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Evaluation of the Stress-Strain State of Aircraft Spherical Plain Bearings Based on Titanium Alloys and Antifriction Composite Materials and the Feasibility of Their Use

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Abstract

The paper presents an analysis of the use of titanium alloys for spherical bearings with antifriction composite materials. An analytical assessment of the use of titanium in spherical bearings is given. A model of the stress-strain state of spherical bearings with composite antifriction materials is presented. It was determined that Zedex ZX324VMT and Iglidur TX1 composite materials, when modeling the stress-strain state, reduce the maximum specific stress by 50 % in the material at loads of 3, 100 and 200 kN, compared to the base bearing on steel. Modeling the stress-strain state of spherical plain bearings with composite antifriction materials proved a reduction in specific stresses in the surface layers of bearing materials when using titanium alloys Ti5Al5V5Mo1Cr1Fe instead of bearing steel X105CrMo17 up to 20 %, depending on the material and load conditions. Economic calculations of the use of spherical plain bearings made of titanium alloys for aircraft were carried out. It was determined that under the conditions of operation of spherical plain bearings for 3000 hours of operation, the economic benefit is about 150 thousand dollars per aircraft. It was also determined that modified maintenance-free bearings with composite materials allow the operation of equipment to be closer to its technical condition by reducing maintenance costs when using aircraft.

Keywords: titanium alloys, spherical bearings, wear resistance, stress-strain state, composite coatings, economic calculations

Introduction

The use of titanium alloys in the aviation industry has been an urgent task for decades. However, the use of titanium alloys for spherical bearings is a revolutionary task that will allow reducing the weight of the aircraft, as well as, for example, the use of titanium alloy bolts in aircraft. Of course, given that titanium alloys do not work well on friction, they will be used together with protective coatings and modern composite materials.

One of the main tasks of the aviation industry is also to reduce the cost of aircraft maintenance. This is achieved either by optimizing maintenance costs or by transferring some components and assemblies of equipment to maintenance according to the actual condition. In turn, this is implemented in several ways:

1. By introducing a large number of sensors and an on-board computer to monitor the technical condition of the equipment.
2. By using special diagnostic devices for non-destructive testing and automatic drones for quick and effective detection of defects.
3. By developing modular structures and components for quick replacement.
4. Using special virtual models (digital twins, information storage and processing systems, etc.) and maintenance strategies.
5. Replacing components and creating maintenance-free structures.

The creation of new components that do not require maintenance during the operation of equipment is one of the main tasks of transferring equipment to maintenance according to the actual condition. The use of titanium alloys with anti-friction composite materials allows for immediate reduction of aircraft weight and the creation of components that last their entire service life without the need for maintenance.

Literature review

Titanium alloys are widely used in aircraft as a material with low weight, high strength and excellent corrosion resistance [1-3]. The growing demand for titanium alloys in the aviation industry is also due to their effective compatibility with carbon plastics in terms of their corrosion resistance and thermal expansion coefficient [4]. The use of titanium alloy-composite material combinations is widely used in the latest generation of aircraft, although this contact has certain problems [5-10] in the conditions of aircraft operation. According to works [6, 8, 11], it is the titanium alloy that is 2-10 times more damaged than composite materials. The authors of works [9-12] note the formation of fatigue cracks on the surfaces of titanium alloys during contact, and therefore it is necessary to use antifriction composite materials or appropriate technological treatment of the metal in such joints [13-15].

The amount of titanium alloys used in Airbus A320, A350, A380, etc. series aircraft with low fuel consumption has increased more than twice that of conventional aircraft [16, 17]. In addition, at the general meeting of ITA (International Titanium Association), it was reported that the demand for titanium alloys for the aviation industry will remain stable in the future [18, 19]. The global size of the aerospace titanium processing market is expected to reach 7.9 billion US dollars by 2033, accounting for 4.89 % during the forecast period from 2023 to 2033 (Fig. 1).

The maintenance costs of aircraft airframes can be effectively reduced by using titanium alloys, which have excellent characteristics of fatigue strength, crack propagation resistance, fracture toughness and corrosion resistance. The advantages of using titanium alloys for aircraft are: weight saving, heat resistance, low brittleness at low temperatures, high corrosion resistance, low thermal expansion. The external temperature during flight can be minus 60 ˚C or lower; however, titanium is resistant to brittleness at low temperatures. In addition, there is no concern about corrosion even when dew condenses after the temperature drops. Moreover, since its low thermal expansion is close to that of carbon fiber, titanium alloys are ideal materials for aircraft [20].

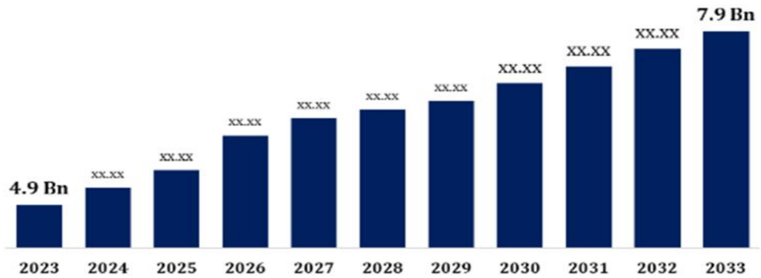

Fig. 1. Global market demand trend (billion USD) for aerospace titanium alloy products in the United States through 2033 [11].

Currently, the percentage of titanium alloy in the weight of the aircraft structure has become one of the important indicators. Titanium alloys occupy 39 % of the F-22 aircraft structure, 42 % for the F-35A/B and F-35C, and close to 40 % for the J-20 and Su-57. The use of titanium alloys increases with the improvement of the aircraft structure and its characteristics. It is used for about 50 % of the structure for fighter aircraft TF-X KAAN, J-31, X-2 (ATD-X) [21]. High resistance to damage is an important indicator of the characteristics of the material for durability, high mobility, low cost and resistance to damage of the structure of new generation fighters [22-24].

