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Studying the influence of HB-4 amorphous alloy on tribological properties of phenylone aromatic polyamide

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The article considers the influence of the content of the amorphous HB-4 alloy on the tribological properties of aromatic polyamide phenylone C-2. It has been established that the introduction of 10–20 wt.% of a dispersed filler leads to a decrease in the intensity of linear wear and roughness by 3.7–5 and 1.3–2.4 times, respectively, on the surface of the original polymer; the maximum positive effect is achieved at 20 mass% filler. The formation of a transfer film on a steel counterbody makes it possible to increase the wear resistance of metal polymers by 1.5 times, that is, friction occurs on a smoother surface according to the "composite-composite" scheme, and the steel counterbody almost does not take part in the friction process. It was found that the effective content of the filler in the polymer matrix is 20 mass%.

Keywords: aromatic polyamide phenylone C-2, HB-4 amorphous alloy, intensity of linear wear, friction coefficient, metal polymers.

Дослідження впливу аморфного сплаву марки НВ-4 на трибологічні властивості ароматичного поліаміду фенілон. *А.-М.В.Томіна, К.А.Єрьоміна*

У статті розглянуто вплив вмісту аморфного сплаву марки НВ-4 на трибологічні властивості ароматичного поліаміду фенілон С-2. Встановлено, що введення дисперсного наповнювача у кількості 10–20 мас.% призводить до позитивного ефекту: зменшення інтенсивності лінійного зношування та шорсткості по відновлювальній поверхні вихідного полімеру у 3,7–5 і 1,3–2,4 рази відповідно, сягаючи мінімальних значень при 20 мас.% наповнювача. Утворення плівки перенесення на сталевому контртілі дозволяє додатково підвищити зносостійкість металополімерів у 1,5 рази, тобто тертя відбувається вже за більш гладкою поверхнею за схемою "композит-композит", а сталеве контртіло майже не приймає участь у процесі тертя. Виявлено, що ефективний вміст наповнювача в полімерній матриці складає 20 мас.%.

1.Introduction

Polymer composite materials (PCMs) based on polyamides (PA) including aromatic ones are widely used instead of serial metals in tribological compounds in many branches of modern industry such as agricultural, metallurgical and automotive ones. As a result of various processing methods, unique properties are achieved: stability of parts under the influence of high temperatures (523 K) and loads, abrasive particles, acids and alkalis; low coefficient of linear thermal expansion, high wear resistance and thermal conductivity [1]. Another important factor of the widespread use of PCMs based on PAs is the economic aspect: the use of 1 ton of PCMs replaces 3–4 tons of steel or 6–7 tons of bronze, while reducing the energy consumption of production by 3.3 times [2].

Fillers (FL) of aromatic PAs to improve mechanical and tribological properties are carbon and organic fibers, powders of graphite, metals, fullerene soot, etc. It is established [3] that the use of PCMs with these

FLs makes it possible to increase the durability and reliability of friction units by 7 times.

The authors of [4] found out that the introduction of dispersed powders of pure metals in the PAs significantly improves their performance properties. It was shown in [5] that MPs obtained by forming finely dispersed metal particles in the bulk of a polymer (methods of dispersion, displacement, polymerization, etc.) are also promising; they are used in various industries. However, their use as a PL for PA alloys, especially amorphous or nanocrystalline ones, has received insufficient attention in the literature. Amorphous metals are superior to known serial materials for structural and tribotechnical purposes in terms of strength and elasticity [6–8]. Given all the above mentioned, the scientific interest is to study the influence of special alloys on the properties of polyamide.

The purpose of this work is to study the effect of the content of the amorphous alloy HB-4 on the tribotechnical properties (linear wear rate, friction coefficient, and roughness) of PCM based on heat-resistant aromatic polyamide phenylone C-2.

2. Experimental

Linear heterochain AP phenylone C-2 was chosen as a polymeric binder for the production of MPs. In the main chain of its macromolecule, there is an amide group –HNCO– connected by phenyl fragments on both sides. This polymer is significantly superior to usual PAs in terms of thermal and chemical resistance, physical-mechanical and tribological properties [9].

A dispersed (17–133 μm) HB-4 brand amorphous alloy (chemical composition is $Fe_{60}Cr_4Co_7V_2W_1Mo_1Nb_1B_{20}C_2Si_2$) manufactured on the equipment of "Melta" LLC (Kyiv) was chosen as a filler for the polymer matrix. The alloy was obtained by grinding fast-hardened amorphous tape in a ball mill; its properties are given in Table 1.

