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АНАЛИТИЧЕСКИЕ И ЧИСЛЕННЫЕ МЕТОДЫ РАСЧЕТА КОНСТРУКЦИЙ
ANALYTICAL AND NUMERICAL METHODS OF STRUCTURAL ANALYSIS

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Analysis of Viscoelastic Behavior of Antifriction Layer Materials in Bridge Spherical Bearings under Thermomechanical Loading

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Abstract. Thermoplastic polymeric materials have found wide application as protective and antifriction coatings and interlayers of friction units. Spherical bearings include relatively thin sliding layers made of antifriction materials. Polytetrafluoroethylene (PTFE) is widely used as a material for sliding layers. However, at present, there are modern composite and modified materials with improved physical and mechanical properties that can be used as sliding layers. Antifriction materials are often modeled in terms of elasticity theory or elastoplasticity theory. However, it has been established that these materials exhibit viscoelastic properties. A series of experiments to determine the thermomechanical properties of the materials is performed in the current work. PTFE, a metal composite based on PTFE with bronze inclusions (MAK (F4BR40M2)) and structurally modified Arflon AR-200 PTFE were investigated using dynamic mechanical analysis. The temperature change range [−40; +80] °C was considered, it corresponds to the operating temperatures of bridge structures. Temperature dependencies of the storage modulus, loss modulus and loss tangent were obtained. Viscoelastic models of material behavior, such as Maxwell bodies using Prony series and temperature-time analogy, were constructed based on experimental data. Viscoelastic behavior of materials was analyzed in terms of deformation of a bridge spherical bearing under static and periodic loads, taking into account the ambient temperature. The relationships for the effect of temperature on the stress-strain response and contact parameters were obtained. The influence of the thermal expansion coefficient of materials on the structure behavior was considered. It was found that the sliding layer made of MAK allows for a more favorable stress-strain state compared to the structure including a sliding layer made of PTFE: the maximum stress intensity is less by ~ 3%; the maximum strain intensity is less by ~ 20%; displacements along the normal to the sliding layer are less by ~ 17.2%.

Keywords: bridge structure, bearing, modeling, viscoelasticity, polymer, composite, Maxwell's model, Prony, finite element method, contact, friction

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Анализ вязкоупругого поведения материалов антифрикционной прослойки сферической опорной части моста при термосиловом нагружении

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Аннотация. Термопластические полимерные материалы нашли широкое применение в качестве защитных и антифрикционных покрытий и прослоек узлов трения. Сферические опорные части включают относительно тонкие слои скольжения из антифрикционных материалов. Политетрафторэтилен (ПТФЭ) широко используется в качестве материала слоев скольжения. Однако существуют современные композиционные и модифицированные материалы с улучшенными физико-механическими свойствами, которые могут применяться в качестве слоев скольжения. Антифрикционные материалы часто моделируются в рамках теории упругости или теории упругопластичности. Но установлено, что данные материалы проявляют вязкоупругие свойства. В текущей работе выполнен цикл экспериментов для определения термомеханических свойств материалов. ПТФЭ, металлокомпозит на основе ПТФЭ с бронзовыми включениями (МАК (Ф4БР40М2)) и структурно-модифицированный ПТФЭ Арфлон AR-200 были исследованы в рамках динамического механического анализа. Рассматривался диапазон изменения температур [−40; +80] °C, он соответствует температурам эксплуатации мостовых сооружений. Получены температурные зависимости модуля накопления, модуля потерь и тангенса угла механических потерь. На основе экспериментальных данных построены вязкоупругие модели поведения материалов, такие как тела Максвелла, с использованием рядов Прони и температурно-временной аналогии. Вязкоупругое поведение материалов было проанализировано в рамках деформирования сферической опорной части мостовых сооружений при статической и периодической нагрузке с учетом температуры окружающей среды. Получены зависимости параметров напряженно-деформированного состояния и контакта от температуры. Рассмотрено влияние коэффициента термического расширения материалов на поведение конструкции. Установлено, что слой скольжения из МАК позволяет получить более благоприятное напряженно деформированное состояние по сравнению с конструкцией, включающей слой скольжения из ПТФЭ: максимальная интенсивность напряжений меньше ~ на 3 %; максимальная интенсивность деформаций меньше ~ на 20 %; перемещения по нормали слоя скольжения меньше ~ на 17,2 %.

Ключевые слова: мостовое сооружение, опорная часть, моделирование, вязкоупругость, полимер, композит, модель Максвелла, Прони, метод конечных элементов, контакт, трение

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1. Introduction

Polytetrafluoroethylene (PTFE) was first synthesized in 1938 by Roy Plunkett and is still considered the “king of plastics” [1]. The chemical structure of PTFE consists of a carbon skeleton surrounded by a protective layer of fluorine atoms [2]. The material exhibits high structural regularity, which can initiate a high degree of microstructure crystallization, which is enhanced when exposed to negative temperatures. After a melting point of 370±5°C, the material does not become viscous, but becomes amorphous with high viscosity [3]. In the temperature range from 10 to 30 °C, the material undergoes a β-transition associated with the transition from a glassy state to a highly elastic state [4]. Chemical inertness, hydrophobicity, resistance to thermal, biological, and oxidative degradation, high strength, and low friction coefficient have earned PTFE the title of “king of plastics.” PTFE accounts for about 60% of the global thermoplastics market [5]. The material is widely used as sliding layers in bearings, expansion joints, and turning mechanisms of bridge structures [6–8]. When in contact with harder bodies, the material exhibits plastic flow and severe abrasion, as well as viscous properties [9; 10]. Creep of the material under certain deformation conditions is also observed [10]. It has been established that even after the manufacturing process, various surface microdefects in the form of pores, cracks, and splits may be present [11]. Poor thermal stability and a high coefficient of thermal expansion of PTFE are also noted [12]. The disadvantages of PTFE include: structural rearrangement at a temperature of +20 °C, a tendency to deform at constant temperatures in an unloaded state, low radiation resistance, and significant, in some cases irreversible, expansion when heated [3].

Advances in materials science have led to the development of a fairly large set of alternatives to the “king of plastics” [3; 13; 14]. Arflon materials (OOO NPP Arflon, company in Moscow, Russia) are noted as an alternative to pure PTFE with improved physical and mechanical properties without loss of functionality [3]. Arflon materials stand out as promising protective coatings and interlayers for the Arctic conditions, as well as areas with severe temperature fluctuations [15]. Other Russian and international alternatives to PTFE are also being considered [3]. For example, Superfluvis, a material with increased wear resistance, is a composite material with a PTFE matrix (~83% of the total mass) and modified crushed carbon fiber with a fluoropolymer nano-coating up to 40 nm thick (17% of the specific weight) [16]. Its application as coatings and interlayers for friction units, as well as a material for bone tissue implants is considered [16; 17]. Improved strength and physical characteristics compared to pure PTFE are noted in a large set of modern anti-friction polymers and composites [3; 13; 18–20]. However, data on the behavior of modern anti-friction polymers and composites are often limited to a narrow range of physical, mechanical, and tribological characteristics.

