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STUDY OF WEAR RESISTANCE OF REINFORCED POLYAMIDE COMPOSITES FOR METAL-POLYMER GEAR DRIVES

STUDIUM ODPORNOŚCI NA ZUŻYCIE WZMACNIANYCH KOMPOZYTÓW POLIAMIDOWYCH DLA METALOWO-POLIMEROWYCH PRZEKŁADNI ZĘBATYCH

Key words: polyamide composites, fillers – glass and carbon fibres, wear of composites, metal-polymer gear drives, durability, contact strength.

Abstract An experimental study of the wear resistance of two dispersion-filled composite materials based on polyamide used in metal-polymer gear drives with a 30% volume content of short glass or carbon fibres was performed according to the technique proposed by the authors. As a result of tribotests in the "pin-disk" scheme, the mass wear of these composites was determined under dry friction conditions for steel 45 at room temperature in the range of contact pressures of 10–40 MPa, as well as the kinetics of the coefficient of sliding friction and the contact temperature of the tribosystem elements. It was established that polyamide strengthened by carbon fibres has almost four times higher wear resistance in comparison with a polyamide filled with glass fibres. The wear resistance characteristics that are the basic parameters of the tribokinetic wear model are calculated, using the durability of the straight spur metal-polymer gear drive on the basis of the original calculation method. It was established that gear drive durability with a pinion or a wheel reinforced with carbon fibres is more than eight times the durability of gear drive with gear wheels from polyamide filled with glass fibres. The gear drive durability with the steel pinion and the composite gear wheel increases in proportion to the gear ratio as compared to the gear drive with the composite pinion and the steel wheel. The change in the maximum contact pressures in the mesh interval was calculated.

Słowa kluczowe: kompozyty poliamidowe, wypełniacze włókna szklane i węglowe, zużywanie kompozytów, przekładnie zębate metalowo-polimerowe, trwałość zużyciowa, wytrzymałość stykowa.

Streszczenie Według metodyki autorskiej przeprowadzono badania doświadczalne odporności na zużycie dwóch materiałów kompozytowych na podstawie poliamidu wypełnionego 30% krótkimi dyspersyjnymi włóknami szklanymi oraz węglowymi stosowanego w zębatych przekładniach metalowo-polimerowych. W wyniku badań tribologicznych wg schematu „pin of disk" zostały oszacowane zużycia masowe przy tarciu suchym materiałów pary tribologicznej kompozyt – stal C45 w temperaturze pokojowej w zakresie nacisków stykowych 10–40 MPa. Została też przebadana kinetyka zmiany współczynnika tarcia ślizgowego oraz temperatury obu elementów układu tarciowego w strefie okołostykowej w trakcie eksperymentu. Ustalono, że poliamid wzmocniony włóknami węglowymi ma prawie czterokrotnie wyższą odporność na zużycie niż wzmocniony włóknami szklanymi. Następnie obliczono dla przebadanych par tribologicznych ich wskaźniki (charakterystyki) odporności na zużycie jako bazowe parametry tribokinetycznego modelu matematycznego zużywania, na podstawie których przeprowadzono wg autorskiej metody obliczeniowej oszacowanie resursu walcowej metal – polimerowej przekładni o zębach prostych. Określono, że trwałość przekładni z zębnikiem lub kołem zębatym wzmocnionym włóknem węglowym (zębnik lub koło zębate) przewyższa trwałość przekładni wzmocnionej włóknem szklanym powyżej ośmiu razy. Trwałość przekładni ze stalowym zębnikiem i kompozytowym kołem zębatym jeszcze wzrasta proporcjonalnie w porównaniu z przekładnią z zębnikiem kompozytowym i kołem stalowym. Przebadano zmianę maksymalnych nacisków stykowych w cyklu zazębienia.

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INTRODUCTION

Metal-polymer gear drives are widespread in technology, thanks to their ability to work without lubrication, the low level of generated noise, the simple technology of manufacturing gear wheels, the ease of maintenance, and other benefits. In order to reduce wear and increase the durability of the metal-polymer gear drives, the reinforcement (filling) of the polymer matrix by strong and rigid particles/fibres, in particular, on the basis of glass and carbon with different volume content [**L. 1, 2**], are widely used. However, carrying out experimental studies of wear of this kind of materials, as a basis for determining the durability of metal-polymer gear drives using appropriate calculation methods, is quite long and complex. There are a very limited number of publications [**L. 3–8**] concerning quantitative experimental studies of this type of composite materials in the literature.

