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Estimation of tribotechnical parameters of composite polymer with metal filler

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Abstract

The use of composition material based on the polyamide (caprolon) Ertalon 4.6 as an anti-friction material in the sliding units in the aviation industry is considered. Low carbon electrotechnical sheet steel 21864 of different concentrations was used as filler of composite material. The article presents the thermal calculation of plain bearings with polymer insert in different operating modes. It is determined that the addition of a metal filler to polyamide causes a temperature decrease in the friction zone due to the effective heat exchange from the shaft to the bearing housing. The article conducts a study of tribo-technical properties of the proposed composite material on installation PT-4C under sliding conditions according to the scheme "cylinder-plane", as well as modeling of the support unit in the software complex DS SolidWorks. It has been experimentally determined that the addition of finely dispersed steel filler enhances the antifriction properties of the Ertalon 4.6 polymer and extends the temperature range of the composite insert performance. Increasing the filler concentration to 20% results in a reduction of the friction coefficient by an average of 3.6 times and an increase in the temperature range of composite material use to 100 °C. The load-bearing capacity of the composite material bushing is increased to 25 MPa at a 20% filler concentration respectively.

The practical significance of the work lies in the analysis of the antifriction properties of the polymer with metallic filler in comparison with the polymer without filler, which will prove the effectiveness of the use of such polymers in friction units instead of non-ferrous metals (bronze, babbitt).

Key words: composite material, polymer, friction coefficient, polyamides, bearing, temperature.

Introduction

For the operation of the aircraft, an important factor is the quality of its parts as well as assembly, in general. An important role in the design of the aircraft is performed by bearings, which are present in almost every structural part of the aircraft.

Bearing – a product that is part of a support or emphasis that supports a shaft, axis or other movable structure with a given stiffness. It fixes the position in space, provides rotation, rolling or linear displacement (for linear bearings) with the least resistance, senses and transfers the load from the movable unit to other parts of the structure. The scope of the bearings is huge – almost no industry is complete without the use of bearings. There are a lot of varieties of bearings, and they are used depending on the operating conditions in a particular mechanism.

In aviation, there is a specificity due to difficult operating conditions such as: high contact pressures; dynamic and vibration loads; abrasive contamination; lack of lubrication, which results in increased wear and kinematic accuracy of the conjugation.

This problem can be solved using new advanced anti-friction materials, such as polymers, in the friction assemblies of aviation equipment. Polymer materials allow to solve several technical tasks aimed at increasing the reliability and service life of the equipment, have good antifriction properties when working in friction units without lubrication. However, their wide use is constrained by the fact that they have low thermal conductivity and, because of this, low heat resistance, and with increased temperatures - low wear resistance.

To eliminate these deficiencies, it is necessary to provide heat dissipation from the friction zone. We propose to include a metal filler in the structure of the polymer plain bearing. Previously, metal frames, nets, etc., were used, which reinforced the bearing and at the same time contributed to the removal of heat from the contact zone. The drawbacks were that they were not in direct contact with the shaft, which reduced their efficiency as a heat conductor element, and the production of such bearings was complex and time-consuming.

Literature review

In the manufacture of bearings, metal (steel, bronze, aluminum, titanium, etc.) is often assumed to be the most suitable material. Depending on the type, bearings can be considered sacrificial components in an assembly. They are designed to accrue wear in a system and to be replaced when they wear out. As such, the material chosen for bearings is selected both because it will have a long life and good wear resistance, or because it will be inexpensive to manufacture and simple to replace. The composite materials provide crucial weight savings to the aircraft, and because it is not made from metallic materials, it will be very resistant to corrosion. This design also reduces the weight of the part by approximately 50% [1].

Over the past few years composites have been dominant in the emerging materials. The applications areas of composite materials have grown steadily in the various systems of Mechanical Engineering, Civil Engineering, Electrical Engineering, Medical Engineering, and Automobile Engineering. In engineering systems, failure of parts may occur due to different types of wear mechanisms. The availability of a range of fiber reinforcements, fillers, matrices, and processing techniques offers ample scope for tailoring properties in composites as required for specific applications [2].

