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TRIBOLOGICAL INVESTIGATIONS ON TRIBOSYSTEMS LUBRICATED WITH VEGETABLE OILS AND MINERAL-VEGETABLE COMPOSITES WITH METALPLATING ADDITIVE. PART II: WEAR

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Abstract. The development of new biodegradable lubricating materials and composites with promoted physicochemical and tribological characteristics appear to be a pressing task of global ecological and economical importance. The subject of the research work on this topic is a comparative investigation of the tribological characteristics of tribosystems upon lubrication with biodegradable oils on vegetable basis and composites, prepared by appropriate combination of vegetable and mineral oils with the addition of multifunctional metal-plating modifiers. The present second part represents the results for the characteristics of the wearing off and the wear resistance of the two bodies in tribosystems in the case of boundary friction with reverse translation movement during lubrication with three different kinds of oils: 100% biodegradable oil on vegetable basis (Bio-DM), 95% vegetable oil with 5% metal plating additive (Bio-DMV) and mineral-vegetable composite, including 60% mineral oil, 35% sunflower oil and 5% metal plating additive (HLP-SV). It has been established that the lowest wear resistance is manifested by the samples in case of lubricating with biodegradable oil on 100% vegetable basis, while the highest wear resistance was observed in the case of lubrication with the composite (HLP-SV). On the surface of the two samples a metal plating film was registered having thickness of 3 μm, which is the result of the occurring processes of selective transferring during the self-organisation of the tribosystems.

Keywords: tribology, biodegradable lubricating materials, wear, self-organisation.

AIMS AND BACKGROUND

The actuality of the research topic originates from its interconnection with solving the problems, connected with protection of the environment and decreasing the energy and material expenses due to friction processes, wearing off and lubrication during the operation of the machines[1–9].

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The subject of research work is to look for options and possibilities to elaborate new biodegradable lubricating materials and composites with enhanced physicochemical and tribological characteristics. To be more specific – it is comparative investigation of friction and wear in tribosystems during lubrication with biodegradable oils on vegetable basis and composites, prepared by combining vegetable and mineral oils with the addition of multifunctional metal plating modifier.

The results from the study are published in two parts. The first part is 'Tribological investigations of tribo-systems upon lubrication with vegetable oils and mineral-vegetable composites with metal plating additive. Part I: Friction'[10] is focused on friction characteristics of the tribosystem, which represents a knot of rolling bearings. The present second part represents the results for the characteristics of wear in tribo-systems for various samples of one and the same material in case of boundary friction under the conditions of reverse translation movement.

EXPERIMENTAL

Materials. The study on friction and wear was carried out using 5 kinds of lubricating oils, divided in two groups. The first group included two kinds of oil: No 1 (Bio-DM) – representing 100% vegetable oil and No 2 (Bio-DMV) – consisting of 95% vegetable oil Bio-DM with the addition of 5% metal plating additive V. The basic physicochemical characteristics are as follows: flash point > 250°C (DIN 51376); density at 15°C – 0.92 g/cm^3 (DIN 51757); viscosity at 40°C of 1000 mm^2/s (DIN 51562).

The second group included three kinds of lubricating oils and composites: No 3 (HLP) – 100% mineral hydraulic oil; No 4 (HLP-S) represents mineral-vegetable composite of 65% mineral hydraulic oil HLP and 35% sunflower oil S; No 5 is mineral-vegetable composite of 60% mineral hydraulic oil HLP, 35% sunflower oil S and 5% metal plating additive V. Table 1 indicates the notations for the studied lubricating oils and composites. The listed notations of the oils, available on the market, do not correspond with their commercial trademarks.

The present publication represents the results from the comparative study of the samples wearing off in tribosystems of one and the same material under the conditions of boundary friction during lubrication with three kinds of biodegradable oils: Bio-DM (No 1), Bio-DMV (No 2) and HLP-SV (No5) (Table 1).

Table 1. Notation and composition of the studied vegetable oils and mineral-vegetable composites

Group of oils	Oil sample	Notation of the oil	Oil composition
	1	Bio-DM	100% vegetable oil
I	2	Bio-DMV	95% vegetable oil plus 5% metal plating additive
	3	HLP	100% mineral oil
II	4	HLP-S	65% mineral oil plus 35% sunflower oil
	5	HLP-SV	60% mineral oil, 35% sunflower oil plus 5% metal plating additive

The biodegradable oil Bio-DM, obtained from renewable resources, is 100% vegetable origin. It contains a complex of additives for enhancing the adhesion properties between the oil and the surfaces of the chain and guiding rim of motor cutter in the agriculture and in the forestry. The adhesion additives prevent the quick leakage of the oil from the cutting chain. The use of 100% biodegradable oil is in favour of the protection of the environment – the soil and the ground waters from toxic components, contained in the conventional mineral oils.