Spherical bearings in the aviation industry are used extensively. In aircraft such as: An-124, An-225, B-777, B-787, A330, A340, etc. more than a thousand such bearings are used. Spherical bearings are used in the bearings of rocket and gas turbine engines in civil aircraft. They are used in landing gear bearings and aircraft control systems. The design of spherical bearings with composite materials has not changed for decades.

With the development of modern technologies, many highly engineered composite materials have appeared on the market. Standardized bearings and sliding bushings with composite materials are produced by a number of companies: INA, SKF, FLURO, Koyo, FAG, etc. There are also companies (IGUS, ZEDEX, ELGES) that offer antifriction materials for use in friction units. The range includes almost 250 types of antifriction materials for one company.

Thus, conducting research aimed at evaluating the use of titanium alloys in spherical bearings with composite materials is a relevant task for the aviation industry.

Purpose

The aim of the work is to develop a model of a spherical bearing with titanium alloys and modern composite materials and to study its stress-strain state depending on the combination of materials.

Development of a model of the stress-strain state of spherical plain bearings with composite materials

The process of friction and wear of tribosystems with composite materials can be considered as a process of sequential change in the structure and properties of materials in the contact zone under external energy influence. External influences consist of forces and energy (mechanical, electrical, thermal). For some tribosystems, the spectrum of external influences can be described with quite high accuracy. But for most tribosystems, this is practically impossible, because the forces change at each point of the system and in time [25, 26]. A tribopair (tribological system) must have a certain structure and a set of interconnected elements that determine its composition. These elements are in a certain mutual relationship that determines their belonging to the tribosystem and structure. Friction includes a complex of physicochemical processes and is determined by a large number of parameters, therefore, to simplify and streamline their description, it is advisable to use system analysis [27-30].

The structural diagram of a tribological system, which corresponds to the system approach in tribology, is presented in Fig. 2. This structural diagram includes elements that are in relative motion and mutual connections between the elements of the system. The input characteristic of the tribological system is the work, which is determined by the parameters of the mechanical effect on the material in the contact zone. The output characteristic of the system is the useful work, which is realized in the transmission of force by the spherical bearing and its rotation by a certain angle. The output characteristics of the tribosystem are also the results of the friction and wear processes, which ultimately lead to the destruction of the tribosystem (separation of wear particles, irreversible change in the shape of the contacting elements, heat generation, noise, accumulation of defects in the material structure, etc.). Additional factors act on the tribosystem, for example: increased temperature, vibration, pollution, corrosion, disturbances in the kinematics of motion (for example, radial runout of rotating machine parts), etc. The properties of tribosystems are determined by their composition and structure and are characterized by wear resistance, friction coefficient, heat resistance, and compatibility of materials of the tribological system.

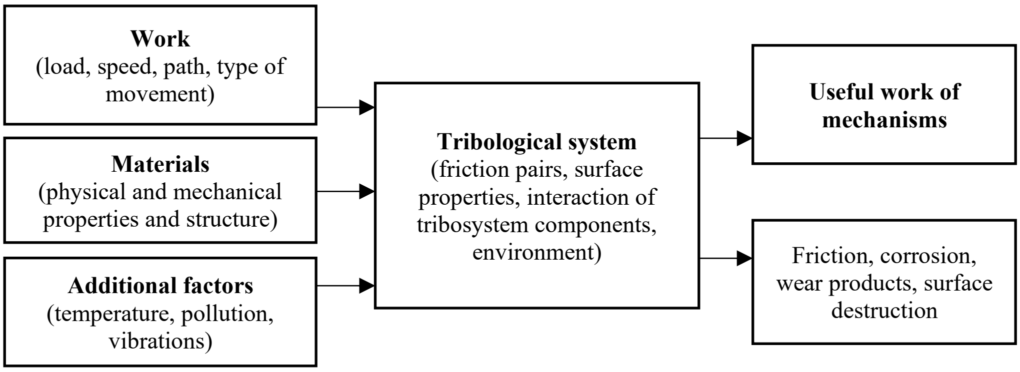

Fig. 2. Structural diagram of a tribological system that corresponds to the systems approach in tribology.

Analysis of a tribological system allows us to determine the internal connections, input and output parameters in the implementation of the purpose of its functioning, which can be the transformation of motion, energy, information and mass. In this case, the system is characterized as an open, dynamic, limit-controlled system [26]. Tribosystems, as a rule, are multiphase (material properties differ) and heterogeneous (properties are not uniform). Tribological systems can be open or closed. Open systems can exchange energy, matter and information with the environment, closed systems - only energy. There are also isolated thermodynamic systems that do not exchange energy or matter with the environment. In tribological systems, various friction and wear processes are implemented, the nature and intensity of which are determined by the functional characteristics of materials. In the general case, functional characteristics describe the transformation of input parameters X into output Y during the interaction of elements of the tribological system (Fig. 3).

The input to the tribological system is equivalent to the influence of the environment on the system, including a combination of mechanical and electrical forces, chemical reactions and thermal effects. External influences have the main influence on tribological processes and are of an energetic nature. Mechanical influences directly affect the parts of the friction pair and through them the lubricants (if any). Thermal influences can cause changes in the properties of the materials of the parts and thermochemical changes in the lubricants (if any).

