bearing length; \( \bar{H} \) – thickness of the porous layer; \( k \) – permeability of the porous layer; \( L' \) – specific heat of melting per unit volume.

References