The tribological properties of polymers and polymer matrix composites (PMCs) and the relevant mechanisms of friction and wear has been reviewed [3]. The influence of both molecular and mechanical components on friction involving polymers as well as the influence of fillers, reinforcements, and dry lubricants on the overall tribological characteristics of PMCs is evaluated. Tribological parameters include surface roughness, the mechanism of adhesion, friction and wear, and chemical interactions with dry lubricants (if present). The article reviews the main factors that influence the wear and frictional characteristics of thermoplastic and thermosetting polymers, short fiber reinforced composites and high-performance unidirectional composites. Examples of quantitative data of different pairs of polymers and PMCs with the counterface are presented.

The article [4] provides an overview of polymer materials of various buildings used as antifriction materials. The experience of using different polymer materials for manufacture of antifriction coatings is considered. The advantages of thermoset and thermoplastic polymers in comparison with metal materials have been identified. Some compositions of carbon and organoplastics developed for plain bearings are described. It is concluded about the direction of research during development new matrixes for antifriction materials.

The article [5] conducts research on influence of rotational friction process on the value of wear of polymer antifriction material, both with metal filler and without filler. The dependence of linear and weight wear of antifriction sleeve of plain bearing is revealed.

Thus, the analysis of these publications shows the relevance of the development of plain bearings with the use of polymer materials in order to increase their antifriction and wear-resistant properties, which is the main precondition for increasing the service life of the bearing.

Purpose

The purpose of the work is to study the dependence of the friction coefficient on the temperature in the contact area at various modes of operation of plain bearings with a polymer insert and to review the influence of the metal filler in the structure of the polymer plain bearing on the temperature in the contact area of the friction surfaces.

Objects of research and experimental conditions

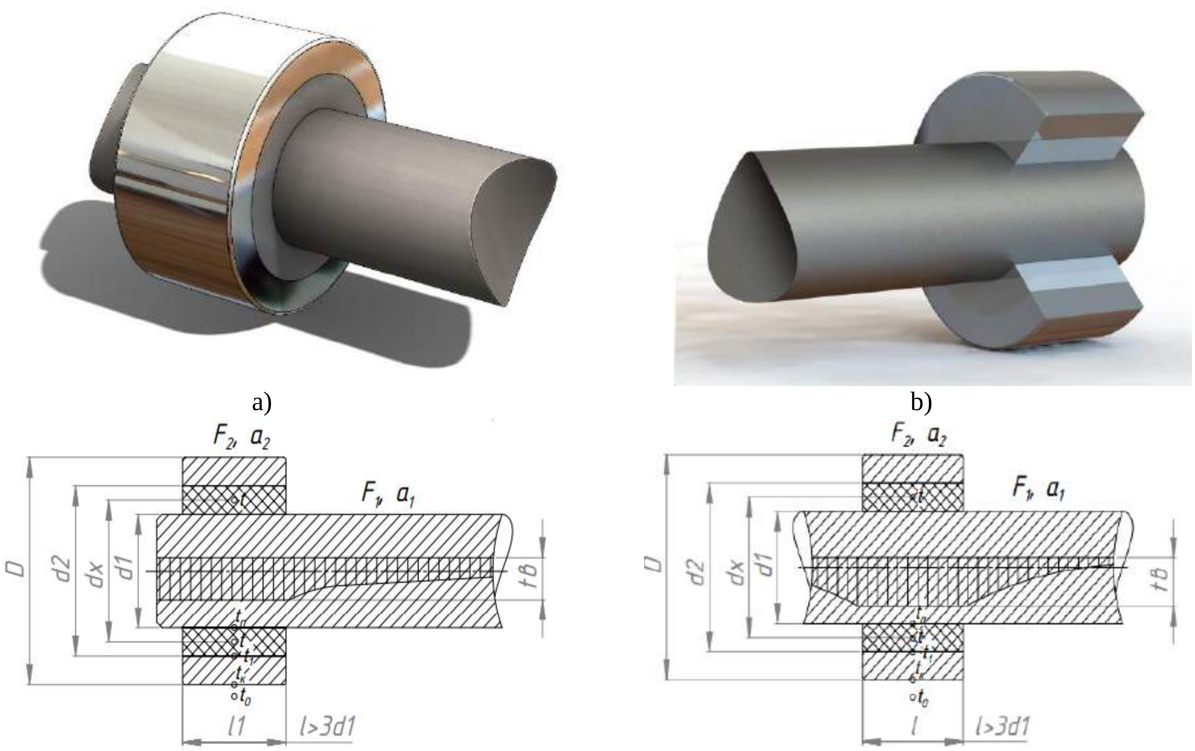
It is proposed to introduce into the bearing structure of fine chips of material with good thermal conductivity. For this graphite, molybdenum disulfide, copper, lead, titanium, or bronze can be used. However, these expensive materials were rejected and the metal shavings of low carbon electrotechnical sheet steel 21864 were used as filler material instead. In order to increase the efficiency of the thermal conductivity of the filler during the formation of the bearing, the action is carried out by a constant magnetic field, in the process of which metal sawdust, as a ferromagnetic material, are arranged in the form of chains, because one pole of the magnet is arranged inside the sleeve, the other pole is arranged on the external side thereof. The chains come into contact with the shaft. Since the shafts are typically made of solid steel and are heat-treated, the softer materials of the filler do not wear out the shaft, but due to direct contact with it, the heat is well dissipated. The heat-conducting links shall be arranged along magnetic field lines which shall be distributed perpendicular to the axis of the sleeve [3]. The optimum metal filler content is 15... 20% by weight. A small amount of low carbon steel filler does not contribute to abrasive wear in the friction bearing, often selective transfer occurs.