A number of scientists have noted the lack of data on the thermomechanical properties of the materials [9; 21; 22]. This hinders the evaluation of the deformed state of friction units, structures, and systems in which they are used within the operating temperature range, as well as the analysis of the possibility of replacing the materials with modern alternatives. Structural and mechanical modeling of material behavior, including contact mechanics and wear problems, is important for creating digital models of structures in terms of predictive analysis and is an effective tool at the design or optimization stages [9]. The construction of digital models of anti-friction materials, taking into account the temperature factor, is a relevant task for predicting their behavior during the manufacturing process, as well as during the operation of structures and systems in which they are used [23].

In this work, a series of experimental studies were conducted on PTFE-based materials modified or filled with metal nano-inclusions, as well as pure PTFE, to determine the relationship between the thermo-mechanical parameters and temperature. Models of material behavior in terms of thermo-viscoelasticity have been constructed. An analysis of the behavior of a spherical bearing with a sliding layer made of three different anti-friction materials has been performed over a wide range of ambient temperatures under static and periodic loads.

2. Materials and Methods

The thermomechanical behavior of a spherical bearing of a bridge structure is analyzed using the case of the L-100 design manufactured by OOO AlfaTech (company in Perm, Russia). The model of the contact unit of the spherical bearing is shown in Figure 1 and includes a spherical steel rocker (1), a lower steel plate with a spherical cutout (2), interacting through a spherical polymer/composite sliding layer (3). The behavior of the structure is considered to be axisymmetric, therefore, the spherical sliding layer does not take into account the depressions for lubricant, which can be formed as spherical holes or annular grooves [24].

The maximum height of the structure is 54 mm, with a height ratio of 20 mm for the spherical rocker, 30 mm for the lower steel plate, and 4 mm for the sliding layer along the central section of the bearing. The maximum width and depth of the structure is $B = 2b = 155$ mm. The standard angle of inclination of the end face of the sliding layer α_p is 30°. The sliding layer protrudes $h_l \approx 2$ mm relative to the lower steel plate to prevent metal-to-metal contact.

At the interface between the interlayer and the steel structural elements, frictional contact is implemented with an pre-unknown distribution of contact states (sticking, slipping, no contact) [14]. The friction coefficient is assumed to be constant and equal to 0.04. The mathematical formulation of the problem and the analysis of the influence of the degree of system discretization on the numerical solution were previously described in [25]. The sliding layer was divided into 16 elements along the height. The size of the finite elements on the interface surfaces $S_{K_1} - S_{K_3}$ corresponds to the partitioning of the sliding layer, and increases gradually with increasing distance from $S_{K_1} - S_{K_3}$. The characteristics of the finite element mesh, finite elements, and other aspects of the problem modeling are presented and described in more detail in [14].

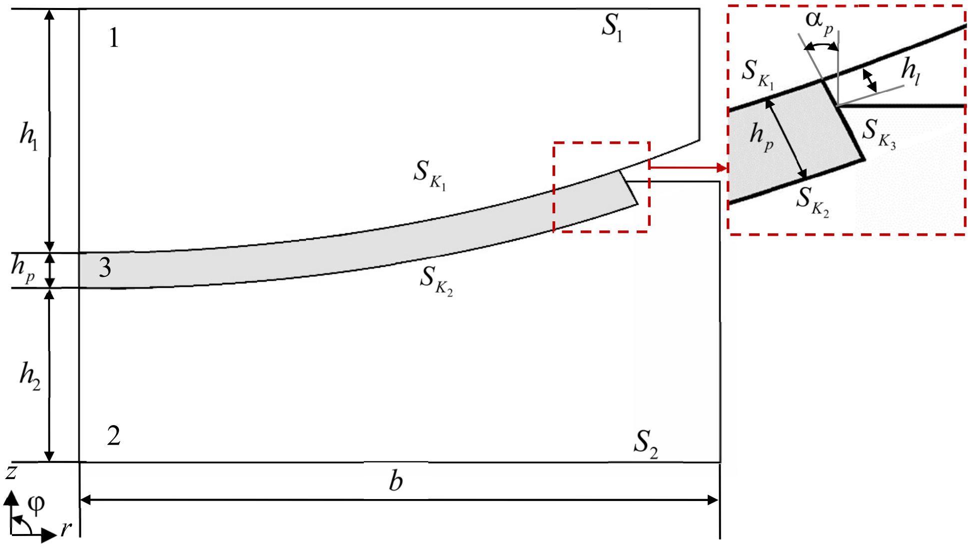


Figure 1. Model of the spherical bridge bearing

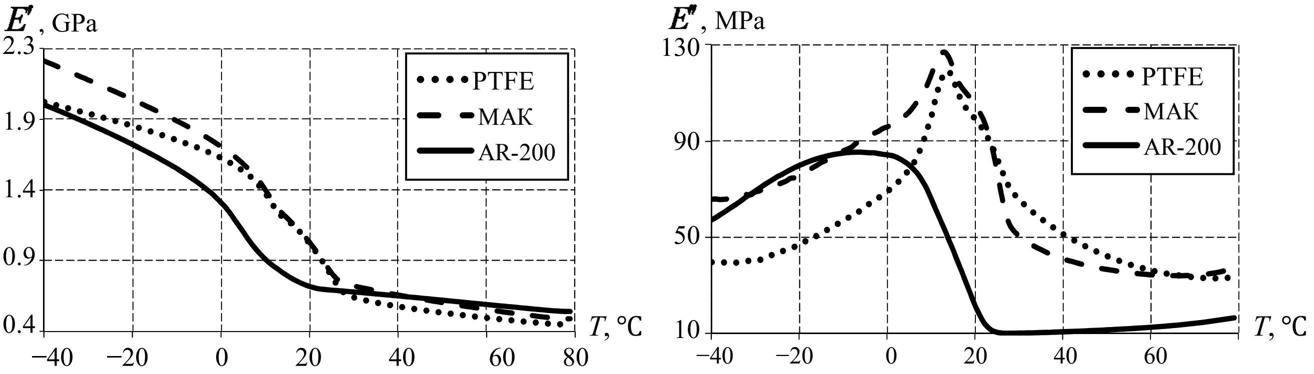
Source: made by A.P. Bogdanova.

The problem of thermomechanical deformation of the bearing was implemented using the finite element method in the ANSYS Mechanical APDL 2021R2 (Liverpool, USA) engineering analysis software. The procedures for constructing a numerical model of the structure, finite element meshing, thermomechanical loading, and processing of results are fully automated using the APDL parametric programming language.

Two loading schemes for the bearing are considered: static and periodic loading, taking into account the temperature field. Static loading was performed at a nominal vertical load of 1000 kN on the bearing. Periodic loading was modeled as a sinusoidal load varying from 500 to 1000 kN, with and without a 60-second hold at 500 and 1000 kN. Different numbers of cycles were considered. Static and periodic loads were applied to surface S_1 of the spherical rocker. The structure was subjected to a constant ambient temperature ranging from −40 to +80 °C. The bearing is assumed to be fixed, therefore normal displacement on surface S_2 of the lower steel plate is restrained. At the same time, the structure is compliant in other directions and has the ability to expand/contract thermally.