MPs were prepared by the compression pressing method described in [8], except for ferromagnetic particles. Since the alloy is based on iron, which is a ferromagnet, ferromagnetic particles were excluded from the mixing process. The ferromagnetic particles of the alloy were magnetized under the action of an external magnetic field; thus, they moved in the direction of the field, which made it possible to uniformly distribute the PL in the bulk of the polymer matrix. Tribological properties (friction coefficient f and intensity of linear wear I_h) were studied under conditions of friction without lubrication on a machine with friction discs [11] at a load of 0.6 MPa and a sliding speed of 1 m/s, the friction path was 1000 m. Friction surfaces of the original polymer and MPs on its basis were studied using a Biolam-M microscope. The roughness of the friction surfaces (R_a, μm) of the test samples was determined using a 170621 profilometer. The microhardness of the particles of HB-4 alloy was measured on a PMT-3M microhardness tester.

Table 1. Properties of HB-4 amorphous alloy tape [10]

Indicators	Values
Tape thickness, μm	35±3
Average interatomic distance, R_{at}, nm	0.25
Glazing temperature, K	818
Density, g/cm^3	5.13
Tensile strength, σv, GPa	4.29–4.89
Microhardness, GPa	12.89±0.06

3. Results and discussion

Table 2 presents the results of tribological tests carried out on aromatic polyamide and MPs based on it during the friction on the restorative surface (imitation of the beginning of the operation of the friction unit) and on the transfer film (imitation of long-term operation of the friction unit). From the data of Table 2 it can be seen that the introduction of the amorphous alloy HB-4 reduces the intensity of linear wear and roughness on the restorative surface of the initial polymer by 3.7–5 and 1.3–2.4 times, respectively, reaching the minimum values at 20 mass % filler.

The increase in the wear resistance of MPs is associated with the presence of a harder FL in the polymer. The softer material deforms quickly as the contacting surface layers are subjected to repeated stresses during the friction process [12]. As a result of the deformation processes, a network of microcracks is formed that contributes to the intensive separation of wear particles and, as a consequence, leads to wear of the material. Thus, a harder FL is able to withstand stress increasing the overall hardness of the material. This inhibits the volumetric deformation of the polymer matrix in the surface layers and, consequently, increases the wear resistance.

Table 2. Tribological properties of phenylone aromatic polyamide and composites based on it

Indicator	C-2	C-2 + 10 % HB-4	C-2 + 15 % HB-4	C-2 + 20 % HB-4	C-2 + 25 % HB-4
Friction on the restorative surface					
Intensity of linear wear, $I_h \cdot 10^{-9}$	34.30	9.18	7.16	6.87	12.01
Coefficient of friction, f	0.520	0.474	0.493	0.633	0.611
Surface roughness, R_a, μm	2.43	1.90	1.02	1.02	1.20
Friction on the transfer film (L = 3000 m)					
Intensity of linear wear, $I_h \cdot 10^{-9}$	31.18	5.98	4.50	4.41	6.54
Coefficient of friction, f	0.477	0.470	0.486	0.582	0.581
Surface roughness, R_a, μm	2.11	1.77	0.97	0.88	1.05

When forming a transfer film, the wear resistance additionally increases by 1.5 times compared to friction on the restorative surface. It is known from literature [13] that the transfer film improves the tribological properties of composites. The transfer film reduces the inhomogeneity of the surface layer of the counterbody (roughness is reduced by 15 %), thus the friction process takes place on a smoother surface according to the "composite-composite" scheme, and the steel counterbody takes almost no part in the friction process.

Table 2 shows that the friction coefficient of acquires a minimum value with the introduction of 10 mass% of the filler both on the restorative surface and on the transfer film. A sharp (by ~ 18 %) increase in this index is observed with a further increase in the HB-4 content to 20 mass%. That is due to the fact that the particles of a harder filler (HV = 607–809 units) are concentrated on the MP surface in the contact zone and increase friction forces, which can probably lead to the formation of deep grooves on the steel counterbody [12].

Figure 1 shows the friction surfaces of the initial polymer (Fig. 1, a) and MPs with an amorphous alloy content of 10–25 mass% (Fig. 1, b–e).

On Fig. 1 (b–d), traces of adherence of composites to the counterbody and the absence of microcracks on the friction surfaces of metal polymers containing 10–20 mass% are observed. This indicates the plastic destruction of the material under the influence of sliding friction. In this case, the higher the wear resistance of the MP, the less traces of adhesion are observed (the surface becomes less deformed).

