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Self-organization Effects on Tribosystems when Lubricated with a Metal-plating Additive „Valena”

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Abstract: The external appearance of self-organization is very low friction and wear, and in some cases there is lack of wear, so a friction effect without wear is observed. In the present study are examined tribosystems of different materials - steel, spheroidal graphite cast iron micro alloyed with 0.051% of tin, bronze and other materials under conditions of border lubrication with grease “Litol 24” with a metal-plated additive “Valena”. A unique multifunctional tribotester has been developed that allows varying load and slide speed across wide ranges and research different types of contact - point, ring, plane. Studies have been carried out on different friction modes and results have been obtained for friction coefficient and the parameters of wear of the specimens and the counter body depend of the friction times. Conditions have been established to produce a No-wear effect due to the formation of a metal-plated copper film on the surfaces of the body and the counter body.

Keywords: self-organization, tribosystems, friction, wear, No-wear effect

1. Introduction

Generally acknowledged self-organization is connected with the spontaneous transition of the open non-equilibrium systems from less complicated and more chaotic forms to more complicated and more arranged forms [1,2,3]. In the non-equilibrium thermodynamics, the Belgian physic-chemist, Nobel Prize winner Ilya Prigozhin has proved, that in the open natural systems independently of their nature: physical, chemical, biological and social there exist possibility for their sustaining in stable non-equilibrium and the latter takes the towards elaboration in their internal structure and their structural enrichment. This evolutionary state of the systems might be supported with the help of stationary energetically and mass streams. Similar conditions are accomplished for processes which are carried out spontaneously and in the human society to the spontaneous actions are added the impacts with set purpose from the side of the humans. The strongly non-equilibrium open system forms structures on the basis of the mechanism of self-organization. In the scientific literature these structures are known as dissipative structures. The term for the latter comes from its basic purpose and function to protect



the system from outer powerful energetic flows by scattering them. Dissipative structures exist and they are developing themselves only in non-equilibrium state of the open systems.

The tribological systems are assigned to the open thermodynamically systems. They are characterized with exchange of substances, energy and information with the environment. In the tribology are well known many effects, which are assigned to the self-organization in the tribosystems: effect of anomalously friction, registered by Silin after the contact surfaces have been irradiated with alfa particles; effect of selective transfer of material from one to the other surfaces under friction; effect of processing of the roughness and the connected triboprocesses of friction; effect of Rebinder, which is expressed with the influence of special surfactants designed to decrease of the surface tension; auto vibrations in contact systems, etc.

Special attention of many scientists and basically of the authors of this publication is the phenomenon *no-wear effect under friction*. This effect has been discovered in 1956 in the Soviet union by a group of researchers under the scientific guidance of D. Garkunov [4÷8]. The effect is observed in cases of friction and it is a result of mechanical and physical-chemical processes, leading to auto-compensation of the wear and decrease of friction. Specific in the essence of this effect is the building and functioning of a protective film where is realized diffusion – vacational of deformations which are proceeding without accumulation of defects as opposed to the fatigue processes. As a result of the processes of self-organization during the friction are formed self-recoverable metal-polymeric structures – serving and servitic films with thickness of 100 nm, where the deformation-plastic phenomena are materialized without accumulation of defects in the crystal structure on the surface.

The processes of formation of such surfaces is carried out under stringent combination of certain conditions – composition and properties of the contacting surfaces; composition and properties of the lubricating material; characteristics of the deformation field; value of the relative pressure; friction rate; contact temperatures. Generally, the basic factor which has an influence for the simultaneous action of tribo-recovering and tribo-coordination processes leading of self-organization is the chaotic auto-vibration of copper containing products in the lubricating material [9÷12].

The self-organization is the basic mechanism for non-wear friction and it is a result of the evolution changes of the contact, which are conditioned by the achievement of stationary (stable) condition of the tribosystem with minimal friction and maximal wear resistance [13÷17].

Especially expressive for the self-organization are the strong non-equilibrium states of the system where the energetic and material flows from the outside are non-linear functions of the temperature gradients and the concentration of the substances.