For example, the results of numerical modelling of a straight spur metal-polymer gear drive with wheels of polyamide 66 are presented in [**L. 3, 4**], where the distribution of the load between the wheels and its influence on contact and bending stresses with experimental verification of the calculation results is studied. The influence of sliding speed on the frictional force was studied for the tribojoint of the PA6 polymer – S355J2 steel in [**L. 5**], by means of disc-disk tests, and the sliding velocities and Hertz contact pressures in the meshing of a cylindrical metal-polymer straight cut gear are calculated. The friction coefficients and the relative volumetric wear of the teeth of the metal-polymer gear drive from polyamide PA6-Mg, PA6-Na, PA66GF-30, polyoxymethylene POM-C, and steel S355 under normal conditions in the air and abrasive media were experimentally established in the works [**L. 6, 7**].

It was established that the wear and durability of glass and carbon composites largely depend on the volume content of the reinforcing phase in [**L. 8**]. However, there are no other studies of this nature in the literature.

The results of extensive experimental studies of materials of miniature sliding bearings with a composite sleeve and steel shaft are presented also in [**L. 9**]. The radial wear of a sleeve made of the following polymeric composites was studied: without lubrication PA6, PA66, POM-C, POM-H, PA66+GF30, PA66+GF50, PA66+GS28, PA610, PA11, PA12; with solid lubricants – PA6+GF25+graphite, PA6+GF25+MoS2 (GF – glass fibres, GS – glass spheres, numbers – their volume content in percentage) at relatively low contact pressures (0.2 -2.5 MPa) and slip velocities (0.0131-0.131 ms^{-1}).

EXPERIMENTAL STUDY

The model study of the wear of polyamide-based composites was performed on a modernized Amsler tribometer by the pin-disk scheme, which ensures that the conditions of the friction process remain unchanged. The pin sample is made of a composite on the basis of polyamide PA6, and the disk is made of steel S45. The experimental conditions are as follows: slip velocity v = 0.4 m/s; contact pressure p_a = 10, 20, 30, and 40 MPa; friction path L = 1440 m.

As a result of the studies, the mass wear ΔM of composite samples was determined. In what follows, their linear wear h was calculated using the following formula:

$$h_i = \frac{\Delta M_i}{\rho A_a} \tag{1}$$

where

ρ is the specific gravity of the composite,
A_a is the nominal contact area,
i is the load stage.

Based on the results of these studies, the experimental values of the characteristic wear function $\Phi_i(\tau_i)$ of the composite are established according to the following relationship [**L. 10**]:

$$\Phi_i(\tau_i) = \frac{L}{h_i} \tag{2}$$

Based on the experimental values of the function $\Phi_i(\tau_i)$, the wear resistance characteristics of materials are established as the basic parameters of the tribokinetic wear model for sliding friction. Accordingly, the values $\Phi_i(\tau_i)$ are approximated using the following relationship [**L. 10**]:

$$\Phi_k(\tau) = C_k(\tau_{sc}/\tau)^{m_k} \tag{3}$$

where

$\tau = f\,p_a$ is the specific friction force,
τ_{sc} is the composite shear strength,
f is the coefficient of sliding friction,
C, m are the characteristics of wear resistance of the material in the conjugation under study,
k = 1; 2 is the numbering of wheels (1 – pinion, 2 – gear wheel).

The values $\Phi_i(\tau_i)$ (markers) and approximating their graphs – the wear-resistance diagrams $\Phi(\tau) - \tau$ in the investigated range of specific frictional force τ are shown for both tested polyamide composites in **Fig. 1**.

The analysis of **Fig. 1** shows that, in the entire region of variation in the specific frictional forces, the carbon composite has a significantly higher wear resistance (about 4 times) than the polyamide reinforced with glass fibres. As a result of approximation of the curves by the method of least squares, the wear resistance characteristics of the investigated composites with 30% reinforcing filler are determined as follows:

- UPA(T) – 6/30UW: $C_W = 4.7 \cdot 10^6$, $m_W = 2.3$ – carbon fibres;
- PA6-LT-SW30-1: $C_S = 1.2 \cdot 10^6$, $m_S = 1.9$ – glass fibres.