The steel structural elements are made of high-strength alloy steel and are modeled in terms of elasticity theory with a Young's modulus of 2×10^{11} and a Poisson’s ratio of 0.3. The following materials are considered for the sliding layer: polytetrafluoroethylene (PTFE); PTFE-based metal composite with dendritic bronze inclusions and molybdenum disulfide (MAK (F4BR40M2)); structurally modified PTFE without fillers AR-200 (OOO NPP Arflon, Moscow, Russia). To develop a model of material behavior in terms of viscoelasticity theory, a series of empirical studies were conducted using dynamic mechanical analysis (DMA) based on a three-point bending test of rectangular samples with average dimensions of 60×12×3 mm made from commercially available polymer blanks of sliding layers. The samples were provided by OOO AlfaTech. The samples were subjected to an oscillating load with an impact frequency of 1 Hz in a temperature range from −40 to +80 °C. The research covered only the area of conventional bridge structures, which corresponds to the design minimum air temperature of up to −40 °C inclusive, according to the GOST R 59623-2021[1] National Standard of the Russian Federation. To ensure the statistical significance of the results, at least four tests were performed on the samples for each type of thermo-mechanical loading. A more complete description of the experimental conditions is given in [14].

As a result of a series of experiments, temperature dependencies of the storage modulus and loss modulus were obtained in the temperature range [−40;+80] °C. The arithmetic mean plots of the thermomechanical characteristics of the materials are shown in Figure 2 and characterize the glassy and highly elastic state of the material at $T \in [-40;+80]$ °C.



a *b*

Figure 2. Thermomechanical properties of antifriction interlayer materials:
a — storage modulus; *b* — loss modulus

Source: made by A.P. Bogdanova.

The β-transition temperature of the sliding layer materials has been established, which is considered to be the vitrification/softening temperature of the material according to the GOST R 56753-2015[2] National Standard of the Russian Federation. The vitrification/softening temperature of PTFE and MAK is

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[1] GOST R 59623-2021. *Automobile roads of general use. Bridge constructions. Design of steel elements*. Moscow: Russian Standardization Institute; 2022.

[2] GOST R 56753-2015. *Plastics. Determination of dynamic mechanical properties*. Moscow: Standartinform; 2016.

approximately 14°C, and that of AR-200 is 8°C. The results of the experiments are consistent with the data from the DMA analysis of PTFE [4].

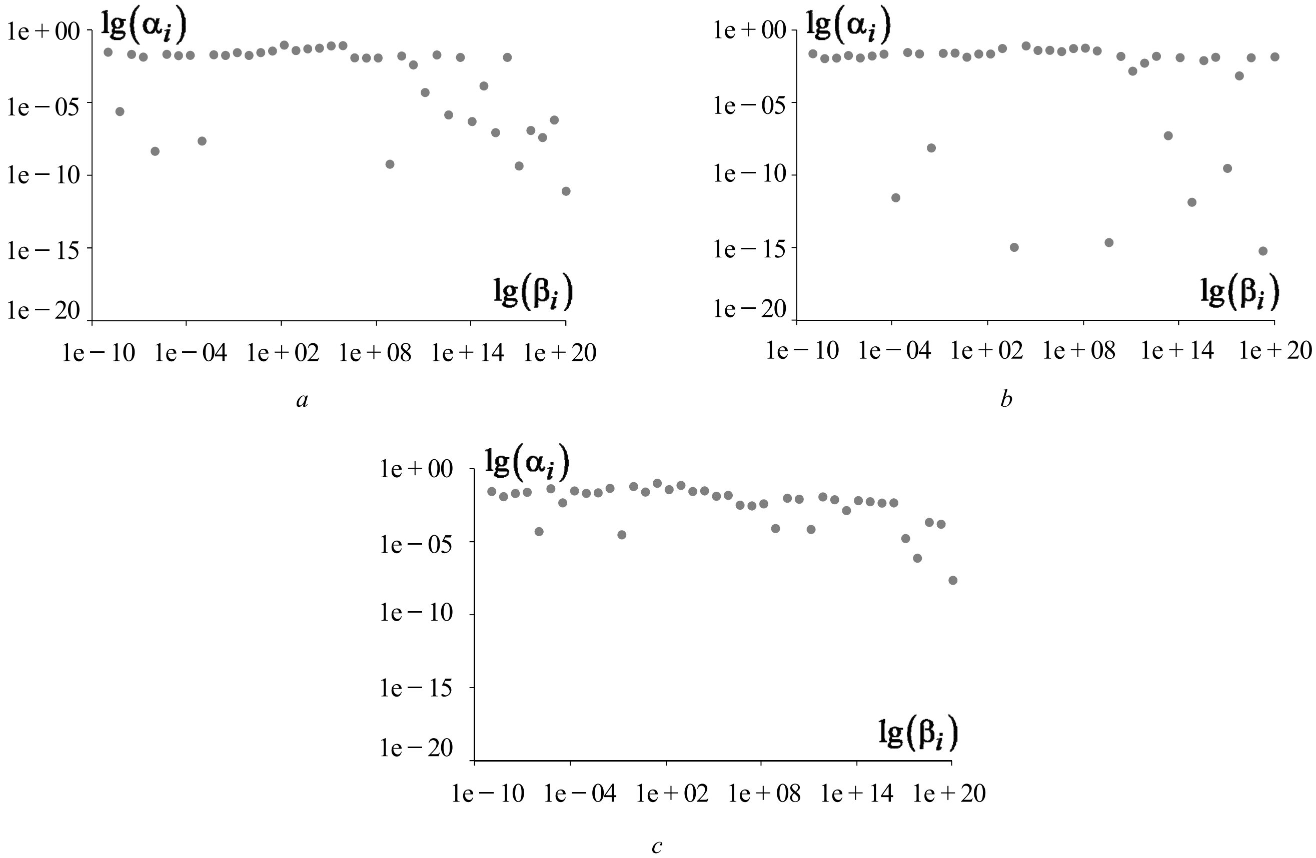
Based on experimental research data, Maxwell's model was chosen as a first approximation for phenomenological constitutive relationships describing the viscoelastic behavior of materials. The model is based on Prony series, taking into account the Williams-Landel-Ferry (WLF) temperature-time analogy. To determine the parameters of the vector of unknowns in the Maxwell and WLF models, a user procedure for numerical identification based on the Nelder-Mead multiparametric optimization algorithm was used; the mathematical manipulations and problem statement were described earlier in [26].

The parameters of the viscoelastic model and WLF are presented in Table, and the relationships between the relative shear moduli and the relaxation time are shown in Figure 3.

Parameters of the temperature-time analogy and viscoelastic behavior model of materials

Material	C_1	C_2	T_r, °K	E_0, MPa	E_∞, MPa
PTFE	203.91	849.00	270.21	2021.39	446.32
MAK	299.10	1069.37	263.79	2313.68	489.78
AR-200	103.24	419.18	266.80	2006.57	541.68

S o u r c e: made by A.P. Bogdanova, Y.O. Nosov.



a *b* *c*

Figure 3. Relationship between the weighting coefficients of the Prony series and the relaxation time:
a — PTFE; *b* — MAK; *c* — AR-200

S o u r c e: made by A.A. Kamenskikh, A.P. Bogdanova, Y.O. Nosov.

