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ENVIRONMENTAL PROTECTION BY SELF-ORGANISATION OF TRIBOSYSTEMS WITH SELF-LUBRICATING MATERIALS IN DRY FRICTION. PART I. INVESTIGATIONS AT DIFFERENT LOADS

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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 at different normal loads. The measurements and expression of the self-organisation show low values of the coefficients of friction and wear of the contacting materials in the tribosystems. This effect is of great importance for the environmental protection because it leads to decrease of use of energy and material resources and also to decrease in the pollution of the environment with gaseous, liquid, solid components and heat from the internal combustion engines and the industrial machines. The self-organisation effects of the tribosystems are sensible towards the combinations of the contacting materials during friction – normal load, sliding rate, presence and properties of the lubrication material. It has been found out that the friction coefficient in tribosystems of self-lubricating composite materials: IPM 304 – Steel 45 and IPM 305 – Steel 45 decreases in a non-linear pattern and reached values which are typical for liquid friction – 0.05 and 0.08, respectively. These results are a proof that on micro level a self-organisation of the tribosystems occurs. For the tribo-system BrO1F1 – Steel 45 the dependence of the friction coefficient has the opposite dependence – its values increase to the range between 0.26 and 0.37 which are typical for dry friction.

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

AIMS AND BACKGROUND

The basic phenomena and processes in the tribosystems are the friction, wearing off and lubrication, which determine the operational characteristics and resources

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of the separate details, on one side, and on the other – of the mechanisms and machines, taken as a whole. The friction is connected to a great extent with some energy losses, consuming about 30–40% of the total energy, produced in the world. The wearing of parts, as a process accompanying the friction, leads to losses of materials and human resources and it is the reason for decommissioning the exploitation of more than 80% of the details and of the machines. The lubricating materials as tribological elements in tribosystems are introduced into the contact zone between the details of the rubbing conjunctions with the aim to preserve and/or extend the energetic, substantial and functional resources and the exploitation characteristics[1–4].

It has been established that the utilisation of the achievements in the field of contemporary tribology enables reduction of the friction losses as well as the wearing off of the machines many times, which would result in an economic effect within the range of 2 up to 4% of the national income of the developed countries in the world[1,5–8].

The technico-economical and ecological aspects of the tribology are arising from the circumstance that the type and the character of the contact interactions – friction, wearing off, contact conductivity, beside the fact that they limit about 90% of the working capacity and reliability of the machines, lead also to pollution of the environment by evolving heat, acoustic effects, discharging solid and liquid wastes and toxic gaseous emissions[1,6–10].

It is generally acknowledged that friction is a destructive process, i.e. during the friction there inevitably occurs with the course of time destruction (or wearing off) of the surface layer of the materials in the contacting conjunctions of the machines. This, in its turn, means that it is not possible to create a material, which is not wearing off during the contact friction[3,4].

At present one can outline 3 basic approaches in tribology for solving the problems, caused by rubbing and wearing off.

The first approach is connected with the elaboration of materials and technologies promoting the hardness of the contact surfaces. Upon increasing the hardness of the surface layers there is decrease in the mutual penitration of roughnesses on the surface of the body between the ruggedness of the counterbody, whereupon the plastic deformations are reduced as well as the oxidation processes and also the action of the abrasive particles, which appear as products of the wearing off process[2,5,9].

This statement is based on the assumption that the high resistance to wearing off and respectively the improved resource of the details is in direct dependence on the hardness of the surface layers. Numerous methods and technologies have been elaborated to promote the hardness of the surface layers and the coatings on them. Using this approach solved many issues, associated with prolonging the lifetime and promoting the reliability of the contact conjunctions in machines[13–26].

Upon increasing the loading and the velocity of movement of the contemporary machines there occurs deterioration of the conditions of lubrication of the details. The increased requirements to the coefficient of efficiency impose the application of special lubricating substances and liquids, whereupon in many cases water is also used in its quality of lubricating substance. In such cases the methods for enhancing the stability to wearing off by increasing the hardness of the material are no longer justified. As it is known, during dry friction and boundary friction, which is almost always present during the operation of the contact conjunctions, the actual contact surface area represents a very small section of the nominal surface area (0.1 to 0.001 part of the whole) and it decreases with the increase in hardness. The greater share of the contact surface area remains unused during the operation of the tribosystem. At the same time, as a result of the discreteness of the contact upon enhancing the loading in case of high hardness in microcontacts there appear relative pressures, which are causing plastic deformations. In order to reduce these pressures, it is necessary to increase the nominal supporting surface, but this requirement is in contradiction with the purpose of the designers to minimise the weight of the construction and the hardness. Upon increasing the nominal surface area it is necessary to guarantee continuity of the boundary lubricating layer in case of deformations[4,27,35,36].