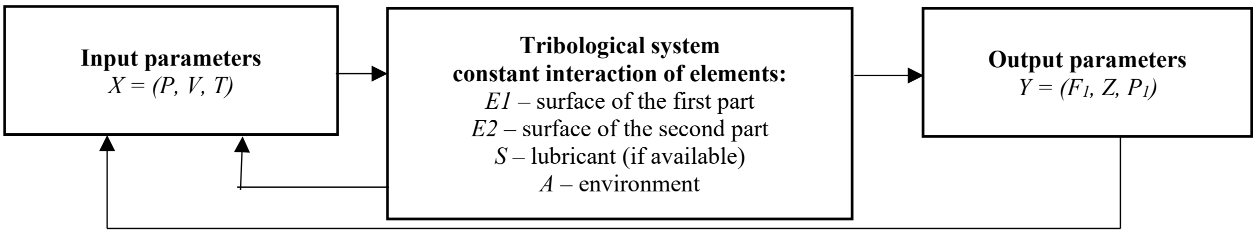

Fig. 3. Scheme of the functioning of the tribological system.

The output of the tribological system can be considered as the system's reaction to an external influence and as a result of tribological processes: friction resistance F_1, wear Z, accompanying processes P_1, for example, an increase in the temperature of the friction surface, triboelectric, tribochemical, thermomechanical, etc. processes. When energy is applied to the friction zone, friction work occurs in the system and the actual contact surface is formed. As a result of the interaction, energy dissipation (dispersion) occurs, which includes the processes [29-31]:

1. Energy accumulation: formation of local defects and dislocations, energy accumulation in the deformed volume of the material.

2. Emission of acoustic waves, light, electrons (Cramer effect).

3. Conversion of accumulated energy into heat, increase in entropy production and dissipation.

When a tribological system transitions from a static state to a dynamic state, processes arise and develop that affect the structure of the system. As a result of the action of the dynamic state, changes occur in the properties of the materials of the parts and the lubricant (if any) and their interaction: $Y = (F_1, Z, P_1)$. There is feedback between the output and the input, the effect of which is manifested in a change in the speed of mechanical-physical-chemical processes when the force changes.

A tribological system can change its functional characteristics in the process of operation, and its state also changes. The period of running-in of the parts of the tribological system (the first state of the system) is a non-stationary state. During this period, the system automatically adapts to the optimal conditions of interaction of the parts (E_1 and E_2) and it can be called the period of self-regulation (running-in). The properties of the parts and the interaction between them change in such a way that, with a constant external energy impact, the intensity of wear decreases. During this period, the formation of the optimal microgeometry of the mating surfaces and favorable changes in the structure and material properties of the parts, which are called tribological adaptations, occur.

After the period of running-in and adaptation, a period of steady state with constant wear intensity (the second state of the system) begins. This period is the main one for the tribological system and has the longest duration compared to other periods of system operation. The longer the steady state lasts, the longer the period of normal operation of the tribosystem.

With the accumulation of defects and degradation of the elements of the tribological system, it enters a state characterized by high and increasing wear intensity (the third state of the system), which can acquire an avalanche character. High-intensity wear occurs due to changes in the properties of materials and parts in frictional interaction, changes in lubricants (aging), the development of adverse side (dynamic) processes, etc. The reliability and durability of tribosystems largely depend on the properties of materials and the correctness of their selection for the given operating conditions of the friction unit. When choosing materials for the tribosystem, it is necessary to take into account their compatibility.

To simulate the stress-strain state of metal-polymer and polymer composite materials in spherical bearings, the Simulation module, which is part of the SOLIDWORKS software package, was used. SOLIDWORKS Simulation Premium allows for effective analysis of nonlinear and dynamic responses, dynamic loads in friction nodes, and also includes three additional types of studies: nonlinear static, nonlinear dynamic, and linear dynamic.

To simulate the stress-strain processes of composite materials in spherical bearings, a bearing model (Fig. 4) was developed with two layers of materials between the metal bearing cages.

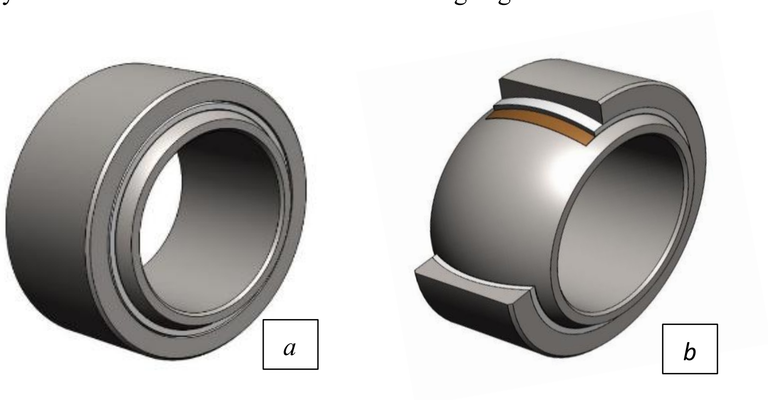

Fig. 4. Calculation model of a spherical plain bearing with antifriction composite materials: a – assembled bearing, b – bearing with an intersection of the outer ring and composite materials

To simplify the calculations and modeling processes, it was determined that the total thickness of the antifriction composite material is 1 mm, which corresponds to a real GE30EW-2RS bearing, and consists of two main layers of material. The first layer of material, which is located closer to the inner ring, has a thickness of 100 microns, is made of PTFE material and remains the same in all study variants. This is the so-called running-in layer, which helps in the running-in processes of the composite materials and in the future helps to reduce the friction coefficient and the displacement moment of the bearing. The second layer of the composite material has a thickness of 0.9 mm and is the main material that works on friction during the operation of the spherical bearing.

Choice of materials

For the production of plane bearings with metal-polymer filling, metal-fluoroplastic tape is usually used. It consists of: a surface made of PTFE+MoS_2 with a thickness of 0.01-0.05 mm, a layer of babbitt (for example, B-

83) with a thickness of 0.20-0.5 mm, a steel base with a low carbon content with a thickness of 0.25-2.70 mm. Provides reliable adhesion between layers, improves heat dissipation during operation.