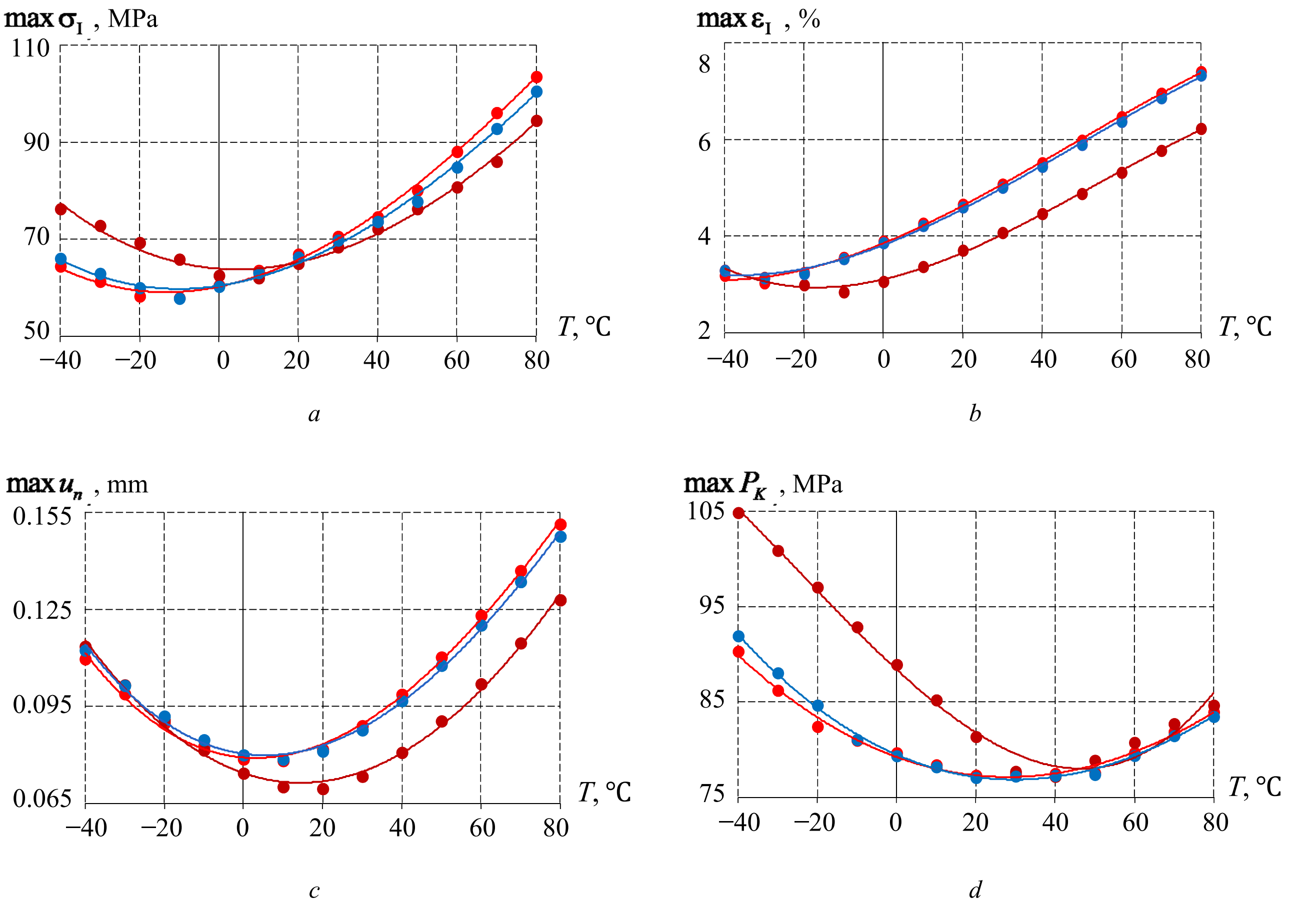
The model parameters were obtained based on simulation modeling of a three-point bending test, with the results of the numerical experiment deviating from the experimental data by less than 5%. Material behavior models were implemented in ANSYS.

The model takes into account the coefficients of thermal expansion (CTE) of the materials. Independent studies to determine changes in the CTE of materials depending on temperature were not conducted. Literature sources indicate variation ranges of CTE from 8 to 32×10^{-5} °C^{-1} for PTFE and from 8 to 24–25×10^{-5} °C^{-1} for AR-200 [3; 27]. The CTE of materials depends on temperature, but to construct a numerical model that takes into account the temperature variation of the parameter, data on the relationship between thermal deformation and temperature are needed. No data on the CTE for the MAK (F4BR40M2) material was found in the literature. As a first approximation, it was decided to analyze the deformation of the bearing with a constant CTE $\alpha = 8\times10^{-5}$ °C^{-1}, the same for all materials under consideration. It was also decided to investigate the effect of variation of $\alpha(T)$ on the stress-strain response of the bearing with a PTFE sliding layer. The CTE of steel elements was also assumed to be constant $\alpha = 1\times10^{-6}$ °C^{-1} [28].

3. Results and Discussion

3.1. Static Load

Data on the distribution of the stress-strain response parameters and contact parameters of spherical bearings with sliding layers made of different anti-friction materials for the ambient temperature range of [−40;+80] °C were obtained. The relationships between the maximum parameter values and temperature are shown in Figure 4.



a *b*

c *d*

Figure 4. *Maximum* stress-strain response parameters as a function of temperature:
a — stress intensity; *b* — strain intensity; *c* — normal displacement with respect to the end face; *d* — contact pressure at the interface between the interlayer and the spherical segment; light red is PTFE; dark red is MAK; blue is AR-200

Source: made by A.P. Bogdanova.

The data is described by a third-degree polynomial, with an error of no more than 2%. The maximum stress intensity value decreases until a temperature of −10°C (PTFE, AR-200) and 0°C (MAK), then begins to increase. The maximum strain intensity value changes little at negative temperatures and increases in the positive temperature range. The maximum displacements of the sliding layer end decrease until a temperature of 10°C (PTFE, AR-200) and 20°C (MAK), then begin to increase. This is due to the transition of materials from a glassy state to a highly elastic state. At the same time, the maximum contact pressure on surface S_{K_1}, along which the spherical segment can rotate, decreases until an ambient temperature of 40°C, with a further increase in the parameter. In the temperature range from −40 to 30–40°C, a detachment zone is observed near the edge of the sliding layer, which is absent at higher temperatures. A redistribution of the zones of complete adhesion and slippage is also observed. The sliding layer made of composite material (MAK) has the smallest values of strain intensity and normal displacements of the sliding layer end. The stress-strain response of the bearings with a sliding layer made of PTFE and AR-200 has insignificant differences. Structural modification of PTFE by radiation as part of the AR-200 manufacturing process allowed to slightly reduce the maximum stress-strain response and contact parameters at temperatures above the vitrification/softening temperature (by no more than 3%). This effect is also due to the fact that at temperatures above room temperature, the material exhibits a greater elastic response compared to PTFE. Similarly, a greater elastic response at $T > 23$ °C compared to PTFE is observed in MAK.

The distribution of the stress-strain response parameters near the edge of the sliding layer is shown in Figure 5 for the case of the structure with a PTFE interlayer at a temperature of 30°C. Normal displacements are shown with a deformation magnification factor to reflect the change in geometry.

