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Resource testing of modified plain bearings for the aviation industry

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Abstract

The resource tests of plain bearings with metal-polymer tribo-systems developed for the aviation industry are presented. The purpose of the work is to determine the wear resistance of modern anti-friction polymer materials in plain bearings in comparison with metal fluoroplastic tape. The uniqueness of the tests lies in the use of a combination of high-performance polymer materials in a pair with chromium and molybdenum coating during the reversible movements of plain bearings. Since the use of such bearings is mass in nature, the use of titanium materials in the manufacture of bearing cages will allow to significantly reduce the weight of the aircraft and increase its efficiency. It was determined that a plain bearing with a polymer material of carbon and polyamide fibers and PTFE with functional additives shows a wear resistance 1.8-2 times greater on the segment of 40-100 thousand cycles than bearings with other materials during laboratory resource tests. Also, industrial tests have established that after 2 million cycles, a hinged bearing with a metal-polymer tape shows a result that is 1.2-1.5 times lower in wear resistance than polymer materials, but all these results are within the tolerances of normal bearing operation. Industrial tests have proven that at replacing the inner ring of a plain sliding bearing with a titanium alloy with a molybdenum coating, the wear resistance is almost the same or slightly lower than when the polymer rubs against steel. Technological recommendations have been developed and a new design and materials of plain sliding bearings with polymer anti-friction coatings for the aviation industry have been proposed. The implementation of technological recommendations in the production of bearings will allow to move away from the universality of the use of plain bearings and extend their wear resistance and durability in general due to the use of the full thickness of the polymer material and the development of bearings with predicted characteristics for a specific task.
Keywords: plain bearings, metal-polymer tribo-systems, durability, wear resistance, reversible movement, loading, coating, titanium alloy, polymer antifriction materials.

Introduction

Plain sliding bearings are widely used in machine building and the aviation industry. They are used for: work in aggressive environments, with high vibration and shock loads, in fixed joints and everywhere where high contact loads and low sliding speeds are required. They are designed to transmit radial, axial and combined loads in moving or stationary connections of machines and mechanisms. They are used to compensate for distortions, temperature and elastic deformations that occur during the operation of aircraft. A special place in the line of plain bearings is occupied by bearings with materials that do not require lubrication during the entire service life of the bearing.

Bearings with metal-polymer tribo-systems are quite widely used in friction units. Different combinations of metal and polymer structural elements make it possible to predict friction nodes for a specific task. In turn, polymeric materials in most cases are quite complex after their modification with functional, as a rule, antifriction fillers.

Literature review

Metal-polymer tribo-systems and polymer composite materials play a progressive role in tribotechnics. They are used to replace scarce metals and alloys, significantly increase the manufacturability, reliability and durability of friction units. Units of machines using polymer composite materials have a smaller mass, work almost silently, have high damping capacity, do not require lubrication. This is especially true for the aviation industry. Parts made of polymer materials can be operated in vacuum and chemically active environments, at cryogenic and elevated temperatures, in a wide range of loads and sliding speeds. Currently, anti-friction polymer materials are widely used in transport and power engineering, technological equipment and household appliances, covering a huge range of friction nodes for technical and medical purposes, starting with lining plates of hydroelectric power plants and ending with microrobots for blood purification [1, 2].

The use of polymer composite materials allows significantly reduce the labor cost of manufacturing parts of friction nodes due to high-performance and resource-saving technologies. For example, when replacing metals with cast plastics, labor costs are reduced by 5...6 times, and the cost price by 2...5 times; when using polymer materials instead of metals and semi-finished products based on them, the cost of the product is reduced by 4...9 times [3].

According to the definition, a composite material consists of one or more continuous phases of a homogeneous matrix with one or more dispersed phases. In this regard, the reliable operation of metal-polymer tribo-systems primarily depends on the structural and morphological factor that affects the tribomechanical characteristics of materials [4]. The principle of obtaining composite materials consists of a previously created combination of two different phases (fillers and matrix) using certain technological techniques. As a result of the filling, materials are obtained, the physical and mechanical properties of which differ from the matrix. The choice of fillers for metal-polymer materials depends on the purpose of the material, the need to change certain tribomechanical characteristics and the type of polymer matrix.