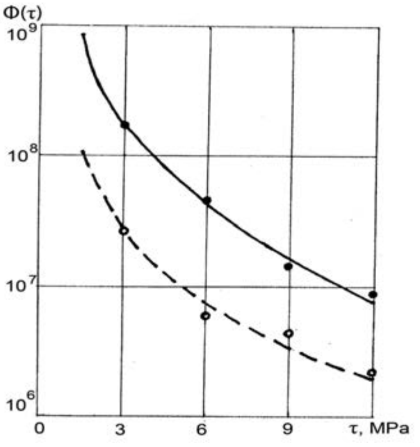

Fig. 1. Diagrams of wear resistance of composites: a solid line – a composite with carbon fibres, a dashed line – a composite with glass fibres

Rys. 1. Diagramy odporności na zużycie kompozytów: linia ciągła – kompozyt z włóknami węglowymi, linia kreskowa – kompozyt z włóknami szklanymi

During the tests, the friction coefficient f and the temperature T in the proximity zone were recorded. With the stable wear of both composite materials in conjunction with steel for friction without lubrication, the friction coefficient was $f_W = f_S \approx 0.3 ... 0.31$. The temperature of the samples during the studies depended on the load and they were as follows: carbon composite (T = 70 ... 100°C) – steel (T = 68 ... 90°C), glass composite (T = 60 ... 120°C) – steel (T = 51 ... 90°C).

STUDY OF SPUR METAL-POLYMER GEAR DRIVE

The numerical study is the next stage in the study of the wear resistance of these polyamide composites by the example of straight spur metal-polymer gear drives with involute teeth: a) pinion – composite, gear wheel – steel ($Z_K – K_S$); pinion – steel, gear wheel – composite ($Z_S – K_K$). The solution of the problem was carried out according to the author's method of studying gear drives, presented in the literature [**L. 11–15**].

The following initial data for calculations were accepted: T_{nom} = 4000 Nmm – the rated torque, n_1 = = 1000 rpm – the number of pinion revolution; K_g = 1.2 – the coefficient of dynamism; m = 4 mm – the engagement module, u = 3 – the gear ratio, z_1 = 20 – the number of teeth pinion, z_2 = 60 – the number of teeth wheel, b = 20 mm – the width of the crown of the gear wheel, $f_S = f_W = 0.3$ – the sliding friction coefficient; h_{k*} = 0.5 mm – the permissible wear of composite wheels, ε_α = 1.372 – the overlap factor in two-one-two-pair engagement.

The wheel materials:

1) steel S45 in the state of delivery, $E = 2.1\cdot10^6$ MPa, ν = 0.3 are the Young modulus and Poisson's ratio, respectively; $C_{st} = 10^9$, $m_{st} = 2$;
2) polyamide composite with carbon fibres UPA(T) – 6/30UW, E_W = 520 MPa, ν_W = 0.42; $C_W = 4.7\cdot10^6$, m_W = 2.3; $\tau_{sc}^{(W)}$ = 48 MPa;
3) polyamide composite with glass fibres PA6-LT-SW30-1, E_S = 390 MPa, ν_S = 0,42; $C_S = 1.2\cdot10^6$, m_S = 1.9; $\tau_{sc}^{(S)}$ = 52 MPa.

The values of the Young modulus and Poisson's ratio are found by technical conditions (TC) of Belarus: E_W, ν_W TC 03535279.049-99; E_S, ν_S – TC 500048054.020-2001.

As a result of the calculations performed, it was established that the minimum durability determined for the accepted permissible wear value h_{k*} of the involute gear wheels will be at the entry point of the teeth into a single-pair gearing. It is for these types of metal-polymer gear drives:

– gear drive $Z_K – K_S$: $t_{min}^{(W)}$ = 50349 hours, $t_{min}^{(S)}$ = 6201 hours; $t_{min}^{(W)}/t_{min}^{(S)}$ = 8.12, correspondingly;
– gear drive $Z_S – K_K$: $t_{min}^{(W)}$ =151048 hours, $t_{min}^{(S)}$ = 18602 hours; $t_{min}^{(W)}/t_{min}^{(S)}$ = 8.12, correspondingly.

The calculations show an eight times higher resources of the gear drive with wheels from the carbon composite in comparison with the wheels from the glass composite. The durability of gear drive also depends on its design. Accordingly, in the $Z_K – K_S$ gear drive with the composite pinion Z_K, it decreases in proportion to the gear ratio in comparison with the gear drive durability of the $Z_S – K_K$ with the steel pinion Z_S, i.e. three times. It should be pointed out that the ratio of the longest (151048 hours) and the lowest (6201 hours) durability of the studied metal-polymer gear drives is very significant and is more than 24 times!

Apparently, the reason for the higher wear resistance of carbon-filled plastic in comparison with glass-reinforced plastic is, on the one hand, the antifrictional property of carbon fibres (similar to the graphite particles added to many polymeric materials to improve wear resistance), and, on the other hand, the sufficiently pronounced abrasive ability of glass fibres.It is expressed in the increased wear of the wheel made of fiberglass and the associated steel pinion.

