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ENVIRONMENTAL PROTECTION BY SELF-ORGANISATION OF TRIBOSYSTEMS WITH SELF-LUBRICATING MATERIALS IN DRY FRICTION. PART II: IINVESTIGATIONS AT DIFFERENT DRY SLIDING RATES

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Abstract. The paper studies the ecological aspects of self-organisation effects in tribosystems, containing self-lubricating composite materials IPM 304 and IPM 305 in copper matrix in atmospheric medium. It has been found out that in stationary regime of dry friction in the atmosphere at small sliding velocity $v = 0.22$ m/s and loading $P = 12.5$ N ($p_a = 1$ MPa), the wear-resistance of the samples of self-lubricating antifriction materials is higher with two orders of magnitude in comparison with the wear-resistance of tin bronze BrO1F1 and it depends on the friction path. It has been proven that in atmosphere under conditions of dry friction at 4 times lower sliding velocity there occur processes of selective transferring and on the surface of the counterbody of steel P6M5 a transfering contact layer is being formed and it is maintained (dissipative structure) having thickness 8–10 μm.

Keywords: friction, self-lubricating materials, self-organisation, environmental protection.

AIMS AND BACKGROUND

A crucial task of tribology is reduction of wear of operating parts and contact joints of mechanisms and machines. Solving this task requires a thorough knowledge of the contact processes, structures and mechanisms in the tribological systems.

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The concepts of classical tribology are related to the inevitable occurrence of destructive (wear) processes during friction. The main technological methods for reducing wear are reduced to improving the quality of the surface layers of the contacting bodies and the quality of the lubricants.

Contemporary ideas in tribology are based on the concept of the system synergetic nature of friction as a phenomenon occurring in the thirdfunctional body (contact) of the triunique tribological system body-contact-counterbody. The creative function of the contact in the friction process consists in building new protective (dissipative) structures and passing of the tribosystem in a low entropy state. Regarded on macro level, manifestation of this state are the extremely low values of the friction coefficient and the wear intensity and, in some cases, the lack of wear (no-wear effect). In such cases, friction as a contact phenomenon generates a protective film called 'servovite' by Latin servovita = save life. The processes of formation of a servovite film with a fractal structure, a certain chemical composition, physico-mechanical and tribological properties are performed under strict conditions and result of the self-organising processes in the contact of the tribosystem[1–7].

The dissipative contact structure is a peculiar state of the matter as it reveals the creative functions of the contact as a third functional body in the tribosystems. It could have an unpredictable value and properties. The investigation of the appearance and the properties of the dissipative structures seem to be solving a fundamental issue for the elucidation of the nature of the friction process and the behaviour of the tribosystems. Some general relationships are characteristic for the dissipative structures. Coherently coordinated behaviour of the system as a whole, leading to the appearance of dissipative structures, is possible only in case of presence of specific conditions for the contact interactions. The formal requirements for the appearance of dissipative structures have been formulated by Prigogine[8,9]. These conditions determine quite specific dissipative systems inclined to undergo self-organisation.

As a result of numerous studies in the field of selective transferring of material in tribosystems gradually a new contemporary concept of the friction process is being formed. In the tribosystem, which is nonequilibrium dissipative system there occur transitions from inferior form of organisation (friction during boundary lubrication) to the superior form – dissipative structure, revealing the phenomenon 'selective transfering'. The evaluation for the appearance of a dissipative structure is reducing by one order of magnitude the forces of friction and two orders of magnitude lowering the rate of the wearing off process. Moreover, the formation of a dissipative structure under certain conditions leads to the occurrence of friction without any wearing off effect – the effect of nonwearing friction.

The aim of the current paper is to be studied the effect of the self-organisation in tribo-systems containing self-lubricationg composite materials with copper matix and tin bronze during friction without any lubrication material in an atmospheric medium and low sliding rates.