The mineral-vegetable composite HLP-SV has been prepared by the authors of the present publication. The metal plating additive represents multifunctional metal-containing oil-soluble composite, designed for the improvement of the tribological properties of lubricating materials and specifically materials having antifriction, antiwear and anti-scratch properties, as well as protection from water wear. It represents a dense liquid dark green colour, which is well soluble in oils and plastic lubricants, forming solution, in which the metal is in the form of molecules and ions. The solubility of the additive is due to its specific composition – metal salts of organic and inorganic acids. The metal salts of the inorganic acids are salts of copper, cobalt, lead, tin, nickel (chlorides, bromides and iodides). The metal salts of the organic acids are usually salts of metals manifesting different valences and the number of the carbon atoms is $C_{15}...C_{18}$ (Ref. 11).

Device and methodology. The wearing off process under the conditions of boundary friction in case of lubrication with biodegradable oils has been studied using a device, enabling reverse-translation movement of the tribosystem. The device has been elaborated in the Centre of Tribology at the Technical University – Sofia (Figs 1 and 2).

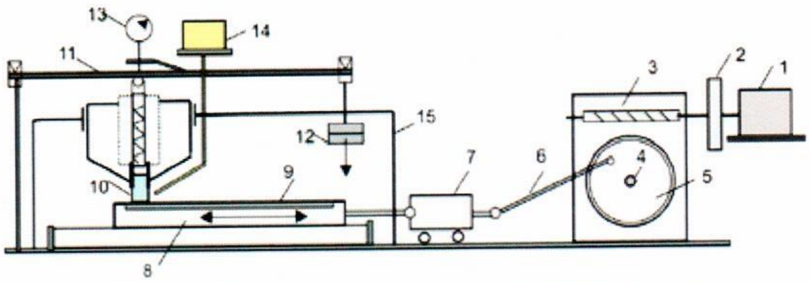

Fig. 1. Scheme of tribotester RT16 for studying the wearing off process in case of reverse-translation movement

Fig. 2. Photograph of tribotester RT16 for studying the wearing off process in case of reverse-translation movement

The device consists of an electromotor 1, which transfers the rotational impulse through the conjunction joint 2 of the hob woo reducer 3. A disk 5 is attached to the outlet shaft 4 of the reducer 3, to which the toggle motor-fork mechanism 6 is mounted. The wheel carrier 7 is attached to the toggle motor-fork 6 by knuckle-joint hinge, which transfers the reverse-translation movement of the sledge (slider runner) 8. By means of the wheel carrier, the knuckle-joint hinge and the cylindrical shape of the directing rod one can achieve a stable bidirectional movement of the sledge – self-adjustment of the samples, which reduces the friction and the vibrations. The studied contact system consists of two samples: a body 10 and a counter-body 9. The sample 10 is made of special instrumental steel, manufactured by a unit of the 'Gardena' chain of the 'Husqvarna' company for the production of machines for trimming bushes and clipping other vegetation. The lower part of the sample is in the shape of cutting edge, so that the contact area between the two samples represents a rectangle with a length of 5 mm and width of 0.5 mm. The counter-body, sample 9 is fixed in the sledge 8 (slider runner) and it accomplishes together with the sledge a reverse-translation sliding movement. It represents a metal plate of dimensions: length of 107 mm, width of 43 mm and 1 mm thickness. The sample 10 is mounted in such a way, that its wide dimension is perpendicular to the sliding line. The normal loading on the body 10 is set by a lever system, which comprises dynamometric beam 11 with a ratio between the shoulder levers 1:3.2 and standard weights 12. The indicator for shifting 13 allows measurement of the relative change in the height of the sample during the process of friction, i.e. the linear wear or the thickness of the metal plating film with a precision of 1 μm.

The maximum loading of the device is 160 N. The length of the sliding distance of the sledge is 73 mm at sliding velocity 56 revolutions/min or $v = 6.8$ cm/s.

During oil lubrication, as is the case of the present experiment, the oil is fed near to the contact area of the system 14 for drop-wise lubrication at flow rate 40 drops/min.

The parameters of the device are: the sample makes 58 cycles for 1 min, i.e. its frequency is 28 double strokes per minute, whereupon it travels a distance of friction $S = 4.09$ m/min at a sliding velocity 6.82 cm/s.

The plate 9 is made of steel St3sp (BDS 5292-61) with chemical composition and hardness, represented in Table 2.