The second approach to promote the reliability of the machines by reducing the wearing off is connected with the perfection of the existing lubricants and proposing new lubricants, guaranteeing less friction and less wearing, avoiding scratching of the surfaces under conditions of boundary lubrication[25,26,28].

The two above described approaches are directed to improving the properties and the quality of the components of the tribosystems – solid state bodies and liquids. They do not take into account the integrity of the tribosystem as one whole consisting of three elements[10].

The tribosystems are open systems, i.e. they exchange energy and substances with the environment. Under specific conditions there occur contact processes and self-organised structures are appearing in the tribosystems and the friction is decreased up to 10 times, while the wearing off process can be reduced down to zero, i.e. no wearing at all[29,30].

The third approach is an interdisciplinary one treating the problem of wearing off. In a few words, this approach is based on a principle, according to which it is possible to create such conditions in the tribosystems (choice of material, construction and operating conditions), which cause transition of the tribosystem into a new state – a state of minimum friction and wearing off.

This principle is based on the phenomenon ‘selective transfer’. As a result of self-organising contact interactions under definite conditions there occurs selective transfer of material into the contact zone and thin metal unoxidisable films are being formed having thickness of 100 nm up to 2–3 μm and in some cases even 20–30 μm, which are separating the rubbing surfaces of the details creating conditions for super-low friction and wear. The friction itself as a phenomenon creates this protective film, called also 'servovital' film. The process of formation of such a film during selective transferring, its composition, structure, physico-mechanical properties and dynamics in the process of friction – all this is accomplished only under precisely determined very specific conditions – tangential and plastic deformations, relative loadings, rates and contact temperature, composition and properties of the lubricating substance.

The interdisciplinary approach implies the priority of the creative function of the contact as a third functional body in the tribosystem, its ability to self-organise the behaviour of the tribosystem in low-entropy state[10].

The selective transfer (ST) during friction is a phenomenon, which in its character is just the opposite of the wearing off phenomenon. If in the case of wearing off all the contact processes represent destruction of the surfaces, then the processes of ST have creative character and they refer to the self-organisation processes in non-living matter. The friction, as a thermodynamically non-equilibrated process, can occur both in systems close to equilibrium, as well as in systems far from equilibrium, forming various classes of structures, the transition to which is realised as a jump from one step into another. In this connection it is possible that there could exist such a state of the tribosystem, in which there is no accumulation of energy in the form of defects in the superficial layers (for example dislocations), but transferring of the energy into the environment. An example of such a system appears to be ST (Refs 33–40).

A specific peculiarity of ST is its appearance under very specific conditions of contact interaction in tribosystems and depending on these conditions there are three possible cases: considerable decrease in the degree of wear; lack of any wearing off symptoms; recovery of the worn off surface.

The mechanisms of formation and the dynamics of the servovital protective film, formed on contact surfaces in the process of friction, are different and they depend on the complex action of factors, which can be classified into three main groups:

- Type and properties of the contacting solid state materials (body and counterbody);
- Type and properties of the lubricating substance in the contact zone;
- Regimes of operation of the tribosystems – contact pressure, velocity of movement, temperature, kinematics of the movement, appearance of vibrations, shocks, etc.

For the realisation of the effect friction without any transfer in tribosystems, the following conditions and factors are needed[3,32,37]:

– The contact interaction is accomplished by soft metallic layer/film, whereupon the contact pressure is decreased as a result of the great actual contact surface area and the basic metal (support) bears much lower pressure;

– The metal layer in case of deformation during the process of friction does not disintegrate and can be deformed many times without being destroyed;

– The interaction occurs without oxidation of the surfaces, whereupon the effect of rebinder is realised to a highest extent;

– The products from the wearing off process do not play a destructive role as in the case of boundary friction, but as a result of tribophysical-chemical interactions form structures and they pass over from one surface to the other and they are retained in the contact zone by the electrostatic forces.