Thus, the first and basic material for our study is PTFE+15%C+5% MoS_2 or F-4K15M5 material applied to the B-83 babbitt base.

Analyzing the materials of the Zedex series, it should be noted that the company offers mainly two materials for the use of plain bearings, under our bearing operating conditions: ZX-100K and ZX-324.

The base material ZX-100 K is proposed to be used up to temperatures of +110 °C. This material is created on the basis of PET with modifying fillings, which are the secret of the company. If we compare it with PTFE, then the material has the following differences: greater dimensional stability under load (not cold); higher wear resistance due to strength (5 times stronger than fluoroplastic); the maximum operating temperature is also lower (for PTFE +250 °C versus +110 °C for ZX-100K); lower chemical resistance than PTFE.

The ZX-324 material is also offered by the company for the use of plain bearings. ZX-324 thermoplastic polycrystalline polymer is designed as a modification of PEEK and has all the advantages of this polymer. The ZX-324VMT material is a modification of this material for difficult working conditions. The material can be used for a long time at temperatures from -50 to +250 °C, while maintaining high mechanical properties. This polymer is characterized by a high tensile strength and a bending endurance limit for the alternating cycle.

Thus, we can say that the ZX-100K material is an analogue of the F-4K15M5 material, and the ZX-324VMT material is an analogue of a metal-polymer tape. In our case, the second material for research was chosen ZX-324VMT, as an analogue of the intermediate material between the races of the plane bearing.

IGLIDUR materials are divided into the following base materials: G, A350, M250, P210, J, TX1, X, P, J260, J350, J3, L250, R, D, Z. All these materials can work as full-fledged plain bearings, but depending on the operating conditions and load, it is necessary to determine the most optimal material for research. The IGLIDUR line of materials includes both pure polymer materials PTFE, PEEK, PEK, PA, and their combinations with various fillers.

After analyzing the material characteristics and operating conditions of the plane bearing, it was determined that the most suitable materials for such operating conditions are IGLIDUR G (for heavy duty, static load up to 200 MPa, dynamic load 140 MPa, high wear resistance and geometry stability, good resistance to liquid media) and IGLIDUR TX1 (exceptionally long service life in extreme conditions, wear resistance and impact resistance even under high loads and temperatures, high wear resistance, especially under high loads, high heat resistance, the material is recommended for extreme loads).

For use in plane plain bearings, taking into account the operating conditions and loads that the bearing perceives, the optimal of those considered will be the IGLIDUR TX1 material, which is chosen as the third material for research.

FLURO specializes in the production of plain bearings and hinge heads. Bearings of this manufacturer work in modern machines around the world: the operating temperature range is from -50 to +150 °C. FLUROGLIDE materials are divided into two types: WEAR SOLID (for maximum static and dynamic loads) and MEDIA SOLID (for heavy dynamic loads). For example, the GE30EW-2RS bearing is a complete analogue of the CH30UT aircraft bearing. A distinctive feature of all bearings is that the special FLUROGLIDE material works in the contact of a polished chrome coating, which is applied to the inner race of the bearing.

Thus, the fourth material for the study was chosen FLUROGLIDE WEAR SOLID, which best meets the conditions of bearing operation in the aviation industry.

Therefore, the following materials were selected for the study:

1. Metal-polymer tape with PTFE+15%C+5%MoS_2 material, with babbit (B-83) on a steel tape.
2. ZX-324VMT material, which is a polymer composite material with a PEEK matrix reinforced with nanocarbon fiber with the addition of PTFE, MoS_2 and other functional additives.
3. IGLIDUR TH1 is a polymer composite material (engineering plastic) reinforced with long fibers with the addition of functional additives. In its composition, it is similar to the design of the ZX-324VMT material.
4. FLUROGLIDE material is a composite material: a reinforced fabric that includes PTFE material and other fillers that are the company's secret.

Analysis of the results of modeling the stress-strain state of spherical plain bearing elements with composite antifriction materials

For the completeness of the simulations of the plane bearing, it is necessary to determine, in addition to combinations of polymeric materials, also options with a change in the materials of the bearing races. Therefore, two sets of planes bearing with materials of the races of steel X105CrMo17 and titanium alloy Ti5Al5V5Mo1Cr1Fe were determined for modeling. Also, all materials and combinations of the plane bearing must be matched to the original bearings. Figure 5 shows the material layers for modeling processes in plane bearings, and Table 1 shows the material options that we used to simulate stress-strain state processes of antifriction composite materials. Sample No. 1 corresponds to real bearings, which use metal-polymer tape as an anti-friction material and are mass-produced for aircraft. Samples No. 2, 3, 4 are combinations of high-performance anti-friction materials for plane bearings, which are located between the steel cages of X105CrMo17 bearing steel. Samples No. 5, 6, 7 are the same materials, but the outer and inner clips are titanium alloy

Ti5Al5V5Mo1Cr1Fe. In reality, titanium alloy performs very poorly on friction due to its tendency to set. Therefore, the friction surface of the bearing cage must be covered with a layer of molybdenum, about 100 microns thick, to increase wear resistance. For studies of the stress-strain state of bearings, molybdenum coating was not taken into account because the main attention will be paid to the distribution of the load during the operation of the bearing with titanium alloys and anti-friction composite materials.

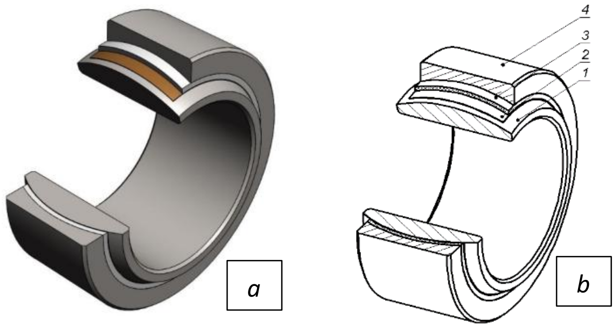

Fig. 5. Layers of materials for modeling the stress-strain state in a spherical bearing, general view (a) and cross-section (b): 1 - inner bearing cage, 2 - inner layer of composite anti-friction material (PTFE), 3 - main layer of composite anti-friction material, 4 - outer bearing cage.