Usually, polymer composite materials used in sliding bearings are divided into composite materials reinforced with continuous fibers or fabrics, dispersion-reinforced composite materials, composite materials based on mixtures of polymers that are not capable of dissolving in each other and are characterized by a certain distribution of polymer particles of the same nature in matrices of another polymer.

Plain sliding bearings with metal-polymer tribo-systems are very popular in the aviation industry [5]. They are made of stainless and corrosion-resistant steels and do not require maintenance. They are compact, have an extremely high weight-to-weight ratio and are used in primary and secondary flight control systems. They have a hinged design. The inner ring is made of high-quality steel with a polished spherical surface. The outer ring is equipped with a composite metal-polymer material based on polytetrafluoroethylene with tin-based bronze (metal-polymer tape). In order to precisely fit the spherical surface of the inner ring and ensure an optimal sliding surface, the outer ring is produced by cold forming around the inner ring.

Recently, many high-tech engineering anti-friction polymer materials have appeared on the market for their use in tribo-nodes of machines [6, 7]. According to their characteristics, these materials in some cases exceed the wear resistance p removing the bearing from the installation. Control was carried out according to the ГОСТ 3635-78 (item 4.10) scheme using a time-type indicator. The control was carried out 3 times for the reliability of the values for each point of the graph. The contact fatigue cracking of the bearing surfaces after the total test cycle after 100,000 cycles was also determined.

4. The frequency of oscillations was 3 Hz.

5. The amplitude of the oscillations was 40 degrees (± 20°) and was determined from the conditions of the kinematic diagram of the lever of the helicopter's swashplate.

6. The load for all tested bearings was 31.5 kN. The load scheme corresponded to ГОСТ 3635-78, chapter 6 "Operating conditions".

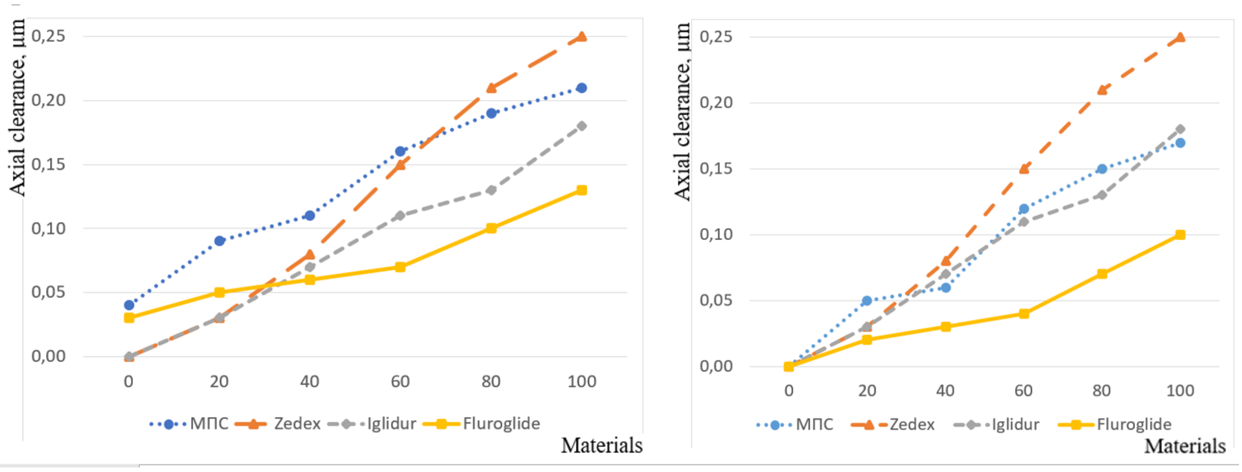
7. All tests were carried out at a temperature of 16 to 20 °C. In the course of research, a slight increase in the temperature of the plain bearings up to 40 °C was observed.