One of the methods for realising the effect of 'non-export friction' is the enrichment of the lubricating material in the contact with some layered additives, conditioners of the metals and nanopreparations: nanodiamonds, fullerenes and reconditioners. The remetalisers (metal coating compositions) represent a special class of preparations for renovations of worn off surfaces, which are based on the mechanisms of self-organisation, elaborated by Prigogine and on the scientific discovery 'Selective transfer during friction' made by Garkunov and Kragelskii. The mechanism of action of the remetalisers consists in metal coating of the contact surfaces as a consequence of the deposition of metal components, which are comprised in the composition of the remetalisers in the form of particles or ions[41–49].

The processes of selective transfer can occur also in the cases of dry friction in tribosystems under the conditions of vacuum and in atmospheric medium[50–58].

The object of the present investigation are the effects of self-organisation in tribosystems, containing self-lubricating composite materials IPM 304 and IPM 305 with copper matrix, during friction without any lubricating material in atmospheric medium.

All the aims of the authors is to measure the decrease of the friction coefficient by self-organisation. As a final result a decrease of the carbon dioxide emissions occurs and there is effect in the environmental protection.

EXPERIMENTAL

MATERIALS

The tribological characteristics in tribosystems under investigation were systems containing self-lubricating composite antifriction materials (SLAM) on copper basis – IPM 304 and IPM 305, tin bronze BrO1F1.

The composite materials IPM 304 and IPM 305 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^{o}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. The copper and its alloys are building up the carrier matrix, the lead fulfills anti-frictional functions.

Table 1. Mechanical properties and chemical composition of the materials IPM 304 and IPM 305

Materials designation	Hardness HV (kg/mm^2)	Boundary of elasticity (MPa)	Coefficient of poisson	Module Yung, 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

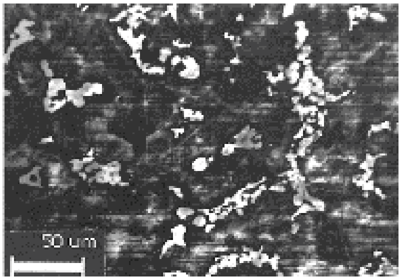

Fig. 1. Microstructure of SLAM IPM 304

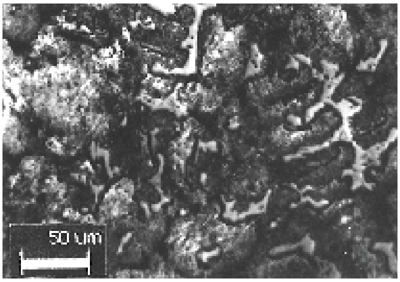

Fig. 2. Microstructure of SLAM IPM 305

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 is of an extraordinary importance for the character of the processes of friction and wearing off (Table 1). 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 material IPM 305 is built up of solid solutions of nickel and partially of phosphorus. The 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 IPM 305, where the light sections are the network of copper phosphide, the grey ones depict the solid solution Cu–Ni, the dark areas are lead.

TRIBOLOGICAL INVESTIGATIONS

Effect of the loading on the wearing off process and on the coefficient of friction (*experimental run I*). A comparative study has been carried out considering the effect of the magnitude of the normal loading upon the wearing off process and on the coefficient of friction in tribosystems, containing composite materials IPM 304, IPM 305 and tin bronze BrO1F1 in contact with the counterbody of St45 at one and the same velocity of sliding $V = 0.82$ m/s. The chemical composition of the counterbody is represented in Table 2.

Table 2. Chemical composition (wt.%) and hardness of the counter body of Steel 45

Element	C	Mn	Si	Ni	S	Cr	Cu	P	Fe
wt.%	0.45	0.53	0.20	0.20	0.04	0.25	0.23	0.02	balance
Hardness					52HRC				

Device and methodology. The study has been carried out using a tribotester of the type ‘Pin-disk’ (Fig. 3).

The studied cylindrical sample 1 (pin) is attached statically in a fixed position in the bed of the holder 2 in the loading head 8, in such a way that the joining surface of the sample is in contact with the surface of the counterbody 3, attached in fixed position to the horizintal disk 4. The disk 4 is driven by the electromotor 6 and it is rotating around its vertical central axis at angular velocity $\omega = \text{const}$.

The normal loading *P* is applied in the centre of gravity of the contact ground between the sample and the surface and it is secured by a lever system in the loading head. The friction path is set by the number of cycles, which is counted by rotameter 7.

The device enables changing the velocity of sliding within limits from 0.55 to 1 m/s by varying the distance *R* between the axis of rotation of the disk 4 and the axis of sample 1.