EXPERIMENTAL

Materials. The tribological characteristics in tribosystems, containing self-lubricating composite antifriction materials (SLAM) on copper basis – IPM304 and IPM305, tin bronze BrO1F1, were under investigation.

The composite materials IPM304 and IPM305 were prepared by the methods of powder metallurgy applying pressing and sintering under the following conditions: pressure 350 MN/m^2 (3500 kg/cm^2), temperature 650°C in the course of 2 h and average size of the particles 150 μm.

The basic technological principle underlying the formation of these materials is to achieve the minimum tribological parameters – low value of friction coefficient, high wear-resistance and stability against scratching.

The chemical constituents of the composite were selected in view of strictly differentiating the functions during the operation of the tribosystem (Table 1). The copper and its alloys are building up the carrier matrix, the lead fulfills antifrictional functions.

Table 1. Mechanical properties and chemical composition of IPM304 and IPM305 materials

Materials designation	Hardness HV (kg/mm^2)	Boundary of elasticity (MPa)	The Poisson coefficient	The Yung module, GP	Chemical composition
IPM 304	150	130	0.34	80	P; Sn; Pb; Cu-balance
IPM 305	98	126	0.34	80	P; Ni; Pb; Cu-balance

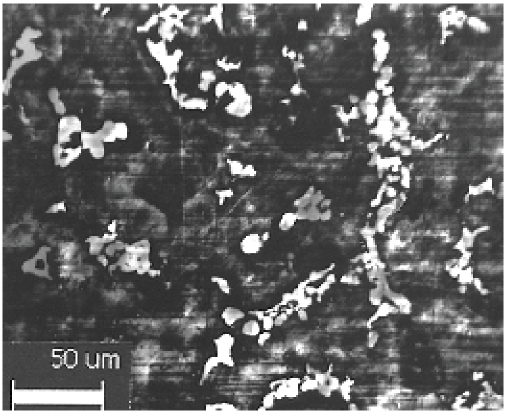

Fig. 1. Microstructure of SLAM IPM 304

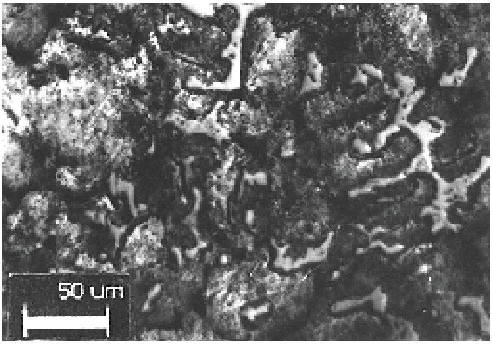

Fig. 2. Microstructure of SLAM IPM 305

The microstructure of SLAM IPM 304 consists of solid solutions of tin and partially phosphorus in the copper. Phosphorus forms a phase of copper phosphide, which is in the form of disrupted network and it is located around the grains of the solid solutions.

The chemical composition, the mechanical characteristics and the pattern of distribution of the internal contact network inside the materials are of an extraordinary importance for the character of the processes of friction and wearing off. In the case under investigation it leads to promotion of the wear-resistance of the material. The alloying with tin enhances additionally the mechanical and the anti-frictional properties. The phase of copper phosphide strengthens the alloy and decreases the plastic deformation of the composite under conditions of dry friction in vacuum.

Figure 1 represents the microstructure of the material IPM 304, where the light spots depict the network of copper phosphide, the grey areas are solid solution Cu-Sn, the dark sections are indicative of lead Pb.

The microstructure of the IPM 305 material is built up of solid solutions of nickel and partially of phosphorus. Phosphorus is included in the phases of copper phosphide and nickel phosphide, distributed in the form of disrupted network along the boundaries of the grains of solid solutions, which increases the mechanical strength of the material, without reducing the plasticity. The alloying with nickel and phosphorus improves its mechanical properties. The nickel, in addition to improving the mechanical strength, leads also to promotion of the corrosion resistance.

Figure 2 represents visualisation of the microstructure of the material IPM305, where the light sections are the network of copper phosphide, the grey ones depict the solid solution Cu-Ni, the dark areas are lead.