Table 2. Chemical composition and hardness of sample St3sp (BDS 5292-61)

Element	C	Si	Mn	Ni	S	P	Cr	Cu	Fe
wt. %	0.18	0.25	0.52	0.25	0.02	0.03	0.28	0.15	balance
Hardness				$HB \times 10^{-1} = 131$ MPa					

The methodology of the investigation on the characteristics of the wearing off process consists of measuring the mass wear of the contacting samples for a definite pathway of friction under permanent set of conditions – loading, sliding velocity, and type of lubricating oil. Thereafter the characteristics of mass wear are calculated – rate of the wearing off process, wear intensity and relative wear resistance.

The specific methodology comprised the following operations:

– Preparation of the samples for the body and counter-body having identical dimensions and the same roughness. The roughness was measured by means of a profile-meter 'TESA Rugosurf 10-10G';

– Measurement of the masses m_0 (g) of the two samples – the body and the counter-body by an electronic balance WPS 180/C/2 with a precision of 0.1 mg. Prior to each measurement on the balance, the sample was cleaned by removing the mechanical and the organic particles and then it was dried up using ethyl alcohol in order to prevent the appearance of electrostatic effect;

– Sample 10 was placed in the holder, while sample 9 was fixed to the sledge 8.

– A certain normal loading was set to 12 and the studied lubricating oil was poured into the reservoir.

– The electric motor was switched on and a definite pathway of friction was set by adjusting the time interval of friction by means of a chronometer.

– The samples were taken out of the device, they were cleaned by removing the residual oil using a solvent, then they were dried up and once again their masses were measured m_i on the same balance.

The following characteristics of the wearing off process were calculated:

– The mass wear m (mg) – it represents the mass destroyed and removed from the surface layer of the sample for a definite pathway length of friction L, i.e.

$$m = m_0 - m_i \tag{1}$$

– Rate of mass wearing off γ (mg/min) – it represents the destroyed mass during the friction per unit of time t:

$$\gamma = m/t \tag{2}$$

– Intensity of mass wear i (mg/m) – it represents the destroyed mass during the friction per unit of friction pathway length L:

$$i = m/L \tag{3}$$

– Mass wear resistance I (m/mg) – it is expressed as the reciprocal value of the intensity of the wearing off process, i.e.

$$I = 1/i = L/m. \tag{4}$$

The mass wear resistance is a number, which indicates how many meters of length of the friction pathway will be traversed by the sample under the given conditions, in order to destroy and remove one milligram of mass from the surface.

All the experiments were carried out under the same conditions of friction – loading, sliding velocity, time interval of friction, dimensions of the samples, initial temperature and flow rate of the oil (Table 3).

Table 3. Parameters of the experimental run using a tribo-tester RT16

Parameter	Value
Loading	10 N
Nominal contact area	$A_a = 2.5$ mm^2
Nominal contact pressure	400 N/cm^2
Initial temperature of the oil	50°C
Time interval of friction	from 10 to 120 min
Friction pathway length	from 41 to 492 m

RESULTS AND DISCUSSION

Following the above described methodology and using the tribo-tester device experimental data have been obtained for the mass wear, rate of wearing off and wear resistance of both samples depending on the time interval of friction during lubrication with the three types of biodegradable lubricating oils – Bio-DM, Bio-DMV and HLP-SV.

The rate of the wearing off process, as well as the wear resistance, have been calculated by the formulae, respectively (2) and (4).

The results for the separate lubricating oils are represented in Tables 4, 5 and 6.

Table 4. Characteristics of wear process during lubrication with Bio-DM oil

	Body					
Time interval (min)	10	20	40	60	90	190
Friction pathway length (m)	41	82	164	246	369	492
Wear (mg)	0.3	0.7	1.1	1.7	2.5	3.5
Wear rate (mg/min)	0.03	0.035	0.0275	0.0283	0.0277	0.0291
Wear resistance (m/mg)	137	117	149	144	147	140
	Counter-body					
Time interval (min)	10	20	40	60	90	190
Friction pathway length (m)	41	82	164	246	369	492
Wear (mg)	41.6	80.5	145.4	220.8	310.5	396.8
Wear rate (mg/min)	4.16	4.025	3.635	3.68	3.45	3.31
Wear resistance (m/mg)	0.98	1.01	1.12	1.11	1.19	1.24