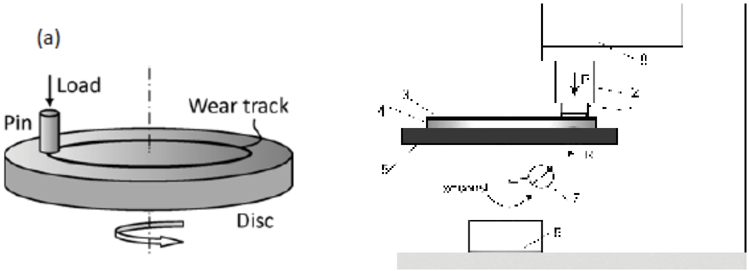

Fig. 3. Schematic presentation of tribotesting device ‘Pin-disk’

Electronic dynamometer is connected to the holder of the sample in the direction of the tangent to the line of sliding for measuring the force of friction. The coefficient of friction at the respective loading is calculated using the formula μ = *T*/*P*, where *T* is the friction force and *T* is the load *P*).

Using the above described device a comparative study has been carried out considering the characteristics of the wearing off process of samples of the materials IPM 304, IPM 305 and Br1O1F at different loadings and constant values of the sliding velocity and nominal contact area. The conditions of the experiment are listed in Table 3.

Table 3. Parameters of the experiment

Parameter	Value
Loading	17.1 N; 37.1 N; 57.1 N
Nominal contact pressure	0.6 MPa; 1.3 MPa; 2.0 MPa
Sliding velocity	$V = 0.82$ m/s
Number of friction cycles	200–1000
Friction path	46.4–232 m
Counterbody	St 45

The samples of the separate materials have cylindrical form with one and the same diameter Φ 6 mm and height 20 mm, one and the same roughness of the contact surface – Ra = 0.838 μm, measured by a profile-meter ‘TESA Rugosurf 10-10G’.

The methodology of investigation of the characteristics of the wearing off process in brief consists of measuring of the worn off mass of the samples for a definite friction path (time interval of friction) at constant set of parameters – loading and sliding velocity. Based on the measured worn off mass one can calculate the characteristics of mass and linear wear – rate of wearing off process, wear intensity, absolute and relative wear-resistance.

The methodology comprises the following sequence:

– Preparation of samples having identical size and one and the same roughness of the contact surface. The roughness is measured using a profile-meter 'TESA Rugosurf 10-10G';

– Measuring of the mass m_0 (g) of the sample by means of an electronic analytical balance WPS 180/C/2 with an accuracy of 0.1 mg. Prior to each measurement the sample is first decontaminated from mechanical particles or organic contaminations, then it is dried using ethyl alcohol in order to avoid the appearance of electrostatic effect;

– The sample is placed in the holder of the loading head, a definite normal loading P is set and the number of friction cycles;

– Once again the mass of the sample m_i is measured and the following characteristics are calculated:

- Worn off mass m:

$$m = m_0 - m_\mathrm{i},\ \mathrm{mg} \tag{1}$$

- Rate of mass wearing off Υ – destroyed mass during the friction, removed from the surface layer for a time interval $t = 1$ min:

$$\Upsilon = m/t,\ \mathrm{mg/min} \tag{2}$$

- Reduced intensity of wearing off i_r – destroyed mass of the surface layer per unit of pathway of friction L per unit of loading P:

$$i_\mathrm{r} = m/(LP),\ \mathrm{mg/mN} \tag{3}$$

- Reduced wear-resistance I_r – represents the reciprocal value of the reduced intensity and characterises the path length L, which will be covered by the studied sample under given loading P, to destroy 1 mg of mass on the surface, i.e.

$$I_\mathrm{r} = LP/m,\ \mathrm{mN/mg} \tag{4}$$

- Relative reduced wear-resistance ε_r – represents the ratio between the wear-resistance of the studied sample I_r^{i} and the wear-resistance $I_\mathrm{r}^{\mathrm{e}}$ of a sample, accepted to be the standard for comparison:

$$\varepsilon_\mathrm{r} = I_\mathrm{r}^{i}/I_\mathrm{r}^{\mathrm{e}} \tag{5}$$

The relative reduced wear-resistance ε_r is a dimensionless quantity showing how many times the wear-resistance of the studied sample is greater or smaller than the wear-resistance of the standard under identical conditions of friction.

All the above described operations are repeated for any other loading value.

RESULTS

Applying the above described methodology and device experimental results have been obtained characterising the wearing off process for different friction path lengths at various normal loading values, which are listed in Tables 4, 5 and 6.