Device and methodology. The second experiment represents a comparative study on the same tribosystems ‘IPM 304-Steel P6M5’, ‘IPM 305-Steel P6M5’ and ‘BrO1F1-Steel P6M5’ by means of a tribotester in accordance with the scheme ‘Pin-disk’, which enables three times lower sliding velocity – $v = 0.22$ m/s and loading P = 12.5 N (Fig. 3). The counterbody is a disk of diameter 100 mm and thickness of 2 mm, made of fast cutting steel P6M5 having chemical composition and hardness, represented in Table 2.

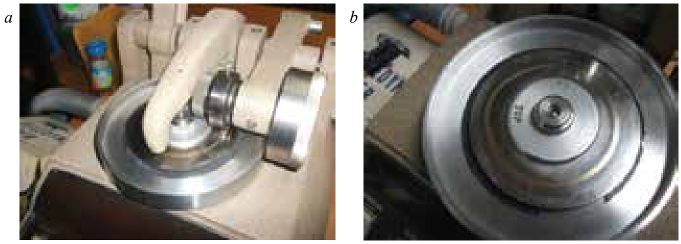

Fig. 3. Photograph of tribotester 'Pin on disk' for studying the degree of wearing off of tribosystems at low sliding velocity (*a*) and photograph of the sample of counterbody Steel P6M5 (*b*) with transferring contact layer in the tribosystem 'IPM 305-Steel P6M5' at friction path length L = 440 m and sliding velocity v = 0.22 m/s

Table 2. Chemical composition and hardness of the counterbody of steel P6M5

Element	C	W	V	Co	Mo	Mn	Si	Cr	Ni	Cu	S	Fe
(%)	0.85	6.4	2.1	0.4	5.2	0.5	0.4	4.2	0.3	0.08	0.01	balance
Hardness	HB 255 MPa; HRC 67											

The methodology includes measurement of the worn off mass in the course of 500 cycles of friction within the range of 500 up to 2000 cycles, which correspond respectively to friction path within the range of 110 to 440 m.

RESULTS AND DISCUSSION

For each experiment and number of cycles of friction the characteristics of wearing off are calculated – mass worn off, mg, wearing rate, mg/min, reduced intensity of wearing off, kg/m N, reduced wear resistance, N m/kg and relative wear resistance by the formulas (1)–(5) (Ref. 1).

The obtained results for the characteristics of the wearing off process for the samples of the three materials are represented in Table 3.

Figures from 4 to 9 represent graphically the dependences of the variation of the wearing off degree, wear rate and the wear resistance on the friction path length for all the materials.

Table 3. Characteristics of wearing off of the studied samples at different loadings

Number of cycles		500	1000	1500	2000
Friction path (m)		110	220	330	440
Friction time (min)		8.35	16.7	25.0	33.3
IPM304-P6M5	(mg)	0.2	0.4	0.7	1.1
P_1=12.5 N	(mg/min)	0.024	0.024	0.028	0.033
p_a=1 MPa	(mg/m N)	0.15×10^{-3}	0.15×10^{-3}	0.17×10^{-3}	0.20×10^{-3}
	(m N/mg)	6.67×10^{3}	6.67×10^{3}	5.58×10^{3}	5.10×10^{3}
IPM305-P6M5	(mg)	0.1	0.3	0.9	1.5
P_1=12.5 N	(mg/min)	0.012	0.02	0.036	0.05
p_a=1 MPa	(mg/m N)	0.07×10^{-3}	0.11×10^{-3}	0.22×10^{-3}	0.27×10^{-3}
	(m N/mg)	14.3×10^{3}	9.1×10^{3}	5.16×10^{3}	3.7×10^{3}
BrO1F1-P6M5	(mg)	9.7	21.3	36.3	47.5
P_1=12.5 N	(mg/min)	1.2	1.3	1.5	1.4
p_a=1 MPa	(mg/m N)	7.1×10^{-3}	7.8×10^{-3}	8.8×10^{-3}	8.6×10^{-3}
	(m N/mg)	0.14×10^{3}	0.13×10^{3}	0.11×10^{3}	0.12×10^{3}