Table 1

Variants of combinations of plane bearing elements with composite antifriction materials for research

Sample	**Bearing layer material**			
№	**Element 1**	**Element 2**	**Element 3**	**Element 4**
1	X105CrMo17	PTFE	Bronze leads.	X105CrMo17
2	X105CrMo17	PTFE	ZX-324VMT	X105CrMo17
3	X105CrMo17	PTFE	TX1	X105CrMo17
4	X105CrMo17	PTFE	Carbon fibers	X105CrMo17
5	Ti5Al5V5Mo1Cr1Fe	PTFE	ZX-324VMT	Ti5Al5V5Mo1Cr1Fe
6	Ti5Al5V5Mo1Cr1Fe	PTFE	TX1	Ti5Al5V5Mo1Cr1Fe
7	Ti5Al5V5Mo1Cr1Fe	PTFE	Carbon fibers	Ti5Al5V5Mo1Cr1Fe

As a basis for calculating the stress-strain state of bearing options, a GE30EW-2RS bearing was chosen, which was calculated at loads of 3, 100 and 200 kN and dimensions of 30x47x22 mm. The load on the bearing occurred over a distributed area from the outer cage to the inner one. The location of the bearing on the shaft with the external distributed load from the lever of the aircraft structure is simulated. Simulation of the stress-strain state of composite coatings was carried out with the reverse movement of the inner cage relative to the outer one at a frequency of 3 Hz and an oscillation amplitude of ±15 °. The physical and mechanical properties of materials for modeling the stress-strain state are given in Table 2.

Having analyzed the results of the stress-strain state of plane bearing models with different variants of anti-friction composite materials and cages, it is possible to neglect element 2 (PTFE) when analyzing the stress distribution and safety margin of the model elements, since at loads of 100 and 200 kN, PTFE material with a thickness of 100 μm completely loses its bearing capacity relative to load distribution (Fig. 6) and acts in a real bearing, as a layer for running in the main composite material (element 3).

Table 2

Physical and Mechanical Properties of Materials of Plane Bearing Elements

Characteristics of materials	**X105CrMo17**	**Bronze**	**PTFE**	**Carbon fiber**	**ZX324VMT**	**TX1**	**Ti5Al5V5Mo1Cr1Fe**
Modulus of elasticity, 10^{10}, Pa	20.4	11	0.5	14	0.78	1.2	11.5
Poisson's ratio	0.27	0.33	0.4	0.25	0.3	0.3	0.3
Shear modulus, 10^9, Pa	-	37	0.75	6.0	-	-	43
Material density, kg/m^3	7750	8300	2320	1750	1480	2100	4620
Tensile strength, MPa	770	262	27	490	142	203	470
Compressive strength, MPa	-	-	12	2000	120	220	-
Yield strength, MPa	420	110	4.24	-	-	184	380

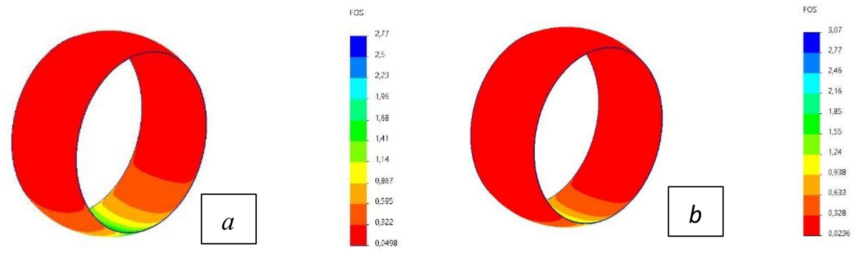

Fig. 6. Safety margin of element 2 of the composite antifriction material of the bearing model (sample No. 3) under loads: a - 100 kN, b - 200 kN.

Also, when analyzing the results of the introduction of titanium cages in models of samples No. 5, 6, 7, we see a decrease in specific stresses in the surfaces of plane bearings, compared to the material X105CrMo17 for samples No. 2, 3, 4. This effect is observed at all stages of modeling the stress-strain state of bearings when comparing samples No. 2-5 (Fig. 7), 3-6 (Fig. 8), 4-7 (Fig. 9) at loads of 3, 100 and 200 kN.

With an increase in the load, stress distribution is more efficiently implemented over all elements of a plane bearing with titanium races than with steel ones. Stress reduction in models reaches up to 20% at loads of 200 kN for individual sections of elements of plane bearing models. This effect can be explained by the fact that the titanium alloy is more ductile than the X105CrMo17 material (see Table 2) and damps and redistributes the load among the elements of the plane bearings.

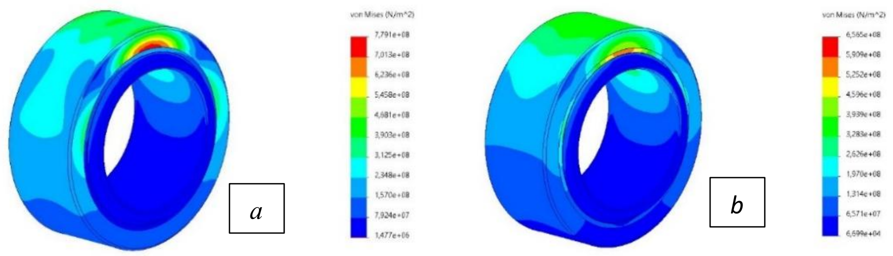

Fig. 7. The nature of the stress distribution in the bearing model at a load of 200 kN: a - sample No. 2, b - sample No. 5.