Table 4. Characteristics of wearing off process for the sample IMP 304 at different loadings under conditions of dry friction

Sample: IPM 304					
Number of cycles		200	400	600	1000
Friction path (m)		46.4	92.8	139.2	232
Friction time (min)		0.94	1.89	2.83	4.72
$P_1 = 17.1$ N	(mg)	0.4	1.1	1.9	2.4
$p_a = 0.6$ MPa	(mg/min)	0.43	0.58	0.67	0.51
	(mg/m N)	0.5×10^{-3}	0.7×10^{-3}	0.8×10^{-3}	0.58×10^{-3}
	(m N/mg)	2.0×10^{3}	1.4×10^{3}	1.2×10^{3}	1.70×10^{3}
$P_2 = 37.1$ N	(mg)	3.4	6.1	9.9	17.0
$p_a = 1.3$ MPa	(mg/min)	3.62	3.23	3.5	3.6
	(mg/m N)	2×10^{-3}	1.8×10^{-3}	1.9×10^{-3}	2.0×10^{-3}
	(m N/mg)	0.5×10^{3}	0.6×10^{3}	0.5×10^{3}	0.5×10^{3}
$P_3 = 57.1$ N	(mg)	5.1	9.4	13.7	22.5
$p_a = 2.0$ MPa	(mg/min)	5.42	4.97	4.84	3.6
	(mg/m N)	1.93×10^{-3}	1.77×10^{-3}	1.72×10^{-3}	1.70×10^{-3}
	(m N/mg)	0.52×10^{3}	0.56×10^{3}	0.58×10^{3}	0.59×10^{3}

Table 5. Characteristics of wearing off process for the sample IMP 305 at different loadings under conditions of dry friction

Sample: IPM 305					
Number of cycles		200	400	600	1000
Friction path (m)		46.4	92.8	139.2	232
Friction time (min)		0.94	1.89	2.83	4.72
$P_1 = 17.1$ N	(mg)	2	2.9	5.6	9.2
$p_a = 0.6$ MPa	(mg/min)	2.13	1.53	1.98	1.95
	(mg/m N)	2.5×10^{-3}	1.8×10^{-3}	2.3×10^{-3}	1.48×10^{-3}
	(m N/mg)	0.4×10^{3}	0.6×10^{3}	0.43×10^{3}	0.70×10^{3}
$P_2 = 37.1$ N	(mg)	4.8	8.3	13.7	20.6
$p_a = 1.3$ MPa	(mg/min)	5.1	4.39	4.84	4.36
	(mg/m N)	2.80×10^{-3}	2.40×10^{-3}	2.6×10^{-3}	2.40×10^{-3}
	(m N/mg)	0.36×10^{3}	0.42×10^{3}	0.38×10^{3}	0.42×10^{3}
$P_3 = 57.1$ N	(mg)	8	14.3	21.2	33.6
$p_a = 2.0$ MPa	(mg/min)	8.51	7.57	7.49	7.12
	(mg/m N)	3.00×10^{-3}	2.70×10^{-3}	2.70×10^{-3}	2.54×10^{-3}
	(m N/mg)	0.33×10^{3}	0.38×10^{3}	0.38×10^{3}	0.39×10^{3}

Table 6. Characteristics of the wearing off process for the sample BrO1F1 at different loadings under conditions of dry friction

Sample: BrO1F1					
Number of cycles		200	400	600	1000
Friction path (m)		46.4	92.8	139.2	232
Friction time (min)		0.94	1.89	2.83	4.72
$P_1 = 17.1$ N $p_a = 0.6$ MPa	(mg)	2.1	5.5	11	20
	(mg/min)	2.23	2.91	3.89	4.24
	(mg/m N)	2.63×10^{-3}	3.45×10^{-3}	4.6×10^{-3}	5.03×10^{-3}
	(m N/mg)	0.38×10^{3}	0.29×10^{3}	0.22×10^{3}	0.2×10^{3}
$P_2 = 37.1$ N $p_a = 1.3$ MPa	(mg)	9.6	23.1	31.6	60.2
	(mg/min)	10.2	11.27	11.2	12.8
	(mg/m N)	5.6×10^{-3}	6.2×10^{-3}	6.1×10^{-3}	7×10^{-3}
	(m N/mg)	0.18×10^{3}	0.16×10^{3}	0.16×10^{3}	0.14×10^{3}
$P_3 = 57.1$ N $p_a = 2.0$ MPa	(mg)	17	39.6	63.1	103.4
	(mg/min)	18.1	21	21.7	21.9
	(mg/m N)	6.4×10^{-3}	7.5×10^{-3}	7.7×10^{-3}	7.8×10^{-3}
	(m N/mg)	0.16×10^{3}	0.13×10^{3}	0.13×10^{3}	0.128×10^{3}

On the basis of the results, listed in Tables 4, 5 and 6, graphical dependences have been plotted, representing the changes in the mass worn off along the pathway of friction (Figs 4, 6, 8) and at different normal loading (Figs 5, 7, 9) for the three types of materials.