Rational thickness of sleeve wall S for connection diameters d = 20... 200 mm is selected from the expression S = (0.050...0.075)d. For the antifriction sleeve we used composite material, the thickness of the bushing wall is 4 mm.

The matrix for the composite sleeve was polyamide (caprolone) Ertalon 4.6 (Mitsubishi Chemical Advanced Materials). Compared with conventional nylons, Ertalon 4.6 features a better retention of stiffness and creep resistance over a wide range of temperatures as well as superior heat aging resistance. Therefore, applications for Ertalon 4.6 are situated in the "higher temperature area" (80 - 150 °C) where stiffness, creep resistance, heat aging resistance, fatigue strength and wear resistance of PA 6, PA 66, POM and PET fall short.

Due to the metal filler in the anti-friction sleeve, one part of the heat is discharged from the friction zone through the metal shaft and the other part through the bearing housing. The temperature of the antifriction layer depends on the ratio of the amount of heat generated in the bearing by friction and the amount of heat transferred to the surrounding area.

The diagram of the bearing unit using a bushing made of filled polymer is presented in fig. 1.



a) b)

c) d)

Fig. 1. Diagram of the bearing unit filled polymer: a, b – bearing units modelled using DS SolidWorks 2020; c - end bearing; d -median bearing; d_1 - shaft diameter in the friction zone; d_2 - outer diameter of bearing; D – outer bearing housing diameter; *l* - bearing length; L - length of shaft with intense heat exchange, $t_в$ – temperature distribution at shaft operation.

At the testing machine PT-4C under sliding conditions of the cylinder-plane scheme (Fig. 2), a study of the tricot technical properties of the proposed composite material was carried out. The material of the counter-sample is 40X steel (HRC 42), the material of the sample is Ertalon polyamide 4.6 without additives and a composite material based on it with the addition of fine steel 21864 chips in concentrations of 10 and 20%.