Resource laboratory tests of plain bearings with polymer materials

In the process of testing plain bearings with metal-polymer coatings, the shedding of polymeric materials in the form of black wear products was observed in all tested samples. After testing for 100,000 cycles, the fractographic analysis did not reveal any seizure sites on the surface of the inner clip. The outer clips with metal-polymer materials did not wear down to the base of the bearing, which may indicate that all plain bearings that participated in the tests are functional and can withstand a longer life, according to ГОСТ 3635-78, DIN ISO 12240-1 (DIN 648) та СТП 651.02.061-92. It should also be noted that all pivot bearings showed an axial gap of less than 0.3 mm after 100,000 cycles, which is considered a critical gap for a bearing of this size.

The results of resource tests are presented in fig. 1. According to ЕТУ 100-4, ГОСТ 3635-78 та DIN ISO 12240-1 (DIN 648), articulated bearings of this type and size should be manufactured with a gap of 0.03-0.08 mm, which corresponds to (Fig. 1, and) during initial measurements of ШН30ЮТ та GE30EW-2RS bearings. However, when bearings were made with other polymer materials, the clearance of the new articulated bearings was zero. What is associated with the peculiarity of the production of trial samples of bearings with ZX-324VMT and TX1 materials.

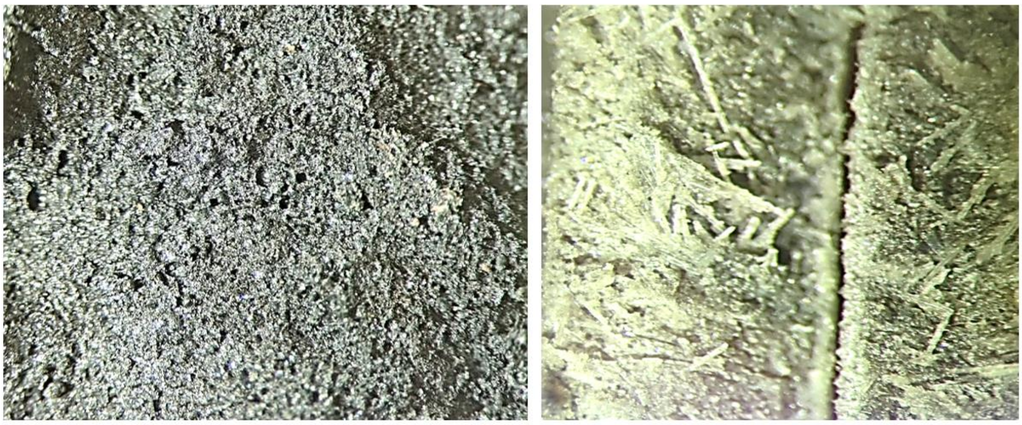
Analyzing the test results of plain sliding bearings, it can be concluded that the bearing with metal-polymer tape and the bearing with Fluroglide material have almost equidistant curves, which are similar in the nature of wear. The difference is observed only in the axial gap results. Initially, the spherical bearings have a certain clearance and the polymer material (PTFE with functional additives) is in a free, uncompressed state. When the load is applied, the compression of the PTFE material, which is part of these polymers, and the so-called running-in of the bearings are observed. Which is characterized by the distribution of the material and the filling of all pores under load and the establishment of a certain wear pattern. This is exactly what the picture shows us. 1 at the primary stages of testing with a run-in time of 20,000 oscillations. When the number of working hours increases to 100,000, uniform wear of the material occurs almost linearly. It should be noted that during the tests, the temperature of the bearing with Fluroglide material rose to 43°C. The GE30EW-2RS bearing heated up more than the metal polymer tape bearing. This is explained by the removal of heat from the friction zone of the face into the inner ring and the metal-polymer contact, and in the bearing with a metal-polymer tape, the contact is metal-(babbit + polymer).



a b

Fig. 1. Dependence of the axial gap (wear) of plain bearings with metal-polymer materials on the number of oscillation cycles at actual values (a) and under the condition of equalization of the initial axial gap (b).

Analyzing the wear resistance of plain bearings with ZX-324VMT and TX1 materials, it can be said that up to 20,000 oscillations, the wear resistance of these materials is the same. It is explained by the fact that the surfaces of the polymer materials of the Zedex and Iglidur companies are almost identical in terms of characteristics. As the number of operations increases and as the surface layers of polymer materials wear, the structure and functional additives that are part of the polymer materials become more and more apparent. In fig. 2 shows the topography of ZX-324VMT and TX1 material structures. It can be seen from the figure that the Iglidur company uses a larger size of reinforcing fibers for strengthening. At 100,000 cycles, it can be seen that the wear resistance of the ZX-324VMT material is the lowest. The difference is already evident after 70,000 cycles. The TX1 material during the tests occupies an intermediate position between the metal-polymer tape and the Fluroglide material.