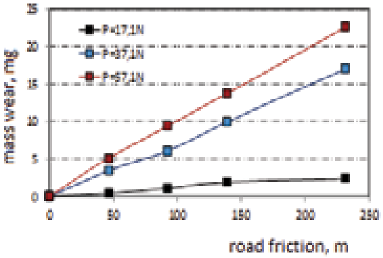

Fig. 4. Changes in the mass worn off for the sample IPM 304 along the friction path

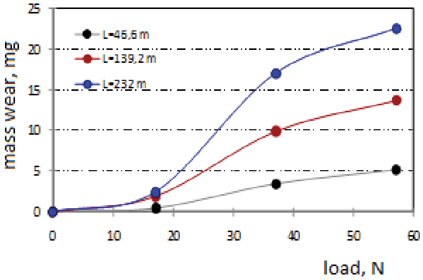

Fig. 5. Changes in the mass worn off for the sample IPM 304 at different loadings

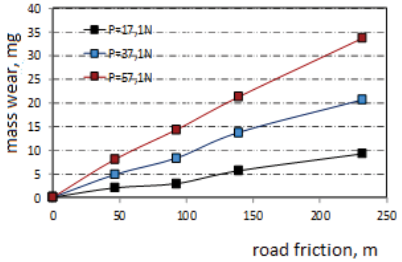

Fig. 6. Dependence of the mass worn off for the sample IPM 305 on the friction path length

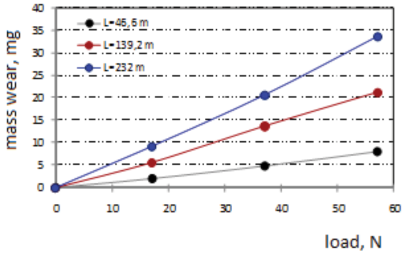

Fig. 7. Dependence of the mass worn off for the sample IPM 305 on the loading

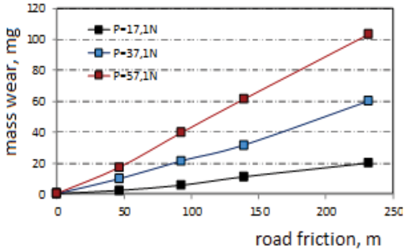

Fig. 8. Dependence of the mass worn off for the sample Br01F1 on the friction path length

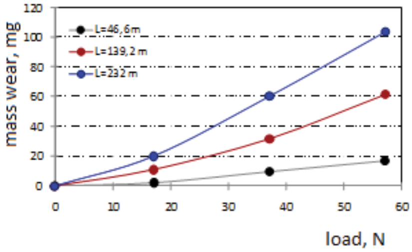

Fig. 9. Dependence of the mass worn off for the sample Br01F1 on the loading

Figures 10, 12 and 14 represent the dependences of the rates of wearing off on the lengths of friction pathways, while Figs 11, 13, 15 – represent the dependences of the rates of wearing off on the loading for the three types of materials.

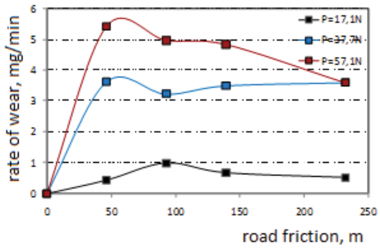

Fig. 10. Rate of wearing off as a function of length for the sample IPM 304

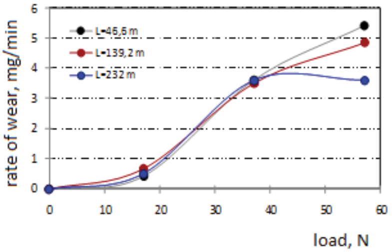

Fig. 11. Rate of wearing off as a function of the friction path the loading for the sample IPM 304