Table 5. Characteristics of wear process during lubrication with Bio-DMV oil

	Body					
Time interval (min)	10	20	40	60	90	190
Friction pathway length (m)	41	82	164	246	369	492
Wear (mg)	0.2	0.4	0.9	1.5	1.6	1.6
Wear rate (mg/min)	0.02	0.02	0.0225	0.025	0.017	0.013
Wear resistance (m/mg)	205	205	182.22	164	230.63	307.5
	Counter-body					
Time interval (min)	10	20	40	60	90	190
Friction pathway length (m)	41	82	164	246	369	492
Wear (mg)	41	62.4	119.4	175.2	249.3	250.3
Wear rate (mg/min)	4.1	3.12	2.985	2.92	2.77	2.09
Wear resistance (m/mg)	0	1.31	1.37	1.4	1.48	1.97

Table 6. Characteristics of wear process during lubrication with HLP-SV oil

Body						
Time interval (min)	10	20	40	60	90	190
Friction pathway length (m)	41	82	164	246	369	492
Wear (mg)	0.1	0.2	0.3	0.5	0.6	0.6
Wear rate (mg/min)	0.01	0.01	0.0075	0.0083	0.0067	0.005
Wear resistance (m/mg)	410	410	546.67	492	615	820
Counter-body						
Time interval (min)	10	20	40	60	90	190
Friction pathway length (m)	41	82	164	246	369	492
Wear (mg)	36.9	76.6	98.8	126.6	188.5	190
Wear rate (mg/min)	3.69	3.83	2.47	2.11	2.09	1.58
Wear resistance (m/mg)	1.11	1.07	1.66	1.94	1.96	2.59

On the basis of the results, listed in the tables, the plots of the dependences of mass wear on the friction pathway length for the body – sample 10 (Fig. 3) and for the counter-body 9 (Fig. 4) for the three cases of lubrication with three different kinds of oils.

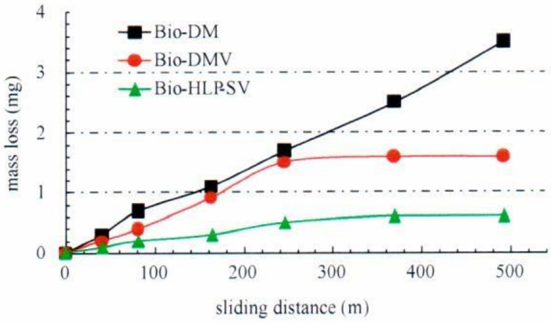

Fig. 3. Mass wear of the sample (body) as a function of sliding distance

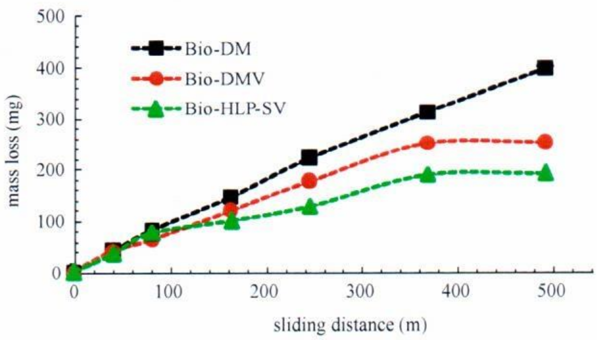

Fig. 4. Mass wear of the sample (counter-body) as a function of sliding distance

Figures 5 and 6 represent the comparative diagrams of the wear resistance of the samples, respectively for the body 10 and for the counter-body 9 during lubrication with the three oils at one and the same pathway length of friction 492 m.

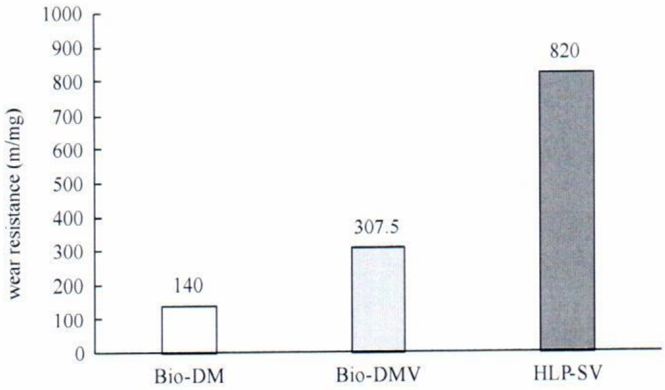

Fig. 5. Diagram of wear resistance of sample 10 (the body) made of instrumental steel during lubrication and sliding distance $L = 492$ m