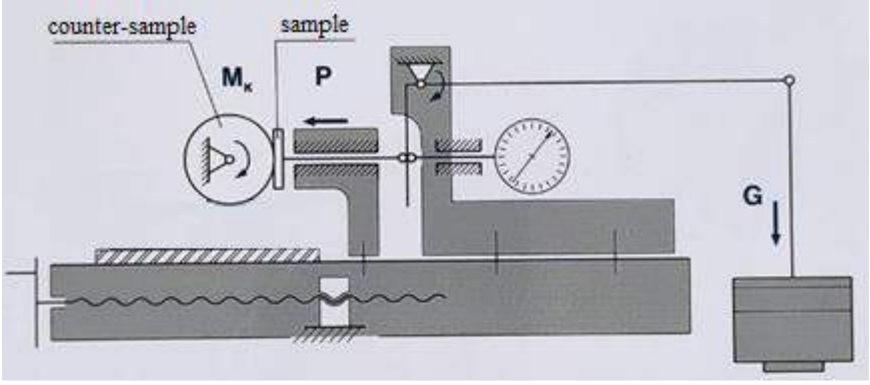


Fig. 2. Diagram of the test machine for determination of tribotechnical characteristics of materials.

The heating calculation is based on the assumption that the heat generated by friction is released into the environment through the shaft surface and partially through the bearing housing, as the thermal conductivity of the polymer (λ_2 = 0.3…0.8 W/(m ºC)) with metal filler well below the thermal conductivity of steel (λ_1 = 42...48 W/(m ºC)). In the process of friction interaction of the working surfaces of the friction unit heat is formed on the bearing support area, limited contact angle θ. Antifriction composite polymer with metal filler allows to allocate one part into the environment through the bearing housing. Lower temperature in the contact area increase the use of this composite material in plain bearings at frequent starts and stops with insufficient lubrication [2, 5].

On the surface of the friction unit the thermal source acts, the amount of heat released during the operation of the bearing is determined by the following formula:

$$Q = \frac{ldf}{427} pv, \tag{1}$$

where Q - bearing specific power, W/m^2; l - bearing length, m; d - bearing diameter, m; f - coefficient of friction; 1/427 - thermal equivalent of mechanical energy, kcal/(kg m); p - average specific pressure, N/m^2; v - slip speed, m/s.

In the process of friction interaction of the working surfaces of the unit the friction in the contact area is formed by heat. The excess temperature is discharged through the shaft in the radial and axial directions (Fig. 1). Outside the bearing support area, the temperature of the working surface decreases: the further away from the friction zone, the less [3].

When the plain bearing is operating, when the shaft rotates relative to the non-metallic layer, the surface temperature of the sleeve friction $t_п$ is some function of the distance r_x selected point from the cylinder axis and angle θ:

$$t_п = u(r_x, \theta). \tag{2}$$

The type of function (2) depends on the angle of contact of the non-metallic anti-friction layer of the sleeve with the shaft surface, the coefficient of thermal conductivity λ2 of the non-metallic layer, the thickness of the sleeve itself, the mode of operation of the friction unit, etc. factors. Since the highest temperature of the antifriction layer is observed in the contact zone of the friction surfaces, where it can be assumed to be constant at θ = 90... 120º, then the temperature distribution in the zone in question can be considered as a function only r_x [2, 6].

In this case, the temperature inside the sleeve:

$$t = t_п - \frac{t_п - t_1}{\ln\frac{d2}{d1}} \ln\frac{dx}{d1}, \tag{3}$$

where t_1 - the temperature on the external surface of the examined antifriction polymer sleeve; d_2 - external cylindrical surface of antifriction sleeve, d_2 = 2r_2; d_1 - the inner surface of the sleeve, d_1 = 2r_1;d_x- the distance of the selected point in the composite sleeve from the cylinder axis.

Since in the friction unit the outer surface of the bushing is in close contact with the metal housing of the bearing, the entire examined surface at the time of the onset of the stationary thermal mode t_1 can be considered constant due to the good thermal conductivity of the metal of the body (λ_1 = 42...48 W/(m ºC)). This value can be determined from the thermal balance:

$$Q_2 = Q_п, \tag{4}$$

where Q_2 - the amount of heat passed through the antifriction layer (in the case of polymers with metal filler) and metal bearing housing, W/m^2; $Q_п$ - the amount of heat given by the bearing housing to the environment, W/m^2.