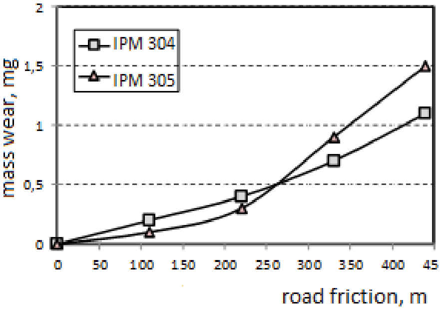

Fig. 4. Dependence of wearing off on the friction path length for IPM304 and IPM30

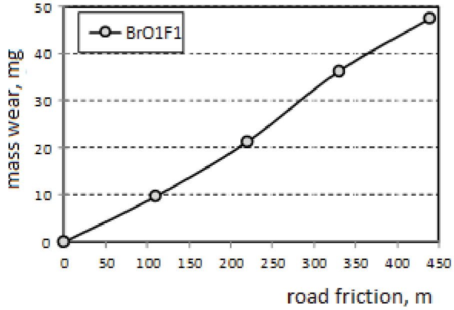

Fig. 5. Dependence of the wearing off on the friction path length for bronze BrO1F1

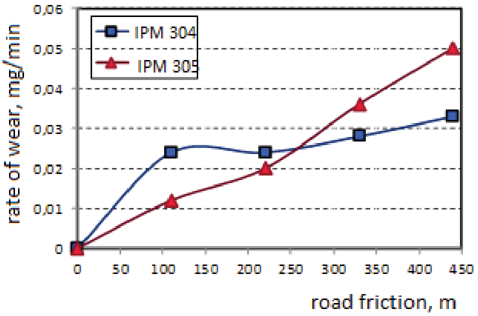

Fig. 6. Dependence of the wearing rate on the friction path length for IPM304 and IPM305

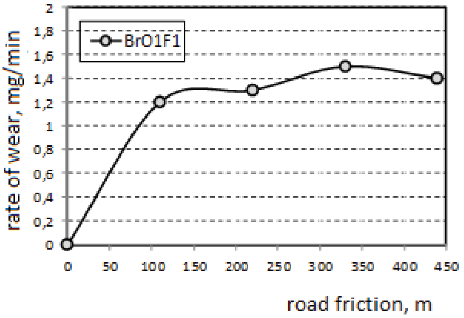

Fig. 7. Dependence of the wearing rate on the friction path length for BrO1F1

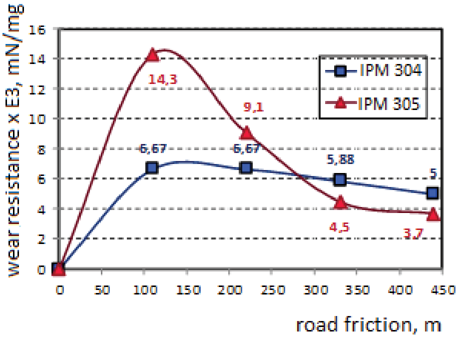

Fig. 8. Wear-resistance versus friction path length for IPM304 and IPM305

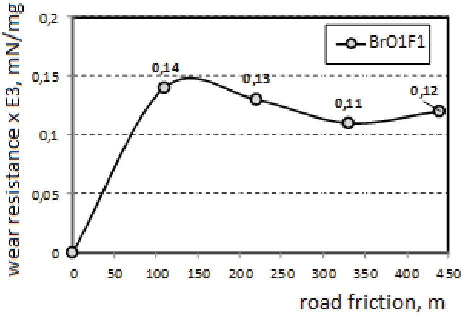

Fig. 9. Wear-resistance versus friction path length for BrO1F1

The results show that the wearing off degree for BrO1F1 is with one order of magnitude greater than the wearing degrees for the composite samples IPM304 and IPM305 and for this reason the graphs are plotted in different coordinate systems.