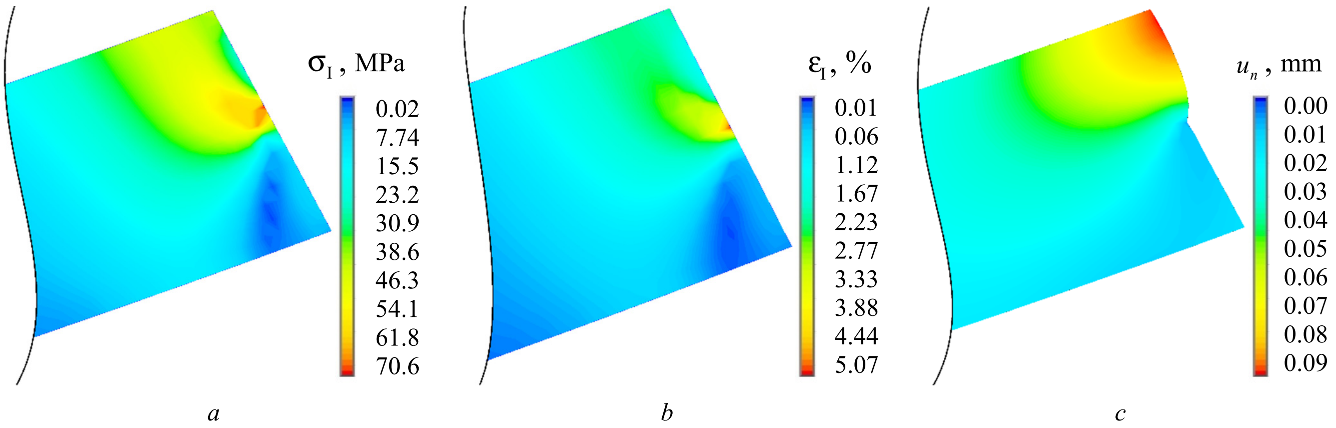


Figure 5. Distribution of the stress-strain response parameters near the edge of the PTFE anti-friction interlayer:
a — stress intensity; *b* — strain intensity; *c* — normal displacement with respect to the end face
Source: made by A.A. Kamenskikh.

It should be noted that the maximum stress and strain intensities are observed near the concentrator (the metal rim of the lower steel plate). In the main volume of the sliding layer, the stress intensity value does not exceed the strength limit of the materials. The maximum strain intensity value does not exceed 10% for all the considered materials of the sliding layer and ambient temperatures. The maximum displacements of the sliding layer end are observed near the interface of the interlayer and the upper rocker; for all the considered materials, they do not exceed 0.16 mm.

An analysis of the influence of CTE on the stress-strain response parameters in the case of a PTFE sliding layer is shown in Figure 6.

It should be noted that the CTE of the material has a significant effect on the behavior of the sliding layer of the bearing. Experimental studies aimed at obtaining the relationship between the CTE and temperature for the entire set of materials under consideration need to be performed as part of the development of a model describing its behavior. The relationship of the effect of CTE on the stress-strain response and contact parameters when the ambient temperature changes is non-linear. The maximum values of the stress-strain response parameters are observed at high positive temperatures, which is associated with the softening of the material and its significant deformation near the rim of the lower steel plate. The maximum value of contact pressure is observed at negative temperatures, which is associated with the crystallization of the material and greater stiffness.

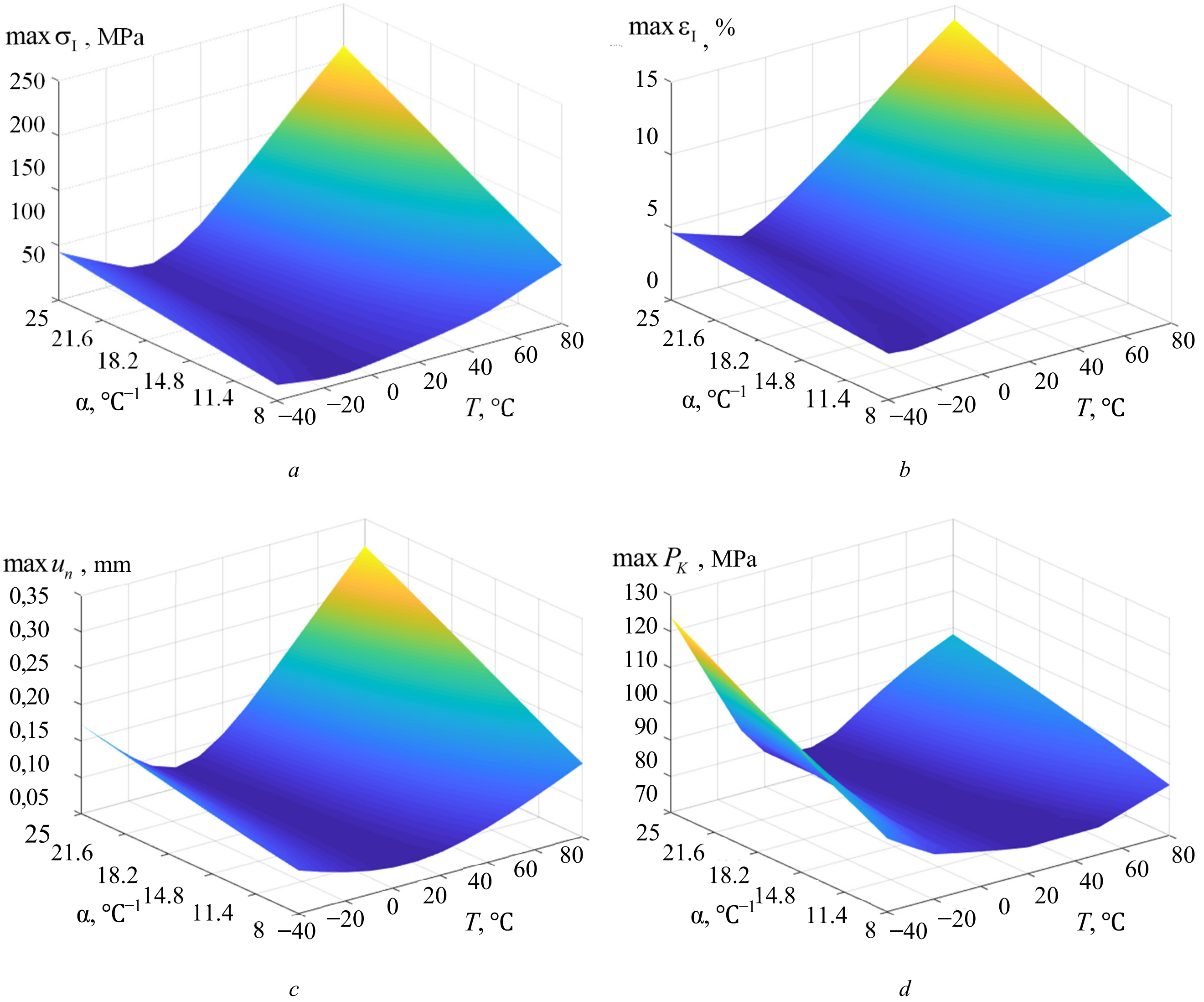


Figure 6. Stress-strain response parameters as functions of temperature and thermal expansion coefficient:
a — stress intensity; *b* — strain intensity; *c* — normal displacement with respect to the end face;
d — contact pressure at the interface between the interlayer and the spherical segment

