The analysis of deformation behavior of antifriction polymeric materials using the example of a spherical bearing

A A Kamenskikh
Department of Computational Mathematics and Mechanics, Perm National Research Polytechnic University, Perm 614990, Russia

E-mail: anna_kamenskih@mail.ru

Abstract. Simulation of the contact interaction of the spherical bearing elements through an antifriction polymeric layer of three materials is considered in the work. The deformation theory of elastoplasticity was chosen as a model describing the behavior of antifriction polymers based on the results of experiments. In the framework of the numerical study it was found that the deformation path in the space of the principal values of the strain deviator have a low degree of curvature at the contact deformation of the bearing, which confirms the choice of the theory of small elastoplastic strains. The relative analysis of the deformation behavior of antifriction polymeric materials as an interlayer of a spherical bearing is carried out in the work. It was found that the antifriction layer of the modified PTFE provides a more favorable distribution of contact parameters: disconnection of contact surfaces near the free edge of the interlayer is absent; the decrease in the efficiency of the part of the structure is observed by 10% of the contact surface; the distribution of contact pressure and contact tangential stress is more uniform and minimal in magnitude than in the other two materials under consideration.

1. Introduction
There is a wide choice of antifriction polymeric materials of Russian and foreign production that are suitable for operation in the contact units: antifriction composite materials based on polyfluoromethylene (PTFE) with different nanofillers, modified PTFE, ultra-high molecular weight polyethylene (UHMWPE) and others. The relevance of research aimed at the study of physicomechanical, frictional, thermomechanical and operational properties of antifriction polymers is due to their wide application in many branches of industry and technology. Such materials are widely used in aeronautical engineering [1], construction [2], medicine [3], mechanical engineering [4-5] and other. New mathematical models of the behavior of such materials, reflecting their thermomechanical and friction characteristics will make it possible to evaluate their performance as an antifriction layer of the bearing parts of bridges and optimize the choice of materials depending on the temperature and strength conditions of the design. These problems are particularly interesting: the influence of friction coefficient and physicomechanical properties on the contact parameters; relation between load and friction coefficient and others. It is especially important to study the effect of the friction coefficient in real systems with antifriction coatings and interlayers, in which the complex nature of the interaction is realized: more than 2 contact surfaces, complex spatial geometry and loading conditions, materials with difficult mechanical behavior. Bearing parts of bridges belong to such constructions. At the same time, numerical modeling of deformation behavior of modern antifriction materials in these structures requires qualitative models describing their behavior and effective numerical methods for implementing contact interaction.
problems [6]. A comparative analysis of the deformation behavior of modern antifriction polymers is also of special interest, it is discussed in the work.

2. Problem statement
The general mathematical problem statement of contact between two elastic bodies through the antifriction layer is given in the work [2] (Figure 1). Deformation plasticity theory is selected to describe the behavior of the material layer [7].

![Figure 1. Model of the spherical bearing.](image_url)

The contact deformation of the spherical bearing with the antifriction layer L-250 (Figure 1) manufactured by "AlfaTech" (Perm) was considered in the work. The maximum height $h = 4.83 \times 10^{-2}$ m, the maximum width $b_i = 2b = 2 \times 0.1369 = 0.2738$ m, thickness of the antifriction polymer layer $h_p = 4.0 \times 10^{-3}$ m. The vertical pressure $p_z = 54$ MPa was applied at the contact unit construction.

The solution of the problem is conducted within the general mathematical statement of the problem of contact interaction of elastic bodies 1 and 2 through an elastoplastic layer 3 (Figure 1) and includes:

- equilibrium relations
  \[ \text{div} \hat{\sigma} = 0, \quad \tilde{x} \in V; \]  

- geometrical relations
  \[ \hat{\varepsilon} = \frac{1}{2} (\nabla \hat{u} + (\nabla \hat{u})^T), \quad \tilde{x} \in V; \]  