In the established thermal mode, the temperature difference between the inner and outer surfaces of the metal bearing housing $\Delta t = t_1 - t_k$ is negligible, so it is possible to take $t_1 \sim t_k$.

The amount of heat passed through the antifriction layer of the composite polymer and metal bearing housing:

$$Q_2 = \frac{\theta \lambda_2 l}{\ln\frac{d_2}{d_1}} (t_п - t_k); \tag{5}$$

$$Q_п = \alpha_2 F'_2 (t_k - t_0), \tag{6}$$

where l is the length of the bearing support, m; λ2 - the coefficient of heat transfer from the bearing housing to the environment, W/(m^2 ºC); F'_2 - external surface area of bearing housing, m^2; t_k- temperature of outer surface of bearing housing, º C; t_0 - ambient air temperature, ºC.

Analysis of the main results

The thermal conductivity of a polymer liner with a metal filler is determined by:

$$\lambda_2 = n_a\lambda_a + n_в\lambda_в, \tag{7}$$

where n_a and $n_в$ - volume fractions of components (steel, polymer); λ_a and $\lambda_в$ - thermal conductivity of materials (steel, polymer).

Thermal conductivity of steel λ_a = 42... 48 W/(m ºC) and thermal conductivity of polymer $\lambda_в$ = 0.3 W/(m ºC). Taking into account that the content of the metal filler does not exceed 20%, the thermal conductivity of the composite material is λ_2 = 4... 8 W/(m ºC).

After the amount of heat removed from the friction zone by the metal housing of the plain bearing has been determined, it is possible to make conclusions about the distribution of the heat flow and, consequently, about the possibility of operation of this composite antifriction material in the friction units. In a straight friction pair, a significant part of the heat is released by the rotating shaft, a smaller part is released through the bearing housing.

In order to determine the temperature on the external surface of the examined sleeve, let us substitute the expressions (5) and (6) into the equation (4), taking into account $t_1 \approx t_r$:

$$t_1 = \frac{\theta\lambda_2 l t_п + \alpha_2 F_2' \ln\frac{d_2}{d_1} t_0}{\theta\lambda_2 l + \alpha_2 F_2' \ln\frac{d_2}{d_1}}. \tag{8}$$

Having determined the temperature on the external surface of the examined polymeric sleeve with a metal filler, it is possible to determine how much heat is released by the outer surface of the plain bearing. Fig. 2 shows the temperature distribution according to the material. Composite material with metal filler (curve 2, 3) allows the heat to be dissipated through the outer surface of the plain bearing casing.

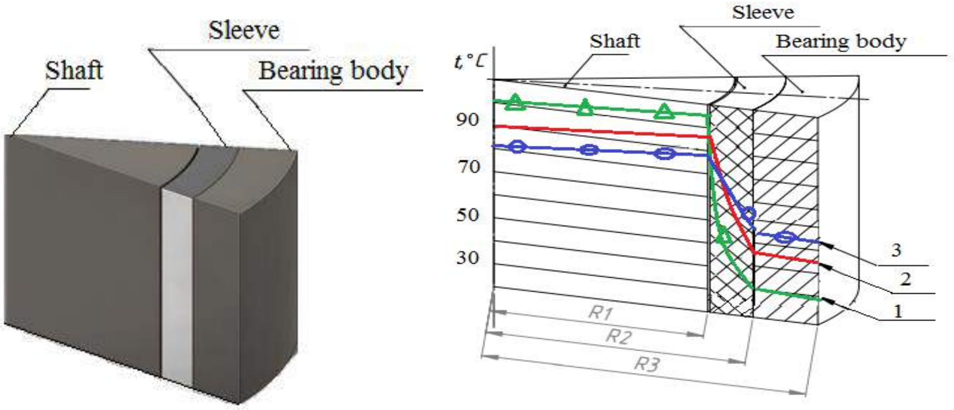


Fig. 2. Temperature distribution in the polymer sleeve bearing (S = 4 mm): 1 - pure polyamide (Ertalon 4.6); 2, 3 - polyamide filled with metal chips (steel 21864) in concentration of 10 and 20% respectively under the action of magnetic field.