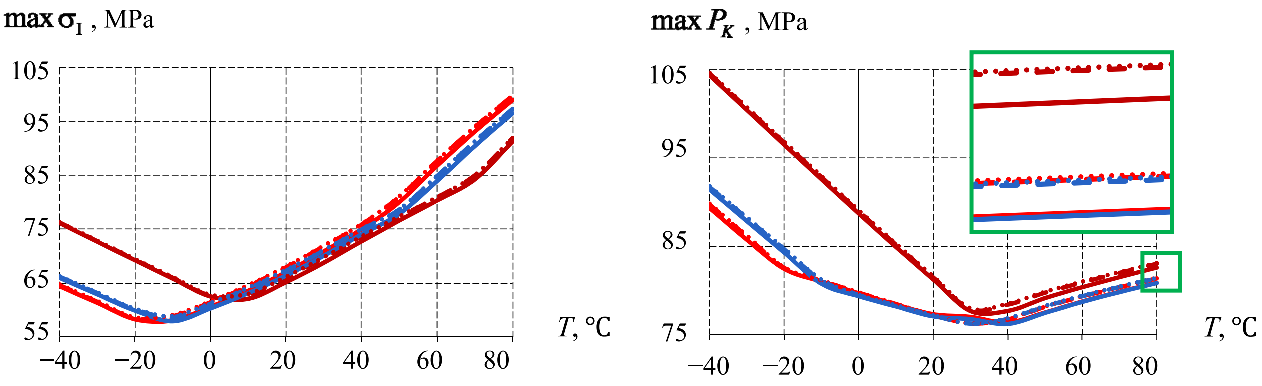
Source: made by Y.S. Kuznetsova.

The numerical modeling results of the bearing deformation are in good agreement with the data from numerical and field studies [29; 30]. The nature of the stress distribution over the volume of the anti-friction layer and the zone of localization of the maximum values are consistent with the data obtained in [30]. The maximum stress and displacement values are also comparable to the data obtained in [29]. The relationships between temperature and the stress-strain response parameters in the small operating temperature range from −10 to 20°C were obtained in [30] for different load levels on the bearing; the relationships are nonlinear, and it was observed that the parameters decrease with increasing temperature. The results are partially consistent with the current study, but cannot be quantitatively compared due to the geometric configuration of the structures and different manufacturers of the sliding layer materials. PTFE obtained from different powders, even using relatively similar molding technologies, have different mechanical properties and reactions to external thermomechanical impact [31].

3.2. Periodic Load

As part of the analysis of the effect of periodic loading, it was established that load exposure does not have a strong influence on the stress-strain response and contact parameters. This is due to the fact that the exposure time is significantly less than the relaxation time of the materials.

The relationship between the maximum stress intensity value and the contact pressure on S_{K_1} for 1, 3, and 15 iterations of the loading cycle is shown in Figure 7. The results are presented for a maximum load on the bearing of 1000 kN.



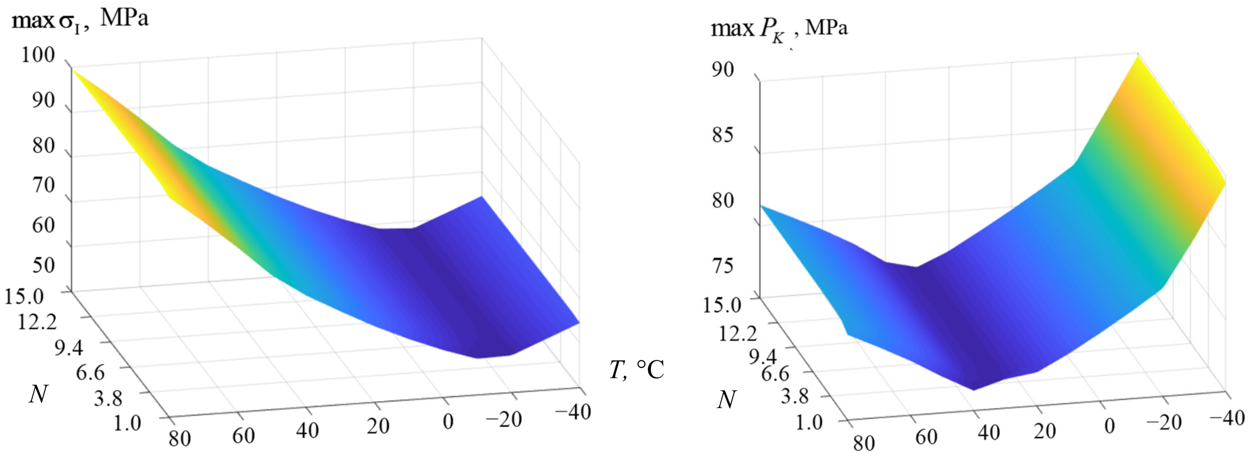
a *b*

Figure 7. Relationship between the stress-strain response parameters and temperature under periodic loading:
a — stress intensity; *b* — contact pressure at S_{K_1}; light red is PTFE; dark red is MAK;
blue is AR-200 solid is 1st loading cycle; dashed is 3rd loading cycle; dotted is 15th loading cycle
S o u r c e: made by A.P. Bogdanova.

It can be noted that there is an increase in the values of the parameters as the number of periodic load cycles increases. The nature of the change does not depend on the number of load cycles.

Two-parameter relationships $\max\sigma_{\mathrm{I}}(T,N)$ and $\max P_K(T,N)$ are shown in Figure 8. With a small number of periodic load iterations, a smooth, insignificant increase in the parameters is observed across the entire range of ambient temperatures. It was decided to increase the number of periodic load iterations to 50 and 100 cycles. The results are shown in Figure 9 at an ambient temperature of 30°C.

