Comparative Analysis of the Contact Deformation of the Spherical Sliding Layer of the Bearing with and without Taking into Account the Grooves with Lubricant

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Abstract. In this paper, the analysis of the contact deformation of elements of spherical bearing through anti-friction polymeric layer made of modified fluoroplastic with and without taking into account the grooves with lubricant is carried out. The effect of grooves with lubricant on contact zone parameters is considered. Comparison of the results of the spherical bearing draft obtained within the framework of numerical and full-scale experiments with a constant coefficient of friction of 0.04 is made: at a nominal vertical load of 1000 kN, the difference between the results of numerical and full-scale experiments is minimal and is ~ 7.13% for the model taking into account the grooves with lubricant. The analysis of frictional properties of modified fluoroplastic under the conditions of contact interaction with and without taking into account the lubrication of the mating surfaces is performed. Approximating functions have been selected to describe the dependence of the friction coefficient on the pressure acting on the contact section. The effect of the friction coefficient obtained experimentally on the contact deformation of the sliding layer is considered. Several qualitative and quantitative regularities have been established.

1. Introduction
Researchers note the main actual problems of transport and logistics systems related to bridge construction: geometric configuration and technology of deformation joints [1, 2], bearings [3, 4], bridge spans [5], hoisting structures of draw bridges [6], as well as other elements of bridge structures. We can note a special interest in the deformation behavior of the bearing of bridge spans [7-11, etc.]. The most of the works are aimed at the analysis of bearing capacity, strength, wear resistance of bridge structure elements, as well as the assessment of the stress-strain state of bearing structures in general [7,10] and the identification of patterns of change in contact zones in particular [10, 12]. Several works are devoted to the studies of the possibility of using modern anti-friction polymeric materials in the structures of bearing parts [9, 10, etc.]. Methods of mathematical modeling as well as effective numerical methods are used in the study of the deformation behavior of the bearings of bridge spans. For qualitative creation of numerical models of bearings, it is necessary to have experimentally confirmed models of behavior of contact sections' materials, in connection with this concomitant direction of research are experimental researches of materials with the purpose of reception of their thermomechanical, frictional and rheological properties. Thus, the actual line of research is the numerical analysis of deformation behavior of elements comprising the bearings of bridge structures taking into account properties of materials from which they are made.

In this paper, we consider contact deformation of an anti-friction layer made of modern polymeric material (modified fluoroplastic) taking into account its physical-mechanical and friction properties. The direction of the research is the analysis of how the design features of a spherical bearing effect on
parameters of a contact zone of steel plates with a spherically thin sliding layer made of an anti-friction polymeric material.

2. Statement of a problem

Friction contact interaction of upper (1) and lower steel plate (2) of the spherical bearing through an elastoplastic polymeric layer (3) is considered in the paper with (Fig. 1, b) and without (Fig. 1, a) grooves with lubricant (4).

Contact deformation of the spherical bearing with the L-100 (Figure 1) anti-friction layer manufactured by AlphaTech LLC (Perm) is considered. The spherical bearing is designed for a nominal vertical load of 1000 kN. Two models of the bearing are considered, we introduce the following designations: model A is model of the spherical bearing without taking into account the grooves with lubricant; model B is model of the spherical bearing without taking into account the grooves with lubricant. Typical dimensions of the spherical bearing: maximum height of the top plate \( h_1 = 0.03 \) m, minimum height of the bottom plate with a spherical neckline \( h_2 = 0.02 \) m (\( h_2 = 0.0179 \) m for the model with taking into account the grooves), maximum width of the structure \( b = 0.155 \) m, thickness of the sliding polymeric layer \( h_p = 0.004 \) m, thickness of the grooves with lubricant \( h_k = 0.003 \) m. The deformation behavior of bridge bearings under the action of indentation force of 500-1250 kN, which corresponds to the indentation force of full-scale experiment on deformation of the spherical bearing, is considered in the paper. Constant indentation force and the bending is prohibited on \( S_1 \), on \( S_2 \) the \( y \)-movements are prohibited.

Previously, the Institute of Continuous Media Mechanics of the Ural Branch of the Russian Academy of Sciences carried out a cycle of experimental studies of the physical and mechanical characteristics of anti-friction materials at complex multistage deformation stories with offloading using a Zwick Z100SN5A testing machine. A series of full-scale experiments included: tests to determine the Brinell hardness of materials by penetrating a ball with a diameter of 5 mm; studies under free compression conditions, as well as studies of constrained compression by pressing cylindrical specimens with a diameter and length of 20 mm in a special fixture with a rigid steel cage. As a result, the physical and mechanical characteristics of materials were obtained: modulus of elasticity \( E \), Poisson's coefficient \( \nu \), deformation diagrams \( \sigma - \varepsilon \). In this paper, we consider a spherical bearing with an anti-friction layer of modified fluoroplastic with modulus of elasticity \( E = 863.8 \) MPa and Poisson's coefficient \( \nu = 0.461 \) of elastic region. Further, the scientific team of Alfa-Tech LLC and IMSS of the Ural Branch of the Russian Academy of Sciences prepared special equipment and carried out a series of full-scale experiments aimed at determining the friction properties of polymeric materials. Within the limits of a series of tests, the friction coefficient \( \mu \) was determined as a function of pressure. Fig. 2 shows the results of full-scale experiments with and without taking into account lubricant on the mating surfaces.
at contact deformation of cylindrical samples with a diameter \(0.097 \pm 0.103\) m and height 0.01 m by steel plates of the press.