- physical relations
  \[ \hat{\sigma} = \lambda I_1(\hat{\varepsilon}) \hat{I} + 2\mu \hat{\varepsilon}, \quad \tilde{x} \in V_1 \cup V_2, \]  

where $\lambda$ and $\mu$ are Lame’s parameters; $\hat{\sigma}$ is stress tensor; $\hat{\varepsilon}$ is strain tensor; $\hat{u}$ is vector of displacements; $\tilde{x}$ is radius-vector of a random point; $I_1(\hat{\varepsilon})$ is the first invariant of strain tensor; $\hat{I}$ is the unit tensor; the area $V$ consists of the subareas occupied by the plates of the press $V_1, V_2$ and the polymeric layer $V_3$ ($V = V_1 \cup V_2 \cup V_3$).

To describe the behavior of the layer’s material the deformation theory of elastoplasticity is chosen, it’s physical relations are:

\[ \hat{\sigma} = \frac{2 \sigma_u}{3 \varepsilon_u} \left( \hat{\varepsilon} - \frac{1}{3} I_1(\hat{\varepsilon}) \hat{I} \right) + K I_1(\hat{\varepsilon}) \hat{I}, \quad \tilde{x} \in V_3, \]  

where $\sigma_u = \sqrt{3 I_2(D_\sigma)}$ and $\varepsilon_u = \frac{2}{3} \sqrt{I_2(D_\varepsilon)}$ are intensities of stress and strain tensors; $I_2(D_\sigma)$ and $I_2(D_\varepsilon)$ are the second invariants of deviators of stress tensor $D_\sigma$ and strain tensor $D_\varepsilon$; $K$ is the
volumetric elastic modulus; \( \sigma_u = \Phi(\varepsilon_u) \) is the function determined by deformation diagram of the layer’s material at uniaxial stress state.

The contact boundary conditions are applied to the surface \( S_k = S_k_1 \cup S_k_2 \cup S_k_3 \), where the two bodies 1 and 2 are in contact along \( S_k \). The types of contact interaction that are implemented in the problem are given below:

- sliding with friction (friction of rest): \( \bar{u}^1 = \bar{u}^2, \quad \sigma_u^1 = \sigma_u^2, \quad \sigma_{u_1} = \sigma_{u_2}, \quad \sigma_{u_2} = \sigma_{u_2} \), wherein \( \sigma_u < 0, \left| \sigma_{u_2} \right| < q(\sigma_u) |\sigma_u| \);
- sliding with friction (sliding friction): \( u_u^1 = u_u^2, \quad u_t^1 \neq u_t^2, \quad u_n^1 \neq u_n^2, \quad \sigma_u^1 = \sigma_u^2, \quad \sigma_{u_1} = \sigma_{u_2}, \quad \sigma_{u_2} = \sigma_{u_2} \), wherein \( \sigma_u < 0, \left| \sigma_{u_2} \right| = q(\sigma_u) |\sigma_u| \);
- no contact: \( u_u^1 - u_u^2 \geq 0, \quad \sigma_{u_1} = \sigma_{u_2} = \sigma_u = 0 \);
- adhesion: \( \bar{u}^1 = \bar{u}^2, \quad \sigma_u^1 = \sigma_u^2, \quad \sigma_{u_1} = \sigma_{u_2}, \quad \sigma_{u_2} = \sigma_{u_2} \),

where \( q(\sigma_u) \) is the friction coefficient, \( \tau_1, \tau_2 \) are axes designation which lie in a plane tangent to the contact surface, \( u_u \) is displacement along a normal to a corresponding contact edge, \( u_t, u_n \) are displacement in a tangential plane, \( \sigma_u \) is stress along the normal to the contact boundary, \( \sigma_{u_1}, \sigma_{u_2} \) are tangential stresses at the contact boundary, \( \sigma_{u} \) is the value of vector tangential contact stresses.