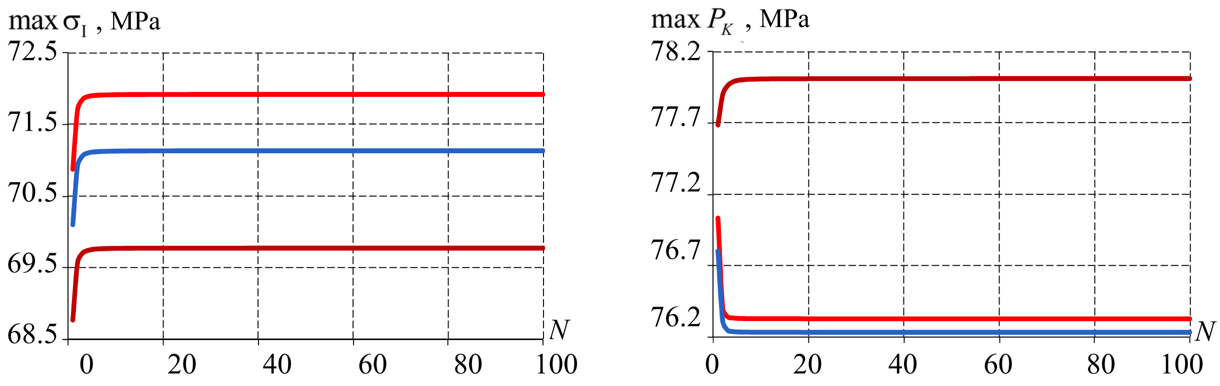
The maximum change in the parameters is observed during the first 5-8 loading cycles, after which the parameters change slowly and reach an asymptote after 25 (PTFE), 54 (MAK), and 46 (AR-200) loading cycles. It can be noted that the maximum stress intensity value is observed in the bearing with a PTFE interlayer, and the minimum — with a MAK interlayer. The relationship between the maximum contact stress value and the number of loading cycles of structures with layers made of different materials differs: with PTFE and AR-200, a decrease in the contact pressure level is observed during the initial loading cycles; with MAK, on the contrary, an increase is observed. The maximum contact pressure value is observed with a MAK interlayer, and the minimum — with AR-200. The differences in the stress-strain response and contact parameters of the structures with PTFE and AR-200 interlayers are insignificant, less than 1.5%. The stress-strain response parameters of the structure with a MAK interlayer compared to PTFE are: $\max\sigma_{\mathrm{I}}$ is ~3% lower; $\max\varepsilon_{\mathrm{I}}$ is ~20% lower; $\max u_n$ is ~17.2% lower.



a *b*

Figure 8. Relationship between the stress-strain response parameters, temperature and periodic load cycle number, PTFE: *a* — stress intensity; *b* — contact pressure at S_{K_1}

Source: made by Y.S. Kuznetsova.



a *b*

Figure 9. Relationship between the stress-strain response parameters and the periodic load iteration, at $T = 30$°C: *a* — stress intensity; *b* — contact pressure at S_{K_1} ; light red is PTFE; dark red is MAK; blue is AR-200

Source: made by A.P. Bogdanova.

The maximum change in the parameters is observed during the first 5-8 loading cycles, after which the parameters change slowly and reach an asymptote after 25 (PTFE), 54 (MAK), and 46 (AR-200) loading cycles. It can be noted that the maximum stress intensity value is observed in the bearing with a PTFE interlayer, and the minimum — with a MAK interlayer. The relationship between the maximum contact stress value and the number of loading cycles of structures with layers made of different materials differs: with PTFE and AR-200, a decrease in the contact pressure level is observed during the initial loading cycles; with MAK, on the contrary, an increase is observed. The maximum contact pressure value is observed with a MAK interlayer, and the minimum — with AR-200. The differences in the stress-strain response and contact parameters of the structures with PTFE and AR-200 interlayers are insignificant, less than 1.5%. The stress-strain response parameters of the structure with a MAK interlayer compared to PTFE are: $\max \sigma_I$ is ~3% lower; $\max \varepsilon_I$ is ~20% lower; $\max u_n$ is ~17.2% lower.

The relationships for the stress-strain response parameters of the bearing obtained in the analysis under periodic loading are consistent with the results of [32]. The deformed state of the bearing reaches an asymptote after a certain number of loading cycles, which depends on the materials of the sliding layer, external loads, and environmental conditions.

To minimize the deviation of the material behavior model from the actual object under study, it is necessary to take into account the plastic deformation that has been established experimentally [4; 9; 22]. The construction of Anand's elastic-viscoplastic model for a set of anti-friction materials is one of the areas of development, including taking into account the effect of temperature on activation energy, initial deformation resistance and sensitivity to deformation rate [33].

4. Conclusion

As part of the study, a numerical and experimental analysis of the behavior of three PTFE-based materials, that can be used to varying degrees as relatively thin sliding layers of bridge bearing structures, was conducted. The experimental studies included a dynamic mechanical analysis over a wide temperature range. Numerical studies included an analysis of the behavior of materials described by viscoelasticity theory under static and periodic loading, taking into account the ambient temperature ranging from −40 to +80 °C.

The following results were obtained in the course of the study:

1. The temperature dependencies of the storage modulus, loss modulus, and mechanical loss tangent were determined for a set of anti-friction materials.
2. Models of the viscoelastic behavior of materials over a wide temperature range were constructed in terms of the Maxwell model using Prony series and temperature-time analogy based on experimental data.
3. The deformed state of the sliding layers of the bridge bearing was investigated, taking into account the viscoelastic behavior of materials under static and periodic loads in the operating temperature range. It was found that structural modification of PTFE has a negligible effect on the behavior of the material within the friction unit, while the design with a composite material (MAK) interlayer has improved the stress-strain response parameters with a commensurate increase in the contact parameters at temperatures below the vitrification/softening temperature.

References

1. Liang X., Wu P., Lan L., Wang Y., Ning Y., Wang Y., Qin Y. Effect of polytetrafluoroethylene (PTFE) content on the properties of Ni-Cu-P-PTFE Composite Coatings. *Materials*. 2023;16:1966. https://doi.org/10.3390/ma16051966 EDN: DDKHGZ
2. Bosq N., Guigo N., Persello J., Sbirrazzuoli N. Crystallization of polytetrafluoroethylene in a wide range of cooling rates: nucleation and diffusion in the presence of nanosilica clusters. *Molecules*. 2019;24:1797. https://doi.org/10.3390/molecules2409179 EDN: QPHYKO
3. Prokimov A., Dzhurinsky K., Smirnova Yu. Promising insulating materials for radio frequency cables and connectors. *Components and technologies*. 2017;2(187):105–113. (In Russ.) EDN: XYEVGL
4. Henri V., Dantras E., Lacabanne C., Dieudonne A., Koliatene F. Thermal ageing of PTFE in the melted state: Influence of interdiffusion on the physicochemical structure. *Polymer Degradation and Stability*. 2020;171:109053. https://doi.org/10.1016/j.polymdegradstab.2019.10905 EDN: RGQHYD
5. Alaraby M., Abass D., Velázquez A., Hernández A., Marcos R. Polytetrafluoroethylene microplastic properties, pollution, toxicity and analysis: a review. *Environmental Chemistry Letters*. 2025;24:27–59. https://doi.org/10.1007/s10311-025-01885-w
6. Li Y., Guo W., Huang X., Chen Z., Gao Y. Friction characteristics and lubrication properties of spherical hinge structure of swivel bridge. *Lubricants*. 2024;12(4):130. https://doi.org/10.3390/lubricants12040130 EDN: BHWEZL
7. Hu Q., Pei Q., Li P. Reducing the Friction Coefficient of Heavy-Load Spherical Bearings in Bridges Using Surface Texturing — A Numerical Study. *Lubricants*. 2025;13:180. https://doi.org/10.3390/lubricants13040180
8. Deng Y., Li A. *Structural health monitoring for suspension bridges*. Singapore: Springer Publ.; 2019. https://doi.org/10.1007/978-981-13-3347-7
9. Maculotti G., Goti E., Genta G., Mazza L., Galetto M. Comprehensive mechanical and tribological characterization of metal-polymer PTFE+Pb/Bronze coating by in-situ electrical contact resistance measurement augmented tribo-mechanical tests. *Tribology International*. 2024;193:109397. https://doi.org/10.1016/j.triboint.2024.109397 EDN: WUJCPF
10. Calaf-Chica J., Bravo-Díez P.-M., Preciado-Calzada M., García-Tárrago M.-J. Application of the Small Punch Creep-Recovery Test (SPCRT) for the estimation of large-amplitude viscoelastic properties of polymers. *Materials*. 2023;16:1179. https://doi.org/10.3390/ma16031179 EDN: OEQJSG
11. Kong Y., Liu Z., Meng Y., Sui X., Chen R., Chen Y., Guo S. Fabrication and the film-forming mechanism of thin polytetrafluoroethylene films with enhanced dielectric and mechanical properties. *Polymer*. 2023;281:126118. https://doi.org/10.1016/j.polymer.2023.126118 EDN: VQUPRC