The purpose of the present paper is to be studied the influence of the metal-plating additive Valena on the intensity of the wear of the tribosystems from different materials and different friction regimes.

2. Materials

The influence of metal-plating composite additive Valena on wear of different materials during friction in grease Litol 24 is studied. Possibilities for obtaining the selective transfer of materials effect are to be found.

Table 1. Designation of the tested contact systems

№	Contact systems	
	Designation	Materials
1	GJS 600-3 - C22	Spheroidal Graphite Cast Iron with 0.051%Sn – Steel
2	Ст4кП - C22	Steel – Steel
3	БрАЖ9-4 - C22	Bronze – Steel
Lubricant	Grease Litol 24 without Valena additive Grease Litol 24 with Valena additive (4 mass %)	

Tables 2, 3, 4 and 5 give the data about the composition, hardness and roughness of the material.

Table 2. Composition and hardness of specimen GJS 600-3 (BDS-EN 1563-00).

Element	C	Sn	Mn	P	Si	Cr	S	Fe
wt. %	3.87	0.051	0.34	0.029	1.55	0.03	0.012	Balance
Hardness	277 HB							

Table 3. Composition and hardness of specimen Ст4кп (GOST 380 - 94).

Element	C	S	Mn	P	Si	Cr	Ni	Fe
wt. %	0.25	0.045	0.55	0.45	0.15	0.30	0.28	Balance
Hardness	135 HV 0.05							

Table 4. Composition and hardness of specimen БрАЖ9-4 (CuAl9Fe3)(GOST 1628-78).

Element	Fe	Al	Mn	P	Si	Pb	Zn	Sn	Cu
wt. %	3.0	9.5	0.45	0.008	0.12	0.088	0.85	0.09	Balance
Hardness	180 HB								

Table 5. Composition and hardness of the counter body C22 (BDS-EN 10083-2/1966).

Element	C	Cu	Mn	P	Si	Cr	Ni	Fe
wt. %	0.19	0.15	0.55	0.05	0.12	0.07	0.03	Balance
Hardness	633 HV 0.05							

3. Experimental results and analysis

The materials are tested by means of the device shown in Figure 1. A multifunctional set of accessories is developed, which allows simultaneous testing of wear and seizure through 180° rotation of the body, with possibility to reconstruct different kinematic situations. The set is located on a common fundament (Figure 2).

The elements of the set are: 1 – fundament; 2 – vertical bearing frame of the chamber 4 for testing of wear; 3 – protective screen; 5 – mandrill; 6 – bearing partition; 7 – chamber for testing the seizure of specimens and oils with and without additive.

Three spheres 8 with diameter 11.4 mm are located in chamber 7, which are loaded with load P through the sphere with equal diameter. The spheres 8 are fixed and covered with lubricant. The test rig allows three cases of kinematic interactions: firstly, when the upper arbor rotates, and the spheres in the chamber are fixed; secondly, when the upper arbor is immovable, and chamber 8 with the spheres rotates; and the third case, simultaneous rotation of the arbor and the chamber with different revolutions and opposite directions. The chamber is driven by motor 14 through the belt drive 12, 11, 10. The motor is located in case 13.