Morphological studies of the friction surfaces of MPs with an alloy content of 25 mass% indicate a fatigue mechanism of surface destruction. On Fig. 1(e), a crack formed at the interface of the "phenylone -filler" is observed, which grows to critical sizes due to repeated loads and greatly facilitates the formation of wear particles. As a result, the wear resistance of these MPs deteriorates (see Table 2). This can be explained by a decrease in the plasticity of the composition due to the excessive amount of the filler. Before the formation of the final products, MPs are exposed to a magnetic field (B = 0.12 T). Under the action of a magnetic field, the ferromagnetic particles of the filler are magnetized. Due to the magnetic interaction, the particles collide during mixing and form agglomerates that behave like elementary magnets. In this case, the higher the amount of filler in the mixture, the greater the probability of intersection of particle trajectories; hence, the more likely is the formation of agglomerates. Such agglomerates are not penetrated by the polymer melt; inside them there are voids, due to which cracks form during friction.

The formation of agglomerates leads not only to the formation of cracks and deterioration of wear resistance of MPs. They also cause intensive wear of the counterbody (see Fig. 2, a–c) due to the high microhardness of the amorphous alloy.

Confirmation of the presence of voids inside the formed FL agglomerates is the fact that the hydrostatic (experimental) density of the metal polymer at a filler content of 25 mass% is less than the calculated one (see Fig. 3); the process of "softening" at