The mathematical formulation is closed by kinematic boundary conditions on surface \( S_2 \): \( u_u = 0, \quad \sigma_u = 0, \quad r \in S_2 \), and also by static and kinematic boundary conditions on surface \( S_1 \): \( \int_{S_1} p_i dS_i = -Q_z \), \( u_u (r,h) = U = \text{const}, \quad \sigma_{u} = 0, \quad r \in S_1 \), where \( Q_z \) is the vertical force applied to \( S_1 \), \( U \) is the unknown quantity, and the remaining outer surfaces are free of load.

There is a number of polymeric materials which are suitable as materials of antifriction layers in contact elements: PTFE (material 1), antifriction composite material on a basis of PTFE with spherical bronze inclusions and a disulfide of molybdenum (material 2), modified PTFE (material 3) and others. Professor A.A. Adamov has executed at Institute of Continuous Media Mechanics a cycle of experimental studies of deformation characteristics of antifriction materials at difficult multistage histories of deformation with unloadings \([8]\). The cycle of experimental studies included: tests by determination of hardness of materials according to Brinell by indentation of a ball with a 5 mm diameter; researches in the conditions of free compression, and also the constrained compression by pressing in special adaptation with a rigid steel holder of cylindrical samples with 20 mm diameter. All tests were carried out by the test car Zwick Z100NS5A. As a result, mechanical characteristics of materials are obtained: elastic modulus \( E \), Poisson’s ratio \( \nu \), deformation diagrams \( \sigma_\varepsilon = \varepsilon_\varepsilon \). Values of \( E \) and \( \nu \) are equal to \( 5.45 \cdot 10^8 \text{Pa} \) and \( 0.466 \), respectively for material 1; \( 8.6052 \cdot 10^8 \text{Pa} \) and \( 0.4388 \) for material 2; \( 8.638 \cdot 10^8 \text{Pa} \) and \( 0.461 \) for material 3.

### 3. Results

To analyze the numerical solution of the contact interaction problem of the polymer antifriction layer with the plates of the spherical bearing, a series of numerical calculations is performed. The problem is solved in the ANSYS software using axisymmetric finite elements with Lagrangian approximation. According to the results of a series of calculations, it is found that the finite element grid with 8 elements through the layer gives the optimal accuracy and time of the solution. The finite element model is used to analyze the deformation of the three materials of the antifriction layer under the conditions of contact interaction, taking into account the friction of between surfaces (the coefficient of friction is constant 0.04).
The model chosen to describe the behavior of the material of the antifriction layer is valid only for paths of deformation in the deformation space close to linear [9]. Based on the results of the problem solution, the deformation path at four points of the antifriction polymer layer near the free end face at different levels of deformation are estimated. Deviator of strain is defined as \( \hat{\mathbf{E}} = \hat{\mathbf{e}} - \frac{1}{3} \mathbf{I} \). The results of the problem solution using the example of an antifriction layer of material 3 are shown in Figure 2.

![Figure 2](image.png)

**Figure 2.** The deformation path in space of principal values of \( \hat{\mathbf{E}} \) at four points of the antifriction layer.

It is bound that in all considered points of the path of deformation have a small curvature. Thus the theory of small elastoplastic deformations described (4) can be applied to the spherical bearing construction with an antifriction polymeric interlayer.

A series of numerical calculations is performed within the framework of the investigation of deformation behavior of an antifriction layer materials. The distribution of stress and strain intensity distribution of contact parameters (contact pressure, contact tangential stress, zones of contact states) are obtained for three materials of the antifriction layer under investigation. The distribution of the relative contact pressure \( P_{\text{ki}} / P \) and the relative contact tangential stress \( \tau_{\text{ki}} / P \) for the three studied materials on \( S_{\text{ki}} \) is shown in Figure 3.