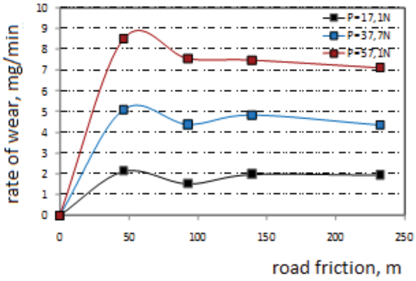

Fig. 12. Rate of wearing off as a function of the friction path length for the sample IPM 305

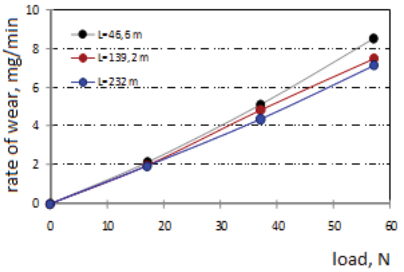

Fig. 13. Rate of wearing off as a function of the the loading for the sample IPM 305

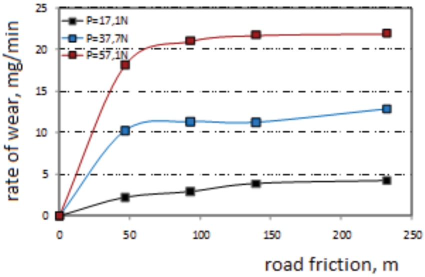

Fig. 14. Rate of wearing off as a function of the friction path length for sample BrO1F1

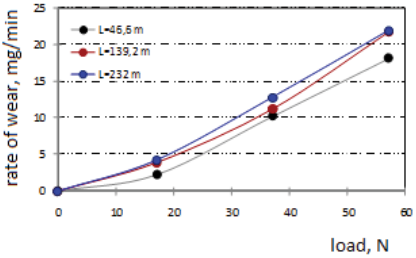

Fig. 15. Rate of wearing off as a function of the loading for sample BrO1F1

The comparison of the results is shown in Figs 16 and 17.

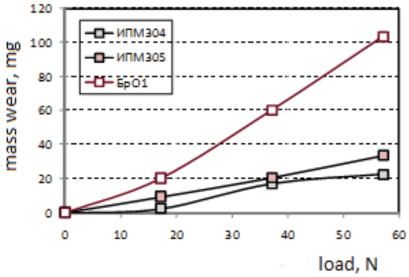

Fig. 16. Dependence of the wearing off on the loading at friction path length *L*= 232 m

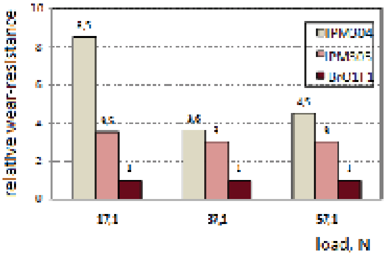

Fig. 17. Diagram of the relative wear-resistance at each loading

Table 7 represents the results for the coefficient of friction in the three contact systems for friction path length L = 232 m = const and sliding velocity v = 0.82 m/s = const. Figure 18 shows graphically the plotted dependence of the friction coefficient on the loading for the three materials IPM 304, IPM 305 and tin bronze BrO1F1.

Table 7. Coefficient of friction at different loadings

Contact system	Loading P_1 = 17.1 N pressure p_a = 0.6 MPa	Loading P_2 = 37.1 N pressure p_a =1.3 MPa	Loading P_3 = 57.1 N pressure p_a = 2.0 MPa
IPM 304-St45	0.18	0.10	0.05
IPM 305-St45	0.20	0.12	0.08
Br O1F1-St45	0.26	0.29	0.37

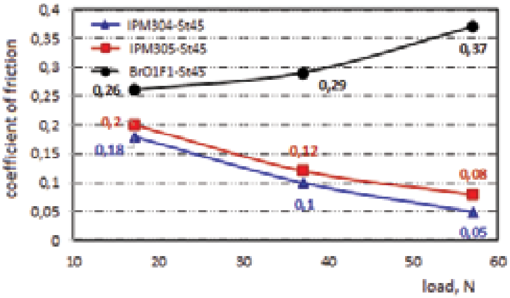

Fig. 18. Variation of the coefficient of friction with the loading for the three contact systems at L = 232 m and V = 0.82 m/s

DISCUSSSION

The dependence of the mass worn off on the friction path length for all the studied samples has linear growing character at each value of the normal loading (Figs 5, 7 and 9). Upon increasing the normal loading for samples IPM 305 and BrO1F1 the degree of wearing off is growing up in a straight proportion, while in the case of sample IPM 304 a non-linear character of this dependence is observed.