In the next stage, the maximum Hertz contact pressures p_{jmax} acting at j points of the tooth profile contact (the rotation angles $\Delta\varphi$ of the pinion) during their interaction are determined as a parameter characterizing the gear drive carrying capacity (**Fig. 2**).

Their magnitude depends, to a great extent, on the number of pairs of teeth that are simultaneously in mesh. In the left-hand region of the double-pair engagement, pressures p_{jmax} reach significantly larger values than its right-hand area. With single-pair meshing (in the central region), their values are partially higher than the pressure in the left region. The greatest value p_{jmax} is reached at the entrance to the single-pair gearing. In the gear drive with the wheel from the carbon composite, the contact pressures are approximately 1.14 times higher than in the gear drive with the wheel from the glass composite.

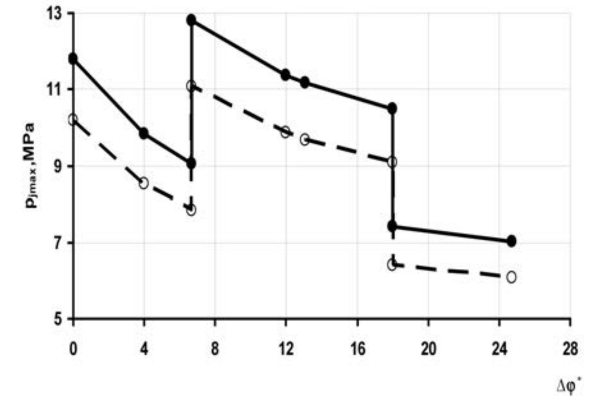

Fig. 2. Maximum contact pressures in the engagement cycle: ○ – glass composite, ● – carbon composite

Rys. 2. Maksymalne naciski stykowe w cyklu zazębienia: ○ – kompozyt z włóknami szklanymi, ● – kompozyt z włóknami węglowymi

The change in sliding speed *v* of the teeth in the process of contact interaction is shown in **Fig. 3.** There is an almost linear dependence of the change in speed from the point where the teeth enter into engagement before exiting it, as well as changing its direction at the engagement point.

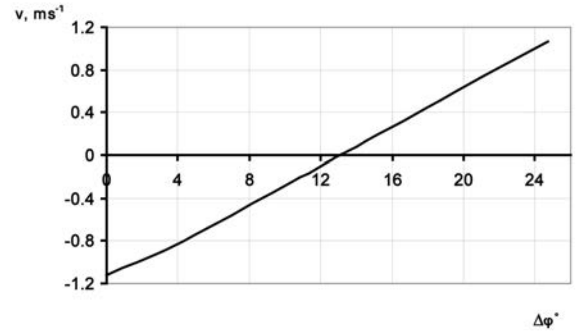

Fig. 3. Sliding speed in the engagement cycle

Rys. 3. Prędkość poślizgu w cyklu zazębienia

CONCLUSIONS

1. The wear resistance of a polyamide composite reinforced with carbon fibres is approximately four times higher than that of polyamide with glass fibres (**Fig. 1**).
2. The calculated durability of a metal-polymer gear drive with a pinion or a wheel reinforced with carbon fibres exceeds the durability of a glass-reinforced drive more than eightfold.
3. The durability of the gear drive is also affected by the design. In the gear drive with the composite gear, the durability will be three times higher (by the magnitude of the ratio) than in the gear drive with the composite pinion.
4. By rational choice of the type of polyamide, reinforced by short glass or carbon fibres, as well as the design of the metal-polymer gear drive, it is possible to increase its life up to 24 times.
5. In the gear drive with the wheel from the carbon composite, the contact pressures are 1.14 times higher than in the gear drive with the wheel from the glass composite.
6. The maximum contact pressures in the engagement cycle have a significant variation, depending on the engagement area and the pinion rotation angle. They reach the greatest value at the entrance to a single-pair gearing, and their value is 1.08 times smaller (**Fig. 2**) at the entrance to the double-pair engagement.
7. The presented technique of experimental determination of wear parameters in combination with the tribo-kinetic wear model allows us to determine the wear of the elements in the metal-polymer tribojoint and to establish the characteristics of their wear resistance. These characteristics, as the basic parameters of the model, are used in the author's calculation method for studying gear drives [**L. 10–15**] to assess their life and wear as described in this publication. Similar methods of calculation, concerning gear drives with wheels from polymers, in the literature are few. An exception is the actual work [**L. 8**], in which the durability of the metal-polymer gear drive with the reinforced composites under consideration was studied in a simplified form.

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