At the same load level, the lowest relative contact pressure and tangential stress are observed in the antifriction layer of material 3. A sharp drop in the values of the contact parameters is observed at \( \sim 63\% \) of the contact surface of the interlayer of material 1, which corresponds to a decrease in the operability of a part of construction. The same situation is observed at \( \sim 40\% \) of the contact surface of the interlayer of material 2 and \( \sim 10\% \) of the contact surface of the interlayer of material 3. The contact state zones on \( S_{\text{ki}} \) for the interlayer of materials 1 and 2 are also shown in Figure 3 (a) and (b), respectively. It should be noted that in the case of material 1, the drop in contact parameters begins in the adhesion zone, which is associated with the interpenetration of the contacting surfaces, since the material is the softest. The "no contact" zone is observed at the edge of the interlayer for materials 1 and 2. Separation of the contact surfaces at the edge of the interlayer from material 3 does not occur, "sliding" is observed at the edge of the interlayer. In this case the decrease in the values of the contact parameters begins at the transition point of the contact states zones.
Figure 3. Relative contact pressure (a) and contact tangential stress (b):
1 – material 1, 2 – material 2, 3 - material 3.

The distribution of normal displacements at the end of the antifriction layer of spherical bearing
$S_{K_1}$ is shown in Figure 4 for the three analyzed materials.

Figure 4. Normal displacements on $S_{K_1}$:
1 – material 1, 2 – material 2, 3 – material 3.

As expected, the maximum normal displacements are observed at the end of the antifriction layer
of material 1, the minimum – of material 3. The character of normal displacements distribution at the
ends of the interlayer of different materials has minor differences. On the free part of the end of the
layer of materials 2 and 3 there is a slight change in the value of normal displacements, the maximum
value of $u_n$ is observed at the free end of the interlayer. The non-uniform distribution of the normal
displacements with the maximum value $u_n$ in the center of the free end has the antifriction layer made
from material 1. The antifriction layer made from material 3 on $S_{K_1}$ has maximum normal
displacements $u_n = 3.36 \times 10^{-4}$ m. In this case, the maximum normal displacement of material 1 is 8
times greater, and for material 2 it is 3 times than for material 3.
4. Conclusion
Modeling of the deformation of the antifriction layer materials of the spherical bearing is performed. The applicability of the small elastoplastic deformations theory to the antifriction layer materials in the contact unit manufactured construction has been verified. The comparative analysis of deformation behavior in the antifriction layers of contact unit from different polymeric materials is performed and the use of a layer made of modified PTFE is recommended, which provides a more favorable distribution of contact parameters.

In the analysis of the results of a series of numerical experiments established:

• A decrease in the operability at 63% of the contact surface is observed in the spherical bearing using pure PTFE for the antifriction layer material, at 40% for antifriction composite material on a basis of PTFE with spherical bronze inclusions and a disulfide of molybdenum, at 10% for modified PTFE.
• The disclosure of contact is not observed in the design of a spherical bearing with an antifriction layer of modified PTFE. In this case, the level of contact pressure and contact tangential stress is less than that of the other two materials under consideration.
• The normal displacement of the free end of the layer $S_n$ from modified PTFE is at least 3 times lower than in the other two considered materials.

Acknowledgments
The study supported by a grant of Russian Science Foundation (project No. 18-79-00147).

References
[1] Bejder E Ya, Donskoj A A, Zhelezina G F, Kondrashov E K, Sytyj Yu V and Surnin E G 2008 *Russ. J. of General Chem.* **3** 30-44
[2] Kamenskih A A and Trufanov N A 2013 *Comp. Continuum Mech.* **1** 54-61
[3] Pinchuk L S, Nikolaev V I, Tsvetkova E A and Goldade V A 2006 *Tribology and biophysics of artificial joints* (London, Amsterdam: Elsevier) 350
[4] Rakowski W A and Zimowski S 2006 *Compos. Part B Eng.* **2-3** 81-88
[5] Balyakin V B, Pilla C K and Khatipov S A 2015 *J. of Friction and Wear* **4** 346-349
[6] Rogovoy A and Ivanov B 1997 *Comput. Struct.* **1** 133-139
[7] Kamenskih A A and Trufanov N A 2015 *J. of Friction and Wear* **2** 170-176
[8] Adamov A A 2013 *Composite materials constructions* **2** 28-37
[9] Kamenskih A A and Adamov A A 2012 *Fundam. and Appl. Problems of Tech. and Technol.* **3-2** 48-55