The dependence of the wearing off degree on the friction path length has linear character for the BrO1F1 sample (Fig. 5), which fact is more easily visible judging from the constant rate of the wearing off process along the entire friction path length (Fig. 7).

In the cases of the samples of the composite material IPM304 there is stable variation of the wearing off degree on the friction path length (Fig. 4). At shorter friction path lengths of up to $L = 220$ m the composite IPM304 have 2 times greater wearing degree than that of the sample IPM305, but at $L > 220$ m it grows up at a very low rate and at friction path length $L = 440$ m the wearing off degree is 1.4 times smaller than that of the material IPM305 (Figs 4 and 6).

Judging from the present study data the greatest degree of wearing off is shown by the sample of tin bronze BrO1F1, for which at friction path length $L = 440$ m it is 43.2 times greater than that for the IPM304 sample and 32 times greater than that for IPM305 (Table 3).

The reduced wear resistance of all the samples decrease upon increasing the friction path length. For the composite IPM305 in case of 4 increased friction path length the wear resistance drops down 4 times, but the dependence of the wear resistance on the friction path lengthacquires exponential character (Figs 8 and 9). Under the same conditions the wearing off degree of the composite IPM304 decreases linearly only 1.3 times. For the samples of BrO1F1 the dependence is non-linear having a well expressed minimum at friction path length $L = 220$ m, and afterwards it grows up. Comparing the samples on the basis of the parameter ‘wear-resistance’ it was established that at friction path length $L = 110$ m the sample IPM304 has 47.6 times greater wear resistance than that of the sample BrO1F1, and comparing with IPM305 – 102 times greater. However, at friction path length $L = 440$ m these ratios are changed respectively – 42 times for IMP304 and 31 times for IPM305.

In the course of analysing the results from the profiling diagrams and the roughness of the surface of the counterbody P6M5 it was established that after dry friction in the tribosystem using tin bronze BrO1F1 the roughness R_a of the trail from the friction on the counterbody has grown twice in comparison with the roughness before the friction. The profilograms of the counterbody P6M5 after friction with IPM304 shows that the roughness values (R_a) has grown from 0.146 up to 0.198 μm, but there is uniform distribution on the worn off surface. The roughness of the surface of the counterbody after friction with IPM305 has grown up and it reaches a value of 0.217 μm – larger than those in the case of friction with bronze.

We can summarise the analysis of the profilograms stating that there is no direct connection between the roughness R_a of the counterbody and the degree of wearing off, and specifically in the case of friction with IPM305 the roughness grows up and it reaches a value higher than that of bronze, while the wearing degree of IMP305 is 31 times lower than that of the same sample of bronze. This fact can be explained by the formation of contact transferring film on the counterbody during its interaction with the composite materials IMP305 and IMP304. This film has low values of the shearing tangential tensions, i.e. low coefficient of friction and respectively low degree of wearing off.

Upon comparing the two composite materials IPM304 and IPM305 at longer friction path $L > 220$ m the lowering degree of wearing off for the material IPM304 is due to the chemical composition and the characteristics of the contact transferring film andmore specifically due to the presence of the chemical element tin.

Considering the mechanisms of formation of transfering contact layer (dissipative structure) in tribosystems with self-lubricating materials during dry friction some authors state as priority the dominating role of diffusion as a process, activated on one side by the difference in the coefficients of thermal expansion in the heterogeneous structure of the composite, while on the other side it is activated by the icreased contact temperature. We should take into account also the circumstance that in case of contact interaction under the conditions of friction without any lubricating material as a result of the increased temperature and the plastic deformation of the thin surface layer there occurs a sharp increase in the physicochemical activity of the surface contact layers. The diffusion of active components from the bulk phase of the material to the surface layer and their high physicochemical activity leads to formation of dissipative structure in the form of thin layers. Then the friction is already occurring over these layers with low resistance in the direction of the sliding velocity.