а б

Fig. 2. Structures of polymer materials ZX-324VMT (a) and TX1 (b) at magnification of x56.

In general, we can say that up to 60,000 cycles, the plain bearing with a metal-polymer tape shows worse wear resistance than polymer materials, but all these results are within the tolerances of normal bearing operation. If we discard the gap that was at the beginning of the bearing tests and compare the results, the picture of the wear of the plain bearings will be somewhat different. (Fig. 1, b) shows the results of (axial gap) wear of plain bearings with metal-polymer materials from the number of oscillation cycles under the condition of leveling the initial gap (the wear curves of Zedex and Iglidur materials are symmetrically shifted to the zero mark).

Analyzing this version of the wearing of metal-polymer materials, it can be stated that the plain bearing with Fluroglide material shows wear resistance almost 2 times higher in the segment of 40-100 thousand cycles than bearings with other materials. It should be noted that this is the only plain bearing where the wear of the polymer material occurs on the steel, and on the chrome coating, which is known for its wear resistance [10, 11]. The combination of reinforced fabric with PTFE and additives from solid lubricants paired with polished chrome, once again proves that the most successful option for tribo-pairs is a solid base with a viscous matrix and solid inclusions.

It should be noted that the testing conditions of the plain bearings did not correspond to the real operating conditions of the plain bearings, which work, for example, in the levers of swashplate of the main gearbox of a helicopter. And the test results were only comparative at a certain calculated load. The temperature of the tests, the number of cycles and the load were selected according to the normative documents of the operating conditions of the helicopter. For example, the number of hours of operation of the main gearbox and the swashplate as a whole from repair to repair is from 2000 to 2500 hours of operation, depending on the type of equipment and operating conditions of the helicopter. At the nominal rotation frequency of the main rotor of 192±2 rpm, the oscillation frequency of the plain bearing is about 3 Hz, and in terms of cycles, 27 million oscillations at 2500 hours. Turn in low gas mode 45±10 rpm. That is, the value of 100 thousand cycles as well as the load of 31.5 kN are standardized passport values.

Therefore, for more reliable results, it is necessary to conduct additional industrial tests in conditions close to real nodes.

Industrial testing of plain bearings

Industrial tests of plain sliding bearings with metal-polymer materials were carried out at an aircraft repair enterprise, which is engaged in maintenance, overhaul and production of parts and assemblies for helicopters of Mi-8/17 series.

The purpose of the research was to manufacture and test the wear resistance of prototypes of plain bearings that were manufactured at the enterprise on the recommendation of the authors of the work in accordance with the contract. The bearings were manufactured according to the scheme described above, but in addition, molybdenum coating was applied to the inner surface of the plain bearings by the vacuum-arc method with a thickness of about 100 microns. Also, the inner cage of some bearings was made of titanium alloy R56260 (Ti6Al2Sn4Zr6Mo).

The installation on which plain bearings were tested was made according to the scheme presented in [12]. The test bench works on the principle of movement of the outer ring with a given amplitude with a fixed inner ring under a combined radial and axial load. The stand allows tests of both spherical and cylindrical sliding and rolling bearings in the mode of reversible motion in a wide range of angles, frequencies and loads in air as well as in other gases or vacuum. The stand also carried out tests at temperatures with the help of heating with infrared radiation at the place of installation of the hinged bearing.

The choice of material combinations of plain bearings for industrial tests was determined from the standpoint of economic efficiency and reliable working conditions from the introduction of experimental samples into industry. The ШН30ЮТ type bearing was used as the basis, which is currently standardized according to all relevant technical documents. The test results of test samples of plain bearings are presented in Table 1.

