Comparative Analysis of the Polymeric Materials Deformation Behavior under Squeezed and Free Compression

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Abstract. The results of experimental studies of the modern antifriction polymer materials and composites based on them are presented in the work. The 6 most promising materials for use as antifriction coatings and interlayers in friction units of critical structures were selected from a set of materials: bearings, expansion joints etc. The deformation theory of elastic-plasticity for the active loading case is chosen to describe the polymer behavior model based on the experiments results in a first approximation. Compression charts are defined for the selected materials. Numerical models of constrained and free compression experiments are constructed. The series of numerical experiments established that the contact pressure level of composite materials is 25-40% lower at a single level of deformation. UHMWPE and modified PTFE under uniaxial deformed conditions state have an almost elastic behavior with weakly nonlinear hardening and in test problems their deformation behavior has small differences.

1. Introduction

A large set of polymer materials of Russian and foreign production suitable for use as antifriction coatings and interlayers in structural units operating in the framework of contact interaction with friction. Such materials are widely used in aviation technology [1], construction [2], medicine [3], engineering [4-5] and other fields. The modern antifrictional polymer materials include: antifriction composite polymer materials based on PTFE [6-9], modified PTFE [8-10], ultra-high molecular weight polyethylenes (UHMWPE) of Russian and foreign production and composite materials based on them [6, 8, 11]. Information on the materials properties and structure is necessary to solve the deformation behavior problems of structures with antifriction coatings and interlayers [6, 12]. Russian and foreign scientists are studying the physicomechanical, chemical, frictional and rheological properties of modern polymeric materials and composites based on them [6-18 and etc.]. Information insufficiency about the materials properties under study is still noted [16, 18], which hinders their effective application in many industries. Experimental study of the polymers properties used as antifrictional layers and the numerical models construction of their behavior in the framework of contact mechanics are relevant areas of research. Interdisciplinary studies of the modern polymers behavior are made in the work and include a series of experiments, processing of experimental data with the modern polymer behavior models construction and numerical simulation of the studied materials deformation behavior on test problems.
2. Experiments

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 antifriction materials at complex multistage deformation stories with offloading using a Zwick Z100SN5A testing machine. A series of full-scale experiments included (figure 1): 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.

Figure 1. Experimental studies of antifriction polymers: a) Brinell hardness, b) uniaxial stress state; c) uniaxial deformed conditions state.

More than 30 modern antifrictional materials and composite materials based on them, suitable to one degree or another as sliding interlayers in friction units were investigated in the experiments series. The 6 modern antifrictional polymers and composites based on them were selected from a wide range of materials as the most promising for application in friction units: carbon filled UHMWPE (Material 1); UHMWPE of Russian production (Material 2); UHMWPE of Germany production (Material 3); antifriction composite material based on PTFE with a dendrite bronze inclusions and molybdenum disulfide (Material 4); antifriction composite material based on PTFE with a spherical bronze inclusions and molybdenum disulfide (Material 5); modified PTFE (Material 6).

The tangent modulus $M$ and elastic modulus $E$ were determined from the test results at free and constrained compression. Other elastic constants of an isotropic elastic body are expressed through measured modules according to [19]. Poisson's ratio is defined by the formula $\nu = E/2\mu - 1$ where

$$\mu = E/8 \left( 1 + 3M/E - \sqrt{(1 + 3M/E)^2 - 16M/E} \right).$$

The elastic mechanical characteristics for the selected set of modern antifriction materials are presented in the table 1.

Table 1. Properties of modern antifrictional materials

| №  | Antifrictional materials | $E$ (MPa) | $\nu$   | №  | Antifrictional materials | $E$ (MPa) | $\nu$   |
|----|--------------------------|-----------|---------|----|--------------------------|-----------|---------|
| 1  | Material 1               | 1420.00   | 0.4402  | 4  | Material 4               | 903.00    | 0.4465  |
| 2  | Material 2               | 1050.00   | 0.4699  | 5  | Material 5               | 860.52    | 0.4388  |
| 3  | Material 3               | 706.00    | 0.4522  | 6  | Material 6               | 863.80    | 0.4610  |
It was found that modern antifrictional polymeric materials and composites based on them exhibit nonlinear properties. The deformational theory of elastic-plasticity is chosen to describe the behavior model of the materials as a first approximation (figure 2).

![Figure 2. Compression diagrams $\sigma - \varepsilon$.](image)

Compression diagrams $\sigma - \varepsilon$ obtained experimentally at low strain rates or determined by constructing envelope curves when processing cyclic free compression diagrams are shown in figure 2. Numerical calculation using the selected material behavior model gives good quantitative agreement with the experimental results for the case of active loading what is established in [17].

3. Mathematical modeling
The numerical simulation of experiments on constrained and free compression of cylindrical samples was performed as part of the influence analysis of the modern antifriction materials properties. The boundary-value deformation elastoplasticity problem in an axisymmetric formulation taking into account frictional contact interaction over the mating surfaces of the press plates and cylindrical samples is realized (figure 3). Contact interaction with a rigid steel cage is not taken into account. Squeezed compression of samples is shown in the scheme 1 and free compression of samples is shown in the scheme 2.