12. Liu F., Jin Y., Li J., Jiang W., Zhao W. Improved coefficient thermal expansion and mechanical properties of PTFE composites for high-frequency communication. *Composites Science and Technology*. 2023;241:110142. https://doi.org/10.1016/j.compscitech.2023.110142 EDN: SFBOEX

13. Yi X., Du S., Zhang L. *Composite materials engineering, volume 1: fundamentals of composite materials*. Singapore: Springer Publ.; 2018. https://doi.org/10.1007/978-981-10-5696-3

14. Kamenskikh A.A., Bogdanova A.P., Nosov Y.O., Kuznetsova Y.S. Influence of the pattern of coupling of elements and antifriction interlayer thickness of a spherical bearing on structural behavior. *Designs*. 2025;9:117. https://doi.org/10.3390/designs9050117

15. Morozova Z.V., Salnikov A.V. Development of a protective coating for structures with increased corrosion resistance and icing resistance. *Resources of the European North. Exploration Technologies and Economics*. 2018;3(13):18–30. (In Russ.) EDN: VREWWQ

16. Shelestova V.A., Grakovich P.N., Danchenko S.G. “Superfluvis” composite and its use in friction joints. *Inorganic Materials: Applied Research*. 2012;4(72):210–216. (In Russ.) EDN: PLCTUH

17. Dovnar A., Zhuk I., Luchko A., Grakovich P. Morphological features of osteointegration of the implant made of the composite material Superfluvis in cranioplastic operations. *Neurology and Neurosurgery Eastern Europe*. 2022;12(2):176–185. (In Russ.) https://doi.org/10.34883/PI.2022.12.2.045

18. Vinogradov E., Valko N. Effect of X-ray radiation on the mechanical properties of fluoroplast. *Vesnik of Yanka Kupala State University of Grodno. Series 2. Mathematics. Physics. Informatics, Computer Technology and Control.* 2025;15(2):104–111. (In Russ.) EDN: ZTLWCS

19. Adamov A.A., Kamenskikh A.A., Pankova A.P., Strukova V.I. Comparative analysis of the work of bridge spherical bearing at different antifriction layer locations. *Lubricants*. 2022;10(9):207. https://doi.org/10.3390/lubricants10090207 EDN: XRYZSQ

20. Wang Q.J., Chung Y.W. *Encyclopedia of tribology*. Boston: Springer Publ.; 2013. https://doi.org/10.1007/978-0-387-92897-5

21. Ahmad J., Niasar M.G. Aging behavior of PEEK, PTFE, and PI insulation materials under thermal oxidative and humid conditions for aerospace applications. *Journal of Applied Polymer Science*. 2025;142:e56858. https://doi.org/10.1002/app.56858

22. Adamov A.A., Keller I.E., Ostrer S.G., Seletkov D.V. Evaluation of the performance of antifriction PTFE composites at a pressure over 60 MPa. I. Comparison of their hardness and deformation properties under free and constrained compression. *Mechanics of Composite Materials*. 2022;58(5):673–688. https://doi.org/10.1007/s11029-022-10058-7 EDN: GWMXZY

23. Than V.-T., Wang C.-C., Ngo T.-T., Lin C.-H. Thermal behavior of polytetrafluoroethylene in the sintering process. *Thermal Science and Engineering Progress*. 2022;30:101247. https://doi.org/10.1016/j.tsep.2022.101247 EDN: NGPRIU

24. Nosov Y.O., Kamenskikh A.A. Influence analysis of lubricant recesses on the working capacity of the bridge span spherical bearing. *Lubricants*. 2022;10:283. https://doi.org/10.3390/lubricants10110283 EDN: BHIFOC

25. Kamenskih A.A., Trufanov N.A. Regularities of interactions between elements of a spherical contact unit with an antifriction polymeric interlayer. *Journal of Friction and Wear*. 2015;36:170–176. https://doi.org/10.3103/S1068366615020075 EDN: UFUXDX

26. Kamenskikh A.A., Nosov Y.O., Bogdanova A.P. The study influence analysis of the mathematical model choice for describing polymer behavior. *Polymers*. 2023;15:3630. https://doi.org/10.3390/polym15173630 EDN: GIKSXV

27. Barsukov V.G., Dal Yu.M., Lubovskaya R.A., Barsukov V.V. Estimation of thermoelastic stresses in the vicinity of fibrous and particulate fillers in composite materials based on fluoropolymers. *Vesnik of Yanka Kupala State University of Grodno. Series 6. Engineering Science*. 2015;2(204):6–13. (In Russ.) EDN: YQPGGR

28. Ashmarin A.A., Betsofen S.Ya., Lozovan A.A., Lukin E.I., Gordeeva M.I., Mitrofanov A.L., Bykadorov A.N. Thermal Expansion of TRIP Steels and Composite Coatings. *Russian Metallurgy (Metally)*. 2024;2024(2):379–386. https://doi.org/10.1134/S0036029524700691 EDN: FMEWNN

29. Yan L., Gou XY., Zhang X., Jiang Y., Ran X.W., Zhang P. Experimental and numerical investigations on the spherical steel bearing capacity of new anti-separation design. *KSCE Journal of Civil Engineering*. 2024;28(2):889–903. https://doi.org/10.1007/s12205-023-1172-z EDN: JMOPYL

30. Deng N., He M., Gu N., Liang H. Design and performance research of a new type of spherical force-measuring bearing of bridges based on button type microsensor. *KSCE Journal of Civil Engineering*. 2024;28:5066–5076. https://doi.org/10.1007/s12205-024-2646-3 EDN: YDQVSO

31. Shindalkar S.S., Humbe S.S., Joshi G.M., Kumar C.R. Engineering properties of Teflon derived blends and composites: a review. *Polymer-Plastics Technology and Materials*. 2022;61(18):1973–1987. https://doi.org/10.1080/25740881.2022.2086815 EDN: UHTTSF

32. Kang X., Zhang M., Qin H., Zeng L., Peng L., Wang X., Deng L., Hu J., Li Zh., Shao G., Lin Q. Experimental and numerical study on the earthquake damage of spherical bearings for chinese high-speed railway bridge. *Shock and Vibration*. 2022;2022:8304408. https://doi.org/10.1155/2022/8304408 EDN: YDNQXA

33. Nosov Y.O., Kamenskikh A.A., Bogdanova A.P. Description of the lubricant behavior based on the theory of elasto-viscoplastic. *Materials*. 2025;18:1360. https://doi.org/10.3390/ma18061360 EDN: OYHTVP