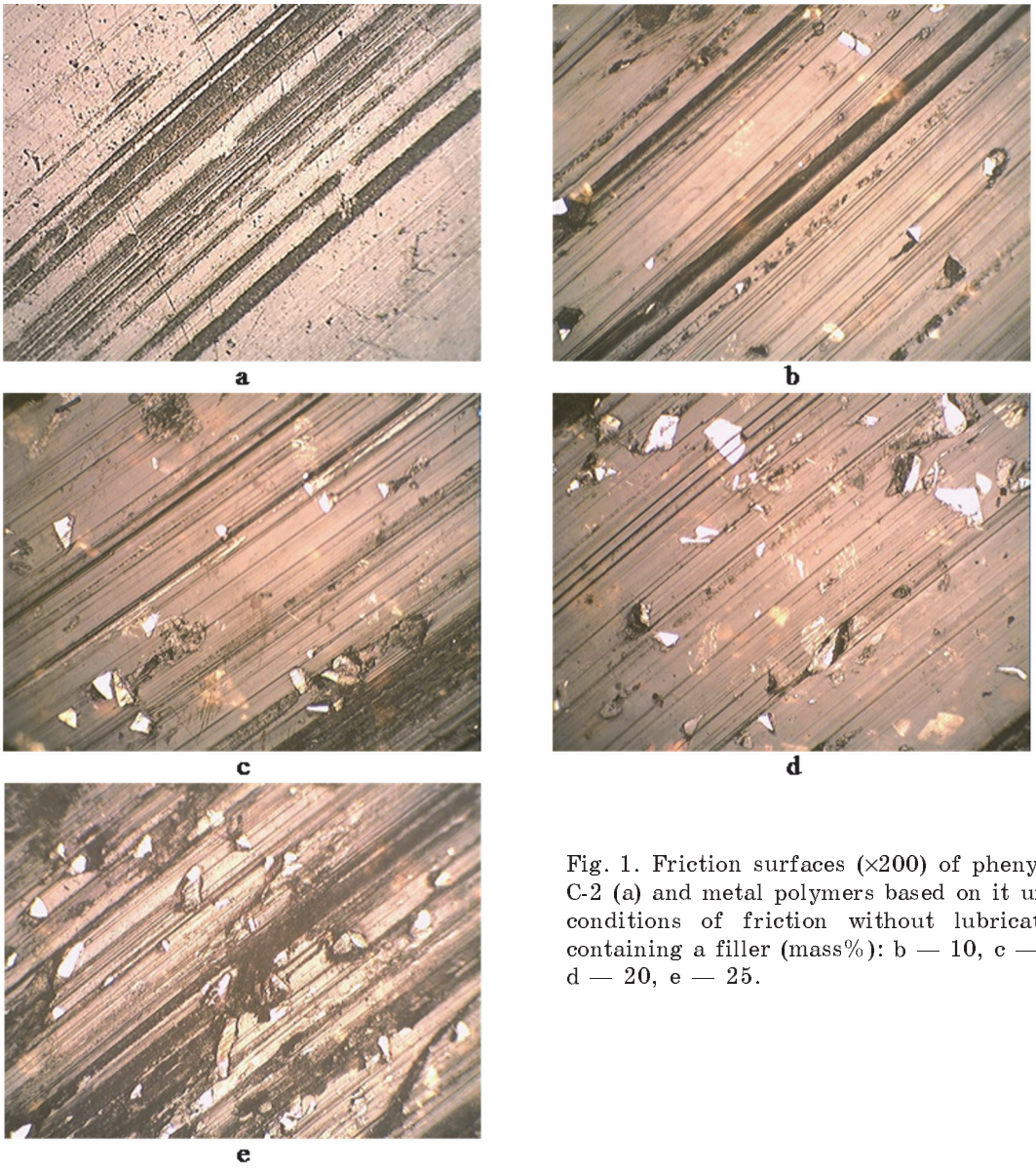

Fig. 1. Friction surfaces (×200) of phenylone C-2 (a) and metal polymers based on it under conditions of friction without lubrication, containing a filler (mass%): b — 10, c — 15, d — 20, e — 25.

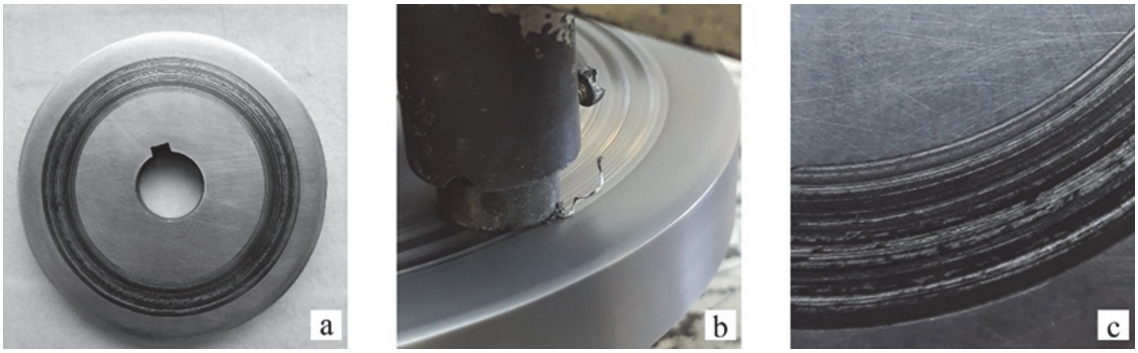

Fig. 2. General view of the counterbody after testing for wear resistance of the MP containing 25 mass% FL (a, c) and the wear process of the steel counterbody (b).

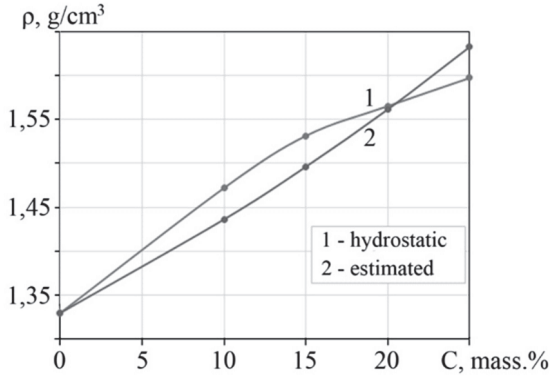

Fig. 3. Dependence of density (ρ, g/cm^3) on the content of the amorphous alloy (*C*, mass %).

the "phenylone-HB-4 amorphous alloy" interface dominates over the ordering process.

Another important factor affecting the tribotechnical characteristics of the MPs is the temperature in the contact zone. It has been established that with a filler content of 25 mass%, the temperature reaches values close to 383 K, that is, the work of friction forces aimed at breaking the intermolecular bonds between the filler and the polymer increases. As a result, microcracks formed on FL agglomerates coalesce into a network that promotes the formation of wear particles, or increase to a significant size; which leads to uprooting of FL particles (Fig. 1e).

4. Conclusions

An analysis of the results of the performance indicators of the developed metal polymers showed that the use of the HB-4 amorphous alloy as a filler for the aromatic polyamide phenylone C-2 is promising for improving its tribotechnical characteristics: reducing the intensity of linear wear on the recovery surface (by 5 times) and on the transfer film (by 7 times) It has been established that the effective content of the filler for the polymer matrix is 20 mass% of the HB-4 amorphous alloy.

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