For testing of plain bearings, the operating conditions were selected based on the operating modes of the lever of the helicopter's swashplate:

1. The frequency of oscillations is 3 Hz.
2. The testing temperature is 50-55 °C.
3. The load on the bearing was 3 kN in the radial direction.
4. The amplitude of oscillations was ±15°.
5. Research base $2 \cdot 10^6$ cycles.
6. Control of the axial gap at $1 \cdot 10^6$ and $2 \cdot 10^6$ cycles.
7. The sliding speed was 32.7 mm/s.

It should be noted that standard bearings of the type ШН30ЮТ and GE30EW-2RS according to [13] DIN ISO 12240-1 (DIN 648) are manufactured with a clearance of 30-80 μm, and test samples of plain bearings were manufactured with a minimum clearance of 5 μm. It is also noted that the surfaces of all polymer coatings were in satisfactory condition after the tests. There were no damages or tears on the surfaces. The gaps of all samples after the tests were within the tolerance of 0.3 mm.

Analyzing the test results of test samples of plain bearings, it can be said that all samples are within tolerance even after 2 million cycles. Also, for a clearer picture, it is necessary to list the characteristics of the wear resistance of plain bearings and to present the test results in the form that the initial value of the axial gap is excluded. Fig. 3 presents a histogram of the results of the axial gaps of plain bearings without taking into account the initial gap.

Table 1

The results of axial gaps of plain bearings during industrial tests

Sample No.	Polymer on the outer ring	Coating on the inner clip	Inner clip material	Axial gap at the number of working cycles, μm		
				0	$1 \cdot 10^6$	$2 \cdot 10^6$
1	Metal-polymer tape	-	95Х18Ш	45	170	200
2	Fluroglide	chrome	95Х18Ш	50	145	155
3	Zedex	-	95Х18Ш	5	120	140
4	Zedex	molybdenum	95Х18Ш	5	120	135
5	Zedex	molybdenum	R56260	5	125	140
6	Iglidur	-	95Х18Ш	5	100	120
7	Iglidur	molybdenum	95Х18Ш	5	95	120
8	Iglidur	molybdenum	R56260	5	105	125

It can be seen from the histogram (Fig. 4) that under moderate loads, in test conditions close to real ones, the selected polymer materials showed better wear resistance results than the metal-polymer tape. This indicates that modern highly modified engineering plastics have better wear resistance (under certain operating conditions) than metal-polymer tape. The FLURO bearing shows the best results in terms of wear resistance. This is confirmed by the experiments of laboratory installations and resource laboratory tests. When analyzing the table. 1, it can be seen that at the beginning of the operation of the bearing, the polymer material is pressed, and the PTFE polymer material is installed in the reinforced fabric. In the future, equilibrium occurs in the zone and all processes of friction and wear of the materials involved in the work are stabilized.

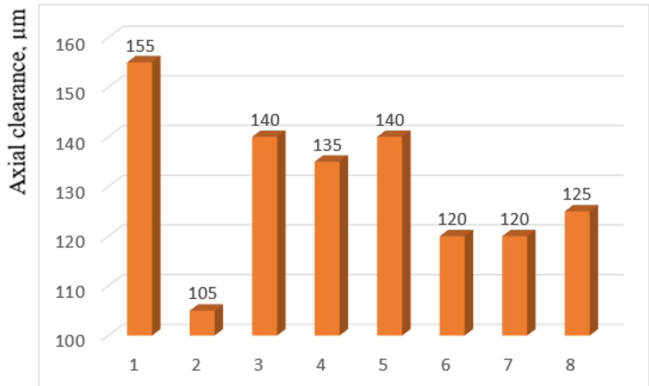


Fig. 3. The results of the axial gap (μm) of the samples without taking into account the initial gap after 2 million oscillation cycles (sample numbers according to T