The full-scale experiment was carried out in the pressure range of 1.2-54 MPa, and the working pressure range of the spherical bearings can reach 90 MPa. Within the limits of the analysis of experimental data, the approximation of results of full-scale experiments was executed, the approximating functions describing results of the experiment with the maximum error of 5 and 8 % for contact with and without taking into account lubrication on mating surfaces, respectively, were selected. The selected functions are required to calculate the friction coefficient for pressure > 54 MPa. In this paper, we consider a spherical bearing of \(L=100\) with a nominal operating vertical load of 1000 kN (~55.5 MPa). The general mathematical statement of the problem of contact interaction of two elastic bodies through the anti-friction polymeric layer taking into account all types of friction contact is described in [12]. The problem is considered in the axisymmetric statement; the deformation theory of elasticity was chosen to describe the model of the behavior of the anti-friction layer material. Lubrication is modeled as a low compressible material with \(E=200\) MPa, \(v=0.4999\) and \(\mu=0.007\). The contact between the lubricant and anti-friction layer is not taken into account.

3. Findings

The problem is implemented in the ANSYS software package using axisymmetric finite elements with the Lagrangian approximation. Previously, it was established that numerical solutions for finite element mesh with 8 and 16 elements in the thickness of the layer for the model without taking into account the grooves with lubricant have minor differences [10]. When introducing the grooves with lubricant into the model, it was decided to choose a mesh with 16 elements in the thickness of the layer for a better solution to the problem. On the selected finite element model, the deformation behavior of the anti-friction layer of modified fluoroplastic was analyzed. At the first stage of research, the contact of elements of a spherical bearing with a constant friction coefficient of 0.04, which corresponds to the reference data of the manufacturer, was modeled. At the second stage of research for nominal load 1000 kN, the contact deformation with friction coefficients of 0.006787 and 0.02713, which corresponds to the friction coefficients obtained experimentally with and without taking into account lubrication on the mating surfaces, respectively, was modeled.

Findings of the numerical modeling of contact interaction of elements of a bearing through an anti-friction layer at a constant friction coefficient of 0.04 are given in Fig. 3-4. The introduction of grooves with lubricant into the model of the bearing has a significant influence on the qualitative and quantitative distribution of contact parameters: contact parameters change irregularly, there is a decrease in the level of contact pressure and contact tangential stress in the area of grooves with lubricant. The contact tangential stress increases near the interface between the lubricant and the sliding layer.

Fig. 3 shows the relative contact pressure distribution for the two spherical bearing models under consideration.
The average maximum contact pressure does not change significantly at the contact boundary $S_{K_1}$, where the spherical segment of the bearing is rotated: there is a slight decrease in the level of $P_{K}/P$ in the contact area with the lubricant, with a further increase in the contact area of the anti-friction material, whereas the value of $P_{K}/P$ in the contact area of the anti-friction material is close to $P_{K}/P$ of the model, without taking into account the grooves with the lubricant. The maximum level of $P_{K}/P$ for model B differs on average by approximately 3% from model A.

Fig. 4 shows the distribution of the relative contact tangential stress.

The greatest effect of the grooves with the lubricant on the parameters of the contact area is observed in the interface area of the layer with the lower steel plate: the maximum contact pressure on the main
contact surface is on average by 8.7% higher, the contact pressure in the contact area with the lubricant is less than 20% lower than that of model A.

On the contact surface $S_{K_1}$, there is a non-uniform distribution of contact tangential stress: there is a strong decrease $\tau_K/P$ in the areas of contact with lubricant, and negative values $\tau_K/P$ are observed in the region of grooves with lubricant. The non-uniform distribution $\tau_K/P$ with zones of positive and negative parameters has a strong influence on the wear of the anti-friction layer. The maximum contact tangential stress at $S_{K_1}$ does not differ significantly for the two models of the bearing under consideration. Similarly to the contact pressure, the greatest influence of the grooves with lubricant is observed in the contact zone with the lower steel plate: the maximum level of contact tangential stress on the main surface of the anti-friction material is greater by 2.5; 6.5; 24.2 times for loads of 500, 1000, 1250 kN, respectively. The influence of the grooves with lubricant on the relatively free edge of the anti-friction layer is not significant.