By substituting the value t_1 into the expression (3), we get the formula for temperature distribution in the polymer antifriction material on the area limited by the angle θ:

$$t = t_п - \frac{t_п - t_0}{\ln\frac{d_2}{d_1} + \frac{\theta\lambda_2 l}{\alpha_2 F_2'}} \ln\frac{d_{2x}}{d_1}. \tag{9}$$

The obtained temperature of the polymeric composite material is comparable to the maximum permitted temperature [t] of the reference material: t ≤ [t]. If the condition is met - the calculation is complete, if not, it is necessary to change the size of the liner and improve the heat exchange conditions either by reducing the thickness of the antifriction layer, or by increasing the quantity of metal filler to the limit value.

It was found that the sleeve made of a polymer composite material with fine metal filler reduces the temperature on the shaft at an average of 1.15... 1.22 times depending on the concentration of the filler.

In the work, special attention was paid to the dependence of the coefficient of friction of the polyamide on the temperature (fig. 3, a). The dependance of coefficient of friction on temperature is strongly expressed in pure Ertalon 4.6, in composite material with metal filler this dependence is less obvious. The addition of fine steel filler significantly increases the antifriction properties of the Ertalon 4.6 polymer and extends the temperature range of the composite bushing. For example, adding a 10% concentration of the filler reduces the friction coefficient at an average working temperature of up to 80 °C. Increasing the concentration of the filler to 20% reduces the friction coefficient by 3,6 times and extend the temperature range of the use of composite material to 100 °C.