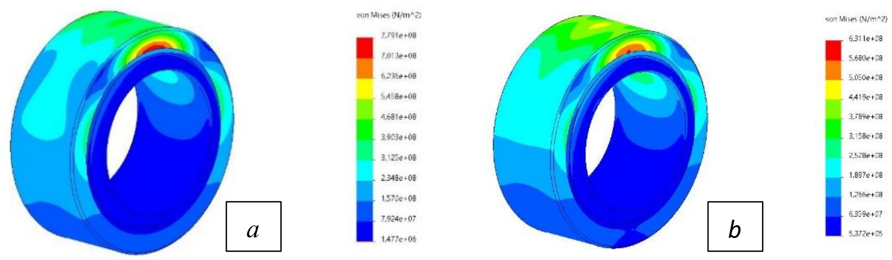

Fig. 8. The nature of the stress distribution in the bearing model at a load of 200 kN: a - sample No. 3, b - sample No. 6.

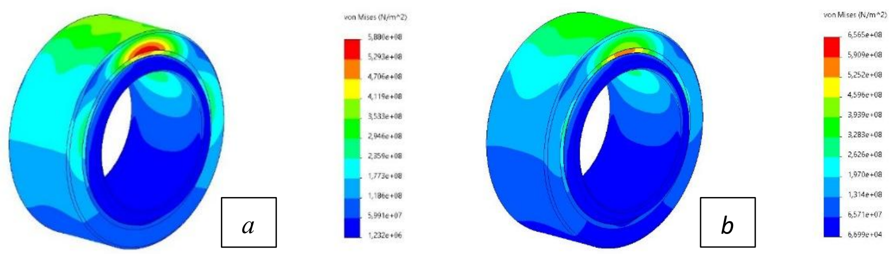

Fig. 9. The nature of the stress distribution in the bearing model at a load of 200 kN: a - sample No. 4, b - sample No. 7.

In works [32-35] the advantages of titanium materials in terms of load distribution during wear resistance tests are shown. Thus, in work [32] the authors investigated the wear resistance of gas-thermal coatings on titanium alloy and steel. The work indicates that the titanium alloy Ti5Al5V5Mo1Cr1Fe, on which the wear-resistant VKNA coating was applied, can increase the wear resistance of the plasma coating at loads up to 30 MPa in fretting corrosion studies due to a more ductile base. On harder steels, wear-resistant high-strength coatings had lower wear resistance at moderate loads.

This is confirmed by the analysis of stresses and the margin of safety of composite materials (element 3) when modeling the stress-strain state of plane bearings, if we compare races made of titanium alloy and steel.

When analyzing the stresses and safety margin of composite materials of materials (element No. 3, samples No. 2-4) in comparison with the model of the original bearing (element No. 3, sample No. 1), it can be stated that at stresses of 3 kN, materials ZX-324VMT and TX1 have stresses 50 % less, compared to the original bearing and material of the model based on carbon fibers, without a conjunction. The carbon fiber model has even 10-15 % higher stresses compared to the metal-polymer tape. This is due to the high physical and mechanical characteristics of carbon fibers (see Table 2), namely the compressive strength of 2 GPa, which is the highest among the materials under study. At the same time, this model lacks a conjunction, the function of which is to redistribute stresses over the entire surface of the material combination. A similar picture can be traced at loads of 100 and 200 kN. There is a decrease in specific stresses in the surfaces of ZX-324VMT and TX1 composite materials by 30-50 % compared to carbon fiber and bronze [7].

Having analyzed the safety margin of composite materials (element No. 3, samples 1-4) at a load of 3 kN, it can be argued that composite materials with carbon fibers have the highest safety margin among the tested materials of 98.4 at the point of maximum load. ZX-324VMT and TX1 materials have a safety margin of 31.7 and 46.2, respectively. These values are higher than those of the material with bronze (15.1) and may indirectly indicate the wear resistance of composite materials.

At loads of 100 and 200 kN, a similar dependence is maintained when calculating the safety margin of composite materials. At loads of 200 kN, the calculations show the safety margins of materials of samples No. 1-4 in 0.2: 0.47: 0.69 and 1.48 units, respectively, at the point of maximum load. That is, theoretically, all materials, except for carbon fibers, have a value of less than one, which means plastic deformation of composite materials in the contact zone.

For a more visual analysis of the stress-strain state of plane bearings using races made of materials X105CrMo17 and Ti5Al5V5Mo1Cr1Fe, we present histograms for a bearing with a metal-polymer tape (sample No. 1) and carbon fiber (sample No. 4 and 7). Figure 10 shows the maximum values of the distribution of normal stresses in composite materials (element No. 3) at loads of 100 and 200 kN. A similar relationship occurs at a load of 3 kN.

The generalized results of modeling the stress-strain state are presented in Table 3 [7]. Based on the results of the assessment, it was found that the use of carbon fibers in their pure form increases the normal equivalent stresses according to Miser by 1.27 times and 1.2 times when modeling the location of fibers of this type on a cage made of X105CrMo17 steel and alloy Ti5Al5V5Mo1Cr1Fe, respectively, compared to a metal-polymer tape. The increase in stresses is due to the stiffness of carbon fibers, their low relaxation capacity, the absence of a connector that provides high damping properties in polymer composite materials. These factors are not taken into account in modeling, the safety factor increases by 5-6 times.