Figure 10 represents a metalographic photograp of a dissipative structure in the tribosystem ‘IPM304 – Steel 45’.

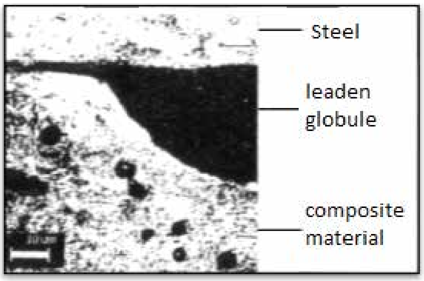

Fig. 10. Dissipative contact structure in the tribosystem 'IPM304 – Steel 15' (Ref. 12)

The lead passes over from globular state into liquid state, it enters the contact loose space and forms adhesion bonds with the microcontacts. The formation of uniform and stable surface layer is a very complicated and multifactorial process. It is this dissipative structure that determines the low-entropy state of the tribosystem – low values of the coefficient of friction and degree of wearing off. Upon increasing the rate of friction and the loading, the temperature in the contact is increased and the quantity of the lead is growing up. In the easier operating regimes the deposition of lead is explained by the process of diffusion. At the higher loadings the transferring of lead is more intensive and its quantity is greater. It can be supposed that this fact is owing not only to the increased contact temperature, but it is also due to the mechanical pushing away of lead towards the surface in case of increased loading[10–12].

The X-ray diffraction analysis shows that the lead on the surface is in metallic (i.e. reduced) state. Its quantity and distribution depend mainly on the distribution of lead inside the structure of the material and on the regime of friction[7]. After friction in vacuum metallic lead is detected on the surface, while after friction in air medium – there appears presence of two oxides of lead – βPbO and PbO.

The chemical composition, the layer thickness and the kinetics of formation of the contact film as a result of selective transfering depend on the combined effects of a series of factors: the ditribution of the lead inside the structure of the material, the loading in the contact, the velocity of sliding, the temperature, the initial chemical composition and the physical-mechanical properties of the surface layers of the body and the counterbody.

CONCLUSIONS

The main results from the investigation of tribosystems, containing self-lubricating materials (SLAM) 'IPM304', 'IPM305' and tin bronze BrO1F1, in the regime of friction without any lubricating materials in atmospheric medium al low sliding rates, can be summarised as follows:

– It has been found out that in stationary regime of dry friction in the atmosphere at small sliding velocity $v = 0.22$ m/s and loading $P = 12.5$ N ($p_a = 1$ MPa), the wear-resistance of the samples of self-lubricating antifriction materials is higher with two orders of magnitude in comparison with the wear-resistance of tin bronze BrO1F1 and it depends on the friction path length as follows: at friction path length $L = 110$ m the sample 'IPM304' has 47.6 times higher wear-resistance than that of BrO1F1, while the 'IPM 305' sample – 102 times; at friction path length $L = 440$ m for 'IPM 304' – 42 times higher, and for 'IPM 305' – 31 times higher.

– It has been proven that in atmosphere under conditions of dry friction at 4 times lower sliding velocity $v = 0.22$ m/s and loading $P = 12.5$ N ($p_a = 1$ MPa) there occur processes of selective transferring and on the surface of the counterbody of steel P6M5 a transfering contact layer is being formed and it is maintained (dissipative structure) having thickness 8–10 µm, whose chemical composition contains the chemical elements copper Cu and tin Sn.

– It is obvious that the results mentioned above lead to decrease of the carbon dioxide emissions in the atmosphere which effect the environmental protection.

The more detailed investigation of the composition, the microstructure and the kinetics of the dissipative structure applying the methods of the contemporary electron microscopy could lead to revealing the essence, the nature and the mechanisms of self-organisation both on micro-level and on nano-level, for example registering the moment when a bifurcation state of the tribosystem is occurring.

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