The histogram shows very clearly the groups of samples 3, 4, 5 and 6, 7, 8. When analyzing the wear resistance of bearings with Zedex material, the dependence is followed that with an increase in temperature and a decrease in load, the wear resistance of the material is greater than in laboratory resource tests (Fig. 1). Under operating conditions close to real ones, the wear resistance of the ZX-324VMT polymer exceeds metal-polymer tape by 10-15%. Also, applying a molybdenum coating of 0.1 μm increases the wear resistance of the bearing. The wear resistance of the molybdenum coating on the titanium alloy shows the same results as when the polymer slides on the 95Х18Ш steel. An approximately the same pattern is observed in the TX1 material, but its wear resistance is even greater under these operating conditions. An interesting fact is that when replacing the inner ring of a hinged sliding bearing with a titanium alloy with a molybdenum coating, the wear resistance is almost the same or slightly lower than when the polymer rubs against steel. A slight deterioration in wear resistance can be explained by the fact that the titanium alloy removes heat from the friction zone worse [14, 15] and the temperature in the contact zone is higher, and as a result, the wear of polymers is greater. But despite this, at light or moderate loads, replacing the inner ring of the pivot bearing from steel to a titanium alloy with protective wear-resistant coatings is an excellent option for the aviation industry. Due to the fact that the use of plain bearings is widespread in aircraft, the benefit in weight will be very noticeable. Provided that the polymer material does not wear out to a critical value and the wear-resistant coating on the inner ring will also work for the entire period of operation of the plain bearing, it is possible to manufacture outer rings from titanium materials. The problem is that the use of polymer materials in plain bearings has limited operating conditions than metals or roller bearings.

Conclusions

1. The results of laboratory resource testing of plain bearings with metal-polymer materials are presented. It was determined that the plain bearing with Fluroglide material shows a wear resistance of 1.8-2 times greater

on the segment of 40-100 thousand cycles than bearings with other materials. It was also established that, up to 60,000 cycles, a plain bearing with a metal-polymer tape shows worse wear resistance than polymer materials, but all these results are within the tolerances of normal bearings operation.

2. Industrial tests have proven that at replacing the inner ring of a plain sliding bearing with a titanium alloy with a molybdenum coating, the wear resistance is almost the same or slightly lower than when the polymer rubs against steel. At low or moderate loads, replacing the inner ring of the plain bearing made from steel to a titanium alloy with protective wear-resistant coatings gives a significant gain in the aircraft weighting.

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Хімко М.С., Хімко А.М., Мнацаканов Р.Г., Мікосянчик О.О. Ресурсні випробування модифікованих шарнірних підшипників для авіаційної галузі

Представлено ресурсні випробування шарнірних підшипників із металополімерними трибосистемами розроблені для авіаційної промисловості. Метою роботи є визначення зносостійкості сучасних антифрикційних полімерних матеріалів у шарнірних підшипниках в порівнянні їх із металофторопластовою стрічкою.

Унікальність випробувань полягає у використанні комбінування високоефективних полімерних матеріалів в парі із покриттям хрому та молібдену при реверсивних рухах шарнірних підшипників. Оскільки застосування подібних підшипників носить масовий характер, застосування титанових матеріалів у виготовленні обойм підшипників дозволить суттєво зменшити вагу повітряного судна та підвищити його ефективність.

Визначено, що шарнірний підшипник з полімерним матеріалом із вуглецевих і поліамідних волокон та PTFE із функціональними добавками показує зносостійкість в 1,8 - 2 рази більшу на відрізку 40-100 тис. циклів, ніж підшипники із іншими матеріалами при лабораторних ресурсних випробуваннях. Також промисловими випробуваннями встановлено, що при наробітку в 2 млн. циклів шарнірний підшипник із металополімерною стрічкою показує результаті в 1,2-1,5 разів нижче по зносостійкості ніж полімерні матеріали, але всі ці результати лежать в полі допусків нормальної роботи підшипників.

Промисловими випробуваннями доведено, що при заміні внутрішнього кільця шарнірного підшипника ковзання на титановий сплав із покриттям молібдену зносостійкість майже однакова або незначно нижче чим при терті полімеру по сталі. Розроблені технологічні рекомендації та запропоновано нова конструкція та матеріали шарнірних підшипників ковзання із полімерними антифрикційними покриттями для авіаційної промисловості. Впровадження технологічних рекомендацій у виробництво підшипників дозволить відійти від універсальності використання шарнірних підшипників та продовжити їх зносостійкість та довговічність в цілому за рахунок використання повної товщини полімерного матеріалу та розробці підшипників із прогнозованими характеристиками під конкретну задачу.

Ключові слова: Шарнірні підшипники, металополімерні трибосистеми, довговічність, зносостійкість, реверсивний рух, навантаження, покриття, титановий сплав, полімерні антифрикційні матеріали