The rate of the wearing off process remains almost constant when varying the friction path length at all values of the loading for all the studied samples. In the cases of composites IPM 304 and IPM 305 there exists a tendency of decrease in the rate of wearing off after friction path length L = 150 m, which is due to the process of fitting up in the tribosystem. Upon increasing the loading the rate of wearing off is growing up, but the dependences have different characters. For the samples IPM 305 and BrO1F1 this dependence has a stable proportional character with some very close values for different friction path length for each one of the samples, but it differs in the absolute values for these two materials. The dependence of the rate of the wearing off process on the loading for the sample IPM 304 has the shape of letter S-curve with three sections (Fig. 11): I section – $0 \leq P_1 \leq 17.1$ N; II section – $17.1 \leq P_2 \leq 37.1$ N and III section – $37.1 \leq P_3 \leq 57.1$ N. In the first two sections the curve is overlapping for the different values of the friction path length. In the third section the wear rate at small friction path length has linear character, but upon increasing the friction path length the rate is gradually decreasing and after fitting it remains constant at length $L = 232$ m.

It becomes obvious from the comparison of the results on the dependence of the wear rate on the loading, that the greatest degree of wearing off is demonstrated by the sample of tin bronze BrO1F1. Its curve is much steeper than the curves of the other two samples, which are similar. Upon increasing the loading 3.3 times the degree of wearing off of the bronze grows up 5.2 times from 20 mg up to 103.4 mg. The greatest degree of wearing of for the bronze sample is observed at the highest loading.

Among all the studied samples the lowest degree of wearing off is manifested by the sample IPM 304. At loading $P = 17.1$ N its degree of wearing off is 8.3 times less than that of the bronze sample and 3.8 times lower than the degree of wearing off of the sample IPM305. Upon increasing the loading, these ratios are changing, but they always remain in favour of the sample IPM 304. After 3 times increase in the loading the wearing rate of bronze grows up 42 times comparing with that of IPM 304. At low loading $P = 1$ 7.1 N the wear rate of bronze is 8.2 times higher than that of the sample IPM 304 and 2.1 times higher than that of sample IPM 305. At three times greater loading $P = 57.1$ N this ratio becomes respectively: wearing rate for bronze is 6.1 times higher than that of IPM 304 and 3.1 times greater than the wearing rate of IMP305.

The relative wear resistance of the samples is represented for better visibility in the form of a diagram (Fig. 17). Judging from the results one can definitely state that the greatest wear resistance is demonstrated by the composite sample IPM 304 at all values of the loading. At loading $P = 17.1$ N its wear resistance is 8.5 times higher than the wear resistance of bronze and 2.4 times higher than the wear resistance of IPM 305. Upon increasing the loading this ratio is changing respectively. At three times greater loading $P = 57.1$ N the wear resistance of IPM 304 is 4.5 times higher than that of bronze and 1.5 times higher than the wear resistance of the IPM 305 sample.

The change in the coefficient of friction (COF) for the different tribosystems at various loadings is to be seen clearly in Fig. 18. In the cases of the tribosystems with composite materials ‘IMP304-Steel 45’ and ‘IPM305-Steel 45’ upon increasing the loading the COF is diminishing almost linearly. At 3 times increase in the loading the COF drops down 4 times in comparison with its value at initial loading. Under the same conditions in the tribosystem ‘BrO1F1-Steel 45’ the COF grows up from the value of 0.26 to the value of 0.37.

CONCLUSIONS

The main results from the investigation of tribosystems, containing self-lubricating materials (SLAM) 'IPM 304', 'IPM 305' and tin bronze BrO1F1, in the regime of friction without any lubricating materials in atmospheric medium can be summarised as follows:

It has been established that upon increasing the normal loading the coefficient of friction in the tribosystems 'IPM304-Steel 45' and 'IPM305-Steel 45' is decreasing non-linearly reaching values, which are characteristic for liquid friction, respectively 0.05 for 'IPM304-Steel 45' and 0.08 for 'IPM305-Steel 45'.

This result is a proof on macro level for the occurrence of processes of self-organisation in these tribosystems. For the tribosystem 'BrO1F1-Steel 45' the dependence of the coefficient of friction has reverse character – it grows up and acquires values ranging from 0.26 to 0.37, which are characteristic for dry friction.

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