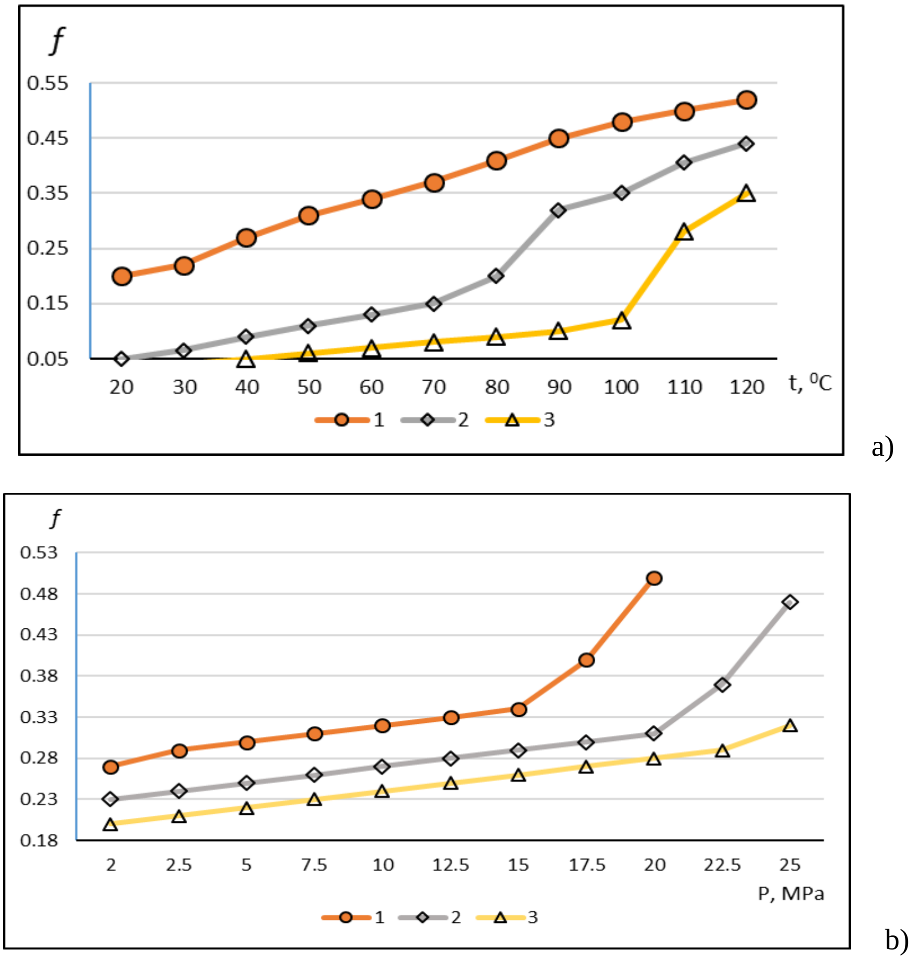


Fig. 3. Dependence of coefficient of friction on temperature at contact load of 7,5 MPa (a) and on the specific load on plain bearing (V = 0,78 m/s; Δ= 0,3 mm, t = 50 ⁰C) (b): 1 - pure polyamide (Ertalon 4.6); 2, 3 - polyamide filled with metal chips (steel 21864) in concentration of 10 and 20% respectively under the action of magnetic field.

Fig. 3, b shows the dependence of the friction coefficient on contact load. It is observed that the working capacity of the sleeve made from pure Ertalon 4.6 polymer reaches contact load of 15 MPa, further increase of contact load leads to sharp increase of coefficient of friction and destruction of the polymer. Adding a fine-dispersion steel filler increases the bearing capacity of the composite sleeve to 20 and 25 MPa at a concentration of 10 and 20% filling respectively.

Thus, the reduction of temperature in the zone of friction contact of plain bearing due to the use of a composite sleeve causes increase of antifriction properties and increase of carrying capacity of a composite, which is a promising direction for introduction of polymeric materials in the aircraft units under the harsh operational conditions.

Conclusions

It was shown that addition of the metal filler in the structure of the polymer plain bearing leads to increased heat dissipation from the bearing contact area and consequently to decrease of the friction coefficient.

Analysis of the laboratory studies shows that the polymer with metal filler has high antifriction properties compared to polymer without filler and in some cases can replace in bearings non-ferrous metals (bronze, babbit).

The use of composite meterial in friction units will extend the service life and reduce the cost of manufacturing such friction units.

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Скворцов О.О., Мікосянчик О.О. Оцінка триботехнічних параметрів композиційного полімеру з металевим наповнювачем

Розглянуто використання композиційного матеріалу на основі поліаміду (капролону) Ertalon 4.6 як антифрикційного матеріалу в вузлах ковзання в авіаційній промисловості. В якості наповнювача композиційного матеріалу використовувалась дрібнодисперсна добавка низьковуглецевої електротехнічної листової сталі 21864 в різних концентраціях. У роботі представлено тепловий розрахунок підшипників ковзання з полімерною вставкою при різних режимах роботи. Визначено, що додавання металевого наповнювача в поліамід обумовлює зниження температури в зоні тертя за рахунок ефективного відведення тепла від валу до корпусу підшипника. Дослідження триботехнічних властивостей запропонованого композиційного матеріалу проводились на установці ПТ-4Ц в умовах ковзання за схемою циліндр – площина, також було проведено моделювання підшипникового вузла у програмному комплексі DS SolidWorks. Експериментально встановлено, що добавка дрібнодисперсного сталевого наповнювача підвищує антифрикційні властивості поліаміду Ertalon 4.6 та розширює температурний діапазон роботоздатності втулки з композитного матеріалу. Підвищення концентрації наповнювача до 20% призводить до зниження коефіцієнту тертя, в середньому, в 3,6 разів та розширення температурного діапазону використання композиційного матеріалу до 100 ^{0}C. Встановлено підвищення несучої здатності втулки з композиційного матеріалу до 25 МПа при концентрації наповнювача 20% відповідно.

Практична значимість роботи полягає в аналізі антифрикційних властивостей полімеру з металевим наповнювачем порівняно з полімером без наповнювача, що дозволить довести ефективність використання таких полімерів у вузлах тертя замість кольорових металів (бронза, бабіт).

Ключові слова: композиційний матеріал, полімер, коефіцієнт тертя, поліамід, підшипник, температура