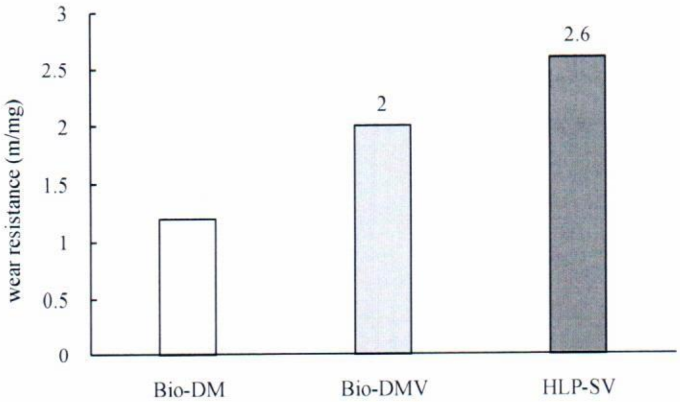

Fig. 6. Diagram of wear resistance of sample 9 (the counter-body) made of steel St3sp during lubrication and sliding distance $L = 492$ m

Upon increasing the sliding distance (time interval of friction) the mass wear of the two samples is increasing non-linearly.

The kinetic curves of the wearing off process of the two samples display one and the same character, but the degree of wearing off differs in the absolute values. The degree of wearing of the plate (the counter-body) is two orders of magnitude higher than that of sample 10, which is made of special cutting steel.

For both samples the greatest degree of wearing off is in the case of lubrication with biodegradable oil Bio-DM, which is 100% of vegetable composition.

The addition of 5% additive Valena to the biodegradable oil Bio-DM reduces the wearing off degree in comparison with that of lubricating with 100% vegetable oil (Bio-DM) for both samples.

The lowest wearing off degree of both samples is observed in the case of lubrication with the combined lubricating oil HLP-SV, which contains 60% mineral oil, 35% vegetable oil and 5 % additive Valena.

The analysis of the diagrams of wear resistance of the samples shows the following:

The wear resistance of sample 10 (the body) is two orders of magnitude larger than that of the counter-body – sample 9 in all three cases of lubricating oils.

The lowest wear resistance is in the case of the samples lubricated with biodegradable oil having 100% vegetable basis – Bio-DM.

The modification with 5% additive Valena to the purely vegetable oil enhances the wear resistance 2,2 times for sample 10, made of instrumental steel, and 1,6 times for sample 9, made of steel St3sp.

The highest wear resistance is displayed by the two samples in case of lubrication with the combined biodegradable oil HLP-SV – mineral oil with vegetable oil and metal plating additive. For the sample 10, made of instrumental steel, the wear resistance is 5.86 times higher than that in case of lubrication with 100% vegetable oil Bio-DM and 2.67 times higher than the wear resistance in case of lubrication with vegetable oil Bio-DMV, containing 5% Valena (Figs 4 and 5). For sample 9, made of steel St3sp the wear resistance in case of lubrication with HLP-SV is 2 times higher than the wear resistance in case of 100% vegetable oil and 1.3 times higher than that in case of lubrication with Bio-DMV oil.

On the surfaces of the two samples a metal plating film of reddish color is observed and its thickness is about 3 μm. The chemical analysis shows that the basic chemical element in the so formed in the process of friction transfer film (around 85%) is the chemical element Cu. The deposition of the protective metal plating film is the result of complicated contact processes of interaction and the effect of selective mass transferring in the course of self-organisation of the tribosystems[12–14].

CONCLUSIONS

The main results of the present work can be summarised as follows:

Experimental data have been obtained on the dependences of the characteristic features of the wearing off process – mass wear, wear rate and wear intensity as well as data on the wear resistance of the two bodies in tribo-systems in the case of boundary friction with reverse-translation movement in the cases of lubrication with three different kinds of oils: 100% biodegradable oil on vegetable basis (Bio-DM), 95% vegetable oil with 5% metal plating additive (Bio-DMV) and mineral oil-vegetable oil composite, comprising 60% mineral oil, 35% sunflower oil and 5% metal plating additive (HLP-SV).

It has been found out for the two bodies of the tribosystem, that the lowest wear resistance is manifested when the lubrication is carried out with biodegradable oil having 100% vegetable basis – (Bio-DM), while the highest wear resistance is observed in the case of lubrication with mineral oil-vegetable oil composite having metal plating additive (HLP-SV).

The obtained results for high wear resistance are in correspondence and harmony with the previous results, represented in Part I (Ref. 10) for the lowest values of the friction characteristics- moment and coefficient of friction in the tribosystem 'rolling bearing', in case of lubrication with the same HLP-SV lubricant.

On the surfaces of the two samples a copper metal plating film has been registered of thickness 3 μm, which appeared as a result of the occurring contact processes of selective mass transfer in the course of self-organisation of the tribosystems. This result confirms the compatibility of the additive to vegetable-mineral composite, containing sunflower oil.

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