The use of polymer composite materials Zedex ZX-324VMT and Iglidur TX1 on X105CrMo17 steel provides a reduction in normal stresses along the Miser by 1.45 and 1.27 times, respectively, compared to metal-polymer tape. In the case of using a titanium alloy bearing Ti5Al5V5Mo1Cr1Fe as a material of the inner and outer race, the normal stresses in Miser in models made of polymeric materials Zedex and Iglidur are reduced by 2.08 and 1.55 times, compared to metal-polymer tape on steel. It should be noted that when using the alloy Ti5Al5V5Mo1Cr1Fe, the reduction of normal stresses during modeling was set by 11 and 7 % for Zedex and Iglidur polymeric materials, compared to the stresses in these polymer materials on steel cages. The safety factor for the model with these polymer composite materials increases by 2.1 and 3 times for Zedex ZX-324VMT and Iglidur TX1 on the Ti5Al5V5Mo1Cr1Fe alloy, compared to the metal-polymer tape on steel [7].

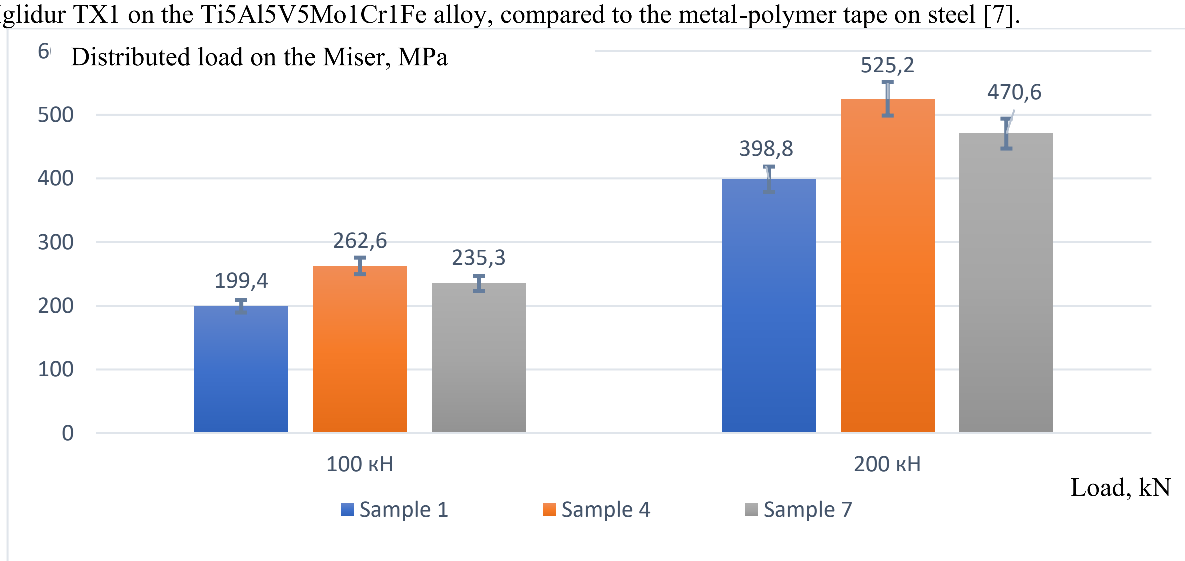

Fig. 10 – Histogram of stress distribution in composite materials (element No. 3) when modeling the stress-strain state of plane bearings under loads of 100 and 200 kN: Sample No. 1 – bronze tin, bearing cage material X105CrMo17; Sample No. 4 – carbon fiber, bearing cage material X105CrMo17; Sample No. 7 - carbon fiber, bearing cage material Ti5Al5V5Mo1Cr1Fe.

Table 3

Results of Simulation of the Stress-Strain State in a Plane Bearing Model

Sample	Materials of the elements of the plane bearing model		Distributed load on the Miser, MPa			Safety factor (by maximum stresses)		
№	3	1, 4	3 kN min/max	100 kN min/max	200 kN min/max	3 kN	100 kN	200 kN
1	Bronze	X105CrMo17	5.458/6.365	199.4/232.5	398.8/465.0	15.1	0.463	0.232
2	ZX-324VMT	X105CrMo17	2.902/3.869	96.75/129.0	193.5/258.0	30.9	0.816	0.463
3	TX1	X105CrMo17	3.792/4.738	126.4/157.9	252.8/315.8	44.4	1.33	0.66
4	Carbon fibers	X105CrMo17	7.879/8.863	262.6/295.4	525.2/590.9	76.1	2.28	1.14
5	ZX-324VMT	Ti5Al5V5Mo1Cr1Fe	2.481/3.708	82.72/123.6	165.5/247.2	31.7	0.951	0.475
6	TX1	Ti5Al5V5Mo1Cr1Fe	3.521/4.688	117.4/156.3	234.8/312.5	46.2	1.39	0.693
7	Carbon fibers	Ti5Al5V5Mo1Cr1Fe	7.059/7.939	235.3/264.6	470.6/529.3	98.4	2.95	1.48

Thus, the results of simulation of the stress-strain state indicate the effectiveness of using polymer composite materials Zedex ZX-324VMT and Iglidur TX1, reinforced with carbon fibers, as wear-resistant anti-friction composite materials for the outer cage of the plane bearing. Replacing the steel cage with a cage made of surface-reinforced titanium alloy provides more effective stress relaxation and an increase in the safety factor during modeling.

Calculation of the economic feasibility of replacing steel races of plane bearings with titanium alloys

The calculation of the economic feasibility of introducing titanium alloys into the plane bearing cages will be calculated using the example of a medium-haul aircraft of the Boeing-737 type, which is the most massive and in demand for 2025 for the countries of the European Union.

Plane bearings are used in aircraft everywhere to connect the arms of units to the hull. The purpose of using bearings is to compensate for distortions that may occur during the operation of aircraft under the influence of external forces - they are also used in movable joints, which during operation make oscillatory movements with an amplitude of up to 60 degrees.

Any version of the aircraft uses plane bearings that require maintenance and those that do not require maintenance during the overhaul period. In the presented calculations, it is assumed that all plane bearings that are on the aircraft will be maintenance-free. Since more and more parts and assemblies have recently transferred maintenance to their actual condition, the idea of replacing bearings with maintenance-free ones is relevant.