![Figure 3. Numerical model of the experiment: a) constrained compression; b) free compression.](image)
The contact problem mathematical formulation of an elastoplastic polymeric material with press plates was previously described in [17-18] and is supplemented by the following boundary conditions:
- on the surface \( S_1 \) \( \vec{u} = 0, \, \vec{\bar{u}} \in S_1 \);
- on the surface \( S_2 \) \( \bar{u}_i = \Delta l, \, \sigma_{\bar{r}} = 0, \, \bar{\bar{u}} \in S_2 \);
- the other external surfaces are free \( \vec{\sigma} \cdot \vec{n} = 0 \).

The polymer-metal surfaces are observed near the sample edge similarly to the first contact zone parameters at the maximum strain. The maximum peaks of contact parameters are observed near the edge of cylindrical sample. This effect is associated with the change of the contact status with the "adhesion" on "sliding". The level of the contact pressure and contact tangential stress rises to the sample edge smoothly by approximately on 25-30\% in the case of free compression. Peaks of contact parameters are observed near the sample edge similarly to the first calculation scheme.

The average values of contact zone parameters at the maximum strain level of 10\% for two design schemes versions are presented in figure 4.

![Graph](image_url)

**Figure 4.** Average values of contact press (a, c) and tangential stress (b, d) on \( S_{\bar{r}} \) at \( \varepsilon = 10 \% \): a, b for scheme 1; c, d for scheme 2; 1-6 are materials 1-6 respectively.

All sample of the UHMWPE and modified PTFE at 10\% strain have small differences between the contact pressure level: within 8 and 20\% for the case of squeezed and free compression respectively. Deformation of samples (material 4-5) equal to 10\% is achieved at significantly lower levels of

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**Table 4:**

| Scheme | Material | Contact Pressure | Tangential Stress |
|--------|----------|------------------|-------------------|
| 1      | Material 1 | 892 MPa | -0.349 MPa |
|       | Material 2 | 828 MPa | -0.293 MPa |
|       | Material 3 | 866 MPa | -0.320 MPa |
|       | Material 4 | 641 MPa  | -0.189 MPa |
|       | Material 5 | 532 MPa  | -0.152 MPa |
|       | Material 6 | 835 MPa  | -0.298 MPa |

**Figure 4:** Graphs showing the average values of contact press (a, c) and tangential stress (b, d) on \( S_{\bar{r}} \) at \( \varepsilon = 10 \% \): a, b for scheme 1; c, d for scheme 2; 1-6 are materials 1-6 respectively.
contact pressure and contact tangential stress than other materials considered: in the case of constrained compression contact pressure level is lower by 25-40% and the contact tangential stress is below by 20-35%; for the case of free compression the level of contact pressure and tangential stress is lower by 35-40%.

The dependences of the maximum level of contact parameters modulo on the cylindrical samples deformation under squeezed compression are shown in figure 5.

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\text{Figure 5. The dependences of the maximum modulo level of contact press (a) and tangential stress (b) on surface } S_{K_1} \text{ on } \varepsilon \text{ (design scheme 1): 1-6 are materials 1-6 respectively.}
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The dependence of the maximum level of contact pressure and contact tangential stress on the samples deformation is close to a linear law. At one level of contact parameters the deformation of samples from modern antifriction composite materials is 25-30% more than that of the other considered polymers. And \( \max |P_K| \) is 0.5-0.7% higher than the average contact pressure \( P_K \). The maximum level of contact shear stress is on average \( \sim 25 \) times less than contact pressure.

The dependences of the maximum level of contact parameters modulo on the cylindrical samples deformation under free compression are shown in figure 6.

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\text{Figure 6. The dependences of the maximum modulo level of contact press (a) and tangential stress (b) on } S_{K_1} \text{ at } \varepsilon \text{ (design scheme 2): 1-6 are materials 1-6 respectively.}
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The dependence of the maximum level of contact pressure and contact tangential stress on the samples deformation is not linear. The maximum contact pressure level of design scheme 2 is approximately 95-96% lower than for design scheme 1. At one level of contact parameters the deformation of samples from modern antifriction composite materials is 30-45% higher than that of the other considered polymers similar to the first design scheme. The maximum level of contact tangential stress is on average \( \sim 35 \) times less than contact pressure.
5. Conclusion
A series of experimental studies of polymer antifriction materials aimed at obtaining data on their physical and mechanical properties was performed as part of the work. The studies were performed for a wide range of modern antifriction polymer materials and composites based on them. The elastic-plasticity deformation theory is chosen to describe the behavior model of materials in a first approximation, Young's modulus and Poisson's ratio of the elastic portion are determined, diagrams $\sigma-\varepsilon$ are described.

As part of the deformation behavior analysis of modern antifriction materials it has been established:
- carbon filled UHMWPE has the best deformation characteristics, but additional experimental studies with various histories of prolonged multi-stage loading are needed to build and identify a qualitative model of its behavior;
- the other UHMWPE’s under consideration and the modified PTFE in the uniaxial deformed state exhibit almost elastic behavior with weakly nonlinear hardening, in test problems their deformation behavior has small differences;
- antifriction composite materials have more significant non-linear and viscoelastic effects, as well as greater pliability compared to other materials studied, rheological effects are more noticeable with dendritic particle shape.

The numerical modeling results do not contradict to the experiments results.

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