Within the framework of the paper, the comparison of numerically obtained values of the spherical bearing draft with the results of a series of full-scale experiments on deformation of the real structure of the spherical bearing L-100 by the vertical load 500-1250 kN, was carried out (Fig. 5).

![Graph of draft comparison](image)

**Fig. 5.** Draft of the spherical bearing and the error of the numerically obtained draft values from the full-scale experiment.

It is found out that at the nominal vertical load of 1000 kN, the difference between the results of the numerical solution of the problem for the model taking into account the grooves with lubricant and the results of the full-scale experiment is minimal and makes ~ 7.13%, for the model without taking into account the grooves ~ 13.05%.

Further, within the limits of research, the comparative analysis of parameters for the zones of contact of a spherical bearing at its deformation with the friction coefficients received as a result of the full-scale experiments and the reference friction coefficient of 0.04, was executed.

Fig 6. and 7. show the relative contact pressure and the relative contact tangential stress, respectively.
Fig. 6. Relative contact pressure at $S_{K_1}$ (a,b) and $S_{K_2}$ (c,d): a, c are model A; b, d are model B; dotted lines is “stick-slip” contact state zone.

For the contact deformation behavior of model A, the contact pressure at the friction coefficient corresponding to the contact with the lubricant is set at more than 9% lower, and without taking into account the lubricant – at more than 19% higher than the corresponding parameter at the contact deformation of the model with the friction coefficient of 0.04. In the case of model B, the maximum level $P_k/P$ with the friction coefficient obtained experimentally is lower by more than 7% and 9% at $S_{K_1}$ and $S_{K_2}$, respectively, than with the contact interaction with the friction coefficient of 0.04.

In model A, the contact tangential stress is more than 83% lower than the friction coefficient declared by the manufacturers of thin sliding bearing materials. When considering the influence of frictional properties of modified fluoroplastic on the contact parameters, we can conclude that the nature of the contact pressure and tangential stress distribution in general does not differ much from the calculations with a coefficient of friction of 0.04.
Fig. 7. Relative contact tangential stress at $S_k$ (a,b) and $S_{k_2}$ (c,d): a, c are model A; b, d are model B; dotted lines is “stick-slip” contact state zone.

It should be noted that the coefficient of friction has a significant impact on the contact state zones: for model A, full contact surface adhesion is observed at 0.4 and 3.5% of the contact surface for $\mu$ with and without taking into account the lubricant, respectively, with 1 to 2.5% of the contact surface near the edge of the layer is not involved in the work of the structure due to the loss of contact.

In the case of the model with taking into account the grooves with lubricant, there is no loss of contact between the top plate of the spherical bearing and the anti-friction layer. At the same time, the level of contact tangential stress in model B is 49% and 23% higher at $S_k$ and $S_{k_2}$, respectively, than in case of contact interaction with the coefficient of friction of 0.04. The distribution of the relative contact pressure differs from the value previously obtained by a large drop of $\tau_k/P$ in the area of the groove near the edge of the anti-friction layer.

4. Conclusions
Within the framework of the study, the deformation behavior of modified fluoroplastic as a material of anti-friction layer of spherical bearing was modeled. The comparative analysis of deformation behavior of two models of the spherical bearing with and without taking into account the grooves with lubricant was carried out. Influence of lubricated grooves on the parameters of the contact zones of the spherical bearing elements with the anti-friction layer was analyzed.

Upon analysis of the results of a series of numerical experiments, it was found out:

- At contact interaction with a coefficient of friction of 0.04, the greatest influence of grooves with lubricant on contact parameters is observed in a contact zone with the bottom steel plate: the maximum contact pressure on the average is more by 8.7 %; the maximum contact tangential stress on the main surface of an anti-friction material is by 2.5; 6.5; 24.2 times higher for loadings 500, 1000, 1250 kN, respectively

- At nominal vertical load of 1000 kN, the difference of results of numerical and full-scale experiment on deformation of the spherical bearing with constant coefficient of friction of 0.04 for the model with
taking into account the grooves lubricant is minimal and makes ~ 7.13%, for the model without taking into account the grooves ~ 13.05%.

- For the model without taking into account the grooves with lubricant, the contact pressure at the coefficient of friction obtained experimentally with the lubrication of the mating surfaces is by more than 9 % lower and the contact tangential stress is by more than 83 % lower than at the coefficient of friction declared by the manufacturers of thin sliding materials of the bearings.

- For the model with taking into account the grooves with lubricant, the contact pressure at the coefficient of friction obtained experimentally with taking into account the lubricant on the mating surfaces, is by more than 7-9% lower, and the contact tangential stress is by more than 23-49% higher than at the coefficient of friction declared by the manufacturers of materials of thin sliding layer of bearings.

- When modeling the contact interaction of spherical bearing elements without taking into account the grooves with lubricant at the experimentally obtained coefficients of friction, there is a loss of contact near the edge of the layer by a maximum of 2.5% of the contact surface. The contact with taking into account the grooves with lubricant results in no contact near the edge of the layer.

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