A feature of the Boeing-737 aircraft families and their modifications is the use of a large range of plane bearings from 6 mm to 35 mm. small diameter plane bearings (up to 12 mm) are used mainly for static objects in aircraft control systems. Medium-diameter plane bearings (up to 20 mm) are used in hydraulic reinforcement systems for control systems and tail units of aircraft. Bearings with diameters up to 35 mm are used in fasteners for landing gear assemblies and power elements of the aircraft. The total number of all bearings is very dependent on the dimensions and modifications of the aircraft and has about 1000 pcs. all options.

For the selected calculation option, we take the average diameter of the bearings equal to 20 mm. Because, for example, a bearing with a diameter of 20 mm weighs 0.1 kg, a bearing with a diameter of 10 mm weighs 0.01 kg, and a bearing with a diameter of 35 mm weighs 0.25 kg. We calculate the weight of bearings from steel cages:

$W_{steel} = 1000*0.1 = 100$ *kg.*

We determine the weight of the bearing, which is made of titanium alloy. The density for steel is 7.9 g/cm^3, and for titanium alloy - 4.5 g/cm^3. Assuming that the volume of the plane bearing is the same, we have that titanium alloy is 57 % lighter than steel. Then the weight of the bearing with a diameter of 20 mm will be 0.57 kg. We calculate the weight of bearings made of titanium alloys:

$W_{titanium} = 1000*0.57 = 57$ *kg.*

That is, the weight advantage for an aircraft, provided that a titanium alloy is used, will be 43 kg.

The price of X105CrMo17 stainless steel in the form of a pipe costs from 150 UAH/kg.

The price of titanium alloy Ti5Al5V5Mo1Cr1Fe in the form of a pipe costs from 1200 UAH/kg.

We determine that the price of steel bearings will cost 15 thousand UAH, and the price of titanium bearings will cost 68.4 thousand UAH. The difference in cost is 53.4 thousand UAH or 1335 $ USA.

A Warsaw-Amsterdam ticket for April 2026 will cost about $200 with a flight length of 2 hours for a Boeing-737 aircraft. That is, an hour of flight for a person will cost $100. When calculating aircraft, a person's weight is considered to be 70 kg plus the weight of luggage. If simplified, it can be said that a gain of 43 kg is approximately 50 $ per hour of commercial aircraft flight. That is, the cost of using titanium bearings for the aircraft will be compensated for in the first 27-30 hours of flight.

We believe that the service life of the plane bearing will be about 3000 hours of operation, then we calculate the net profit from the use of races made of titanium alloys will be equal to:

Profit = 2970*50 = 148.5 thousand dollars of profit for the aircraft.

Conclusions

1. A model of the stress-strain state of plane bearings with composite antifriction materials has been developed. It was determined that the composite materials Zedex ZX324VMT and Iglidur TX1 when modeling the stress-strain state reduce the maximum specific stress by 50 % in the material at loads of 3, 100 and 200 kN, compared to metal-polymer tape.

2. Simulation of the stress-strain state of plane bearings with composite antifriction materials has proven a decrease in specific stresses in the surface layers of bearing materials when using titanium alloys Ti5Al5V5Mo1Cr1F instead of X105CrMo17 bearing steel up to 20 %, depending on the material and load conditions.

3. The calculation of the economic feasibility of using titanium alloys for bearings with composite materials established that the benefit is about 150 thousand dollars per aircraft, provided that the plane bearings operate for 3000 hours.

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Хімко А.М., Хімко М.С., Мікосянчик О.О. Оцінка напружено-деформованого стану авіаційних шарнірних підшипників ковзання на основі титанових сплавів та антифрикційних композитних матеріалів та доцільність їх використання.

У статті представлено аналіз використання титанових сплавів в авіаційній промисловості на літаках нового покоління та оцінена можливість застосування титану для шарнірних підшипників з антифрикційними композитними матеріалами. Представлено аналіз антифрикційних композиційних матеріалів для авіаційної промисловості із підвищеними фізико-механічними характеристиками. Метою роботи було розробка моделі шарнірних підшипників із полімерними композиційними матеріалами та аналіз економічної доцільності використання титанових сплавів в таких підшипниках ковзання в повітряних суднах. Наведено аналітичну оцінку використання титану в сферичних підшипниках. Розроблено модель напружено-деформованого стану сферичних підшипників з композиційними антифрикційними матеріалами. Визначено, що композиційні матеріали Zedex ZX324VMT та Iglidur TX1 при моделюванні напружено-деформованого стану знижують максимальні питомі напруження в матеріалі на 50 % при навантаженнях 3, 100 та 200 кН, порівняно з базовим підшипником на сталі. Моделювання напружено-деформованого стану шарнірних підшипників ковзання з композиційними антифрикційними матеріалами довело зниження питомих напружень у поверхневих шарах матеріалів при використанні титанових сплавів Ti5Al5V5Mo1Cr1Fe замість підшипникової сталі X105CrMo17 до 20 %, залежно від матеріалу та умов навантаження. Було проведено економічні розрахунки використання шарнірних підшипників ковзання з титанових сплавів для літаків. Визначено, що застосування шарнірних підшипників протягом 3000 годин під час експлуатації повітряного судна економічна вигода становить близько 150 тисяч доларів на один літак. Також представлено, що модифіковані необслуговувані підшипники з композитними матеріалами дозволяють наблизити експлуатацію деяких вузлів повітряних суден до обслуговування за фактичним станом за рахунок зниження витрат на технічне обслуговування.

Ключові слова: титанові сплави, шарнірні підшипники, зносостійкість, напружено-деформований стан, композиційні покриття, економічні розрахунки.