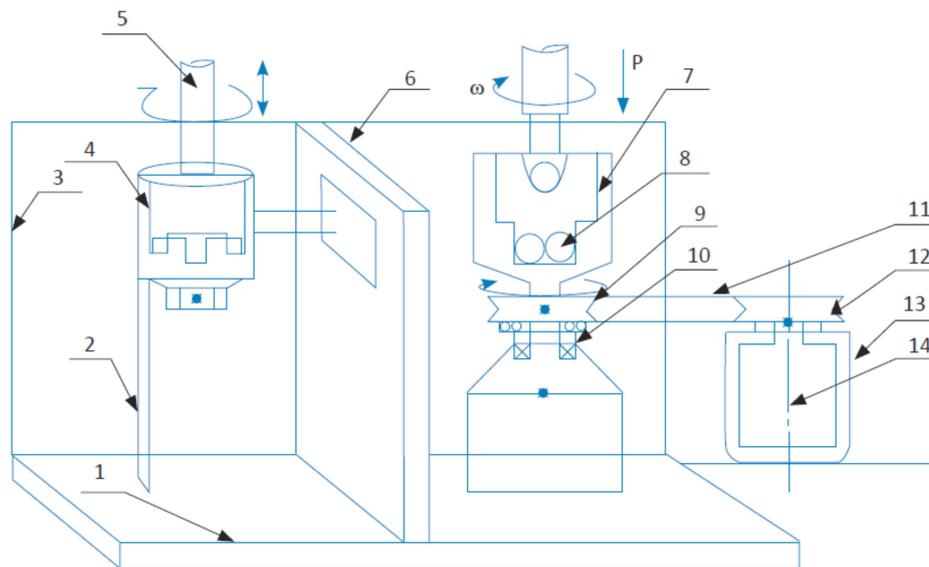


Figure 1. Set of accessories for testing of selective transfer at the specimens under normal and under seizure conditions.

Cylindrical specimens are prepared of the three materials, namely spheroidal graphite cast iron micro alloyed by 0.051% tin (GJS 600-3), steel (Ст4кп) and bronze (БрАЖ9-4). The specimens with their dimensions are shown in Figure 2a. The counter body is in the form of rectangular plate with dimensions $30.5 \times 35 \times 9$ mm (Figure 2 b).

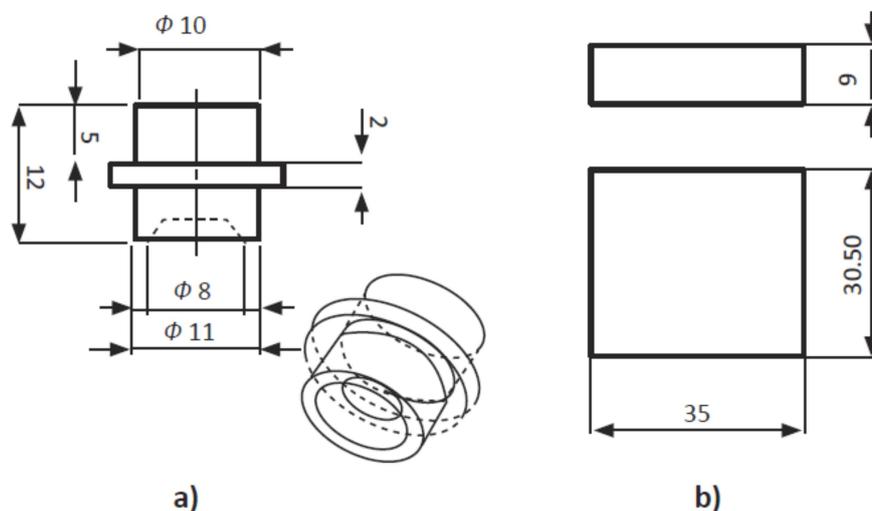


Figure 2. Dimensions of: the specimens (a); the counter body (b).

The interaction between specimen and counter body occurs in an annular contact with nominal area $A_a = 44.75 \times 10^{-6} \text{ m}^2$. The space above the annular contact is filled with lubricant, providing permanent penetration in the contact zone, and avoiding thus the regime of boundary and/or dry friction (Figure 2a).

The tests are carried out at two regimes of friction: the first one is realized at low load and high number of revolutions, i.e., big peripheral sliding speed, and the second one - at high load and small peripheral sliding speed. Wear is tested at every friction regime in two cases: lubrication with grease Litol 24 without Valena and lubrication with grease Litol 24 with Valena (Table 6). The time of friction for all tests is 40 min.

Table 6. Parameters of friction regimes in Litol 24 without and with Valena.

Regime of friction	Load N	Pressure MPa	Revolutions min ⁻¹	Friction way m	Speed m/s
Regime I	10	0.22	2300	2744.40	1.33
Regime II	20	0.45	870	1038.00	0.5

Experimental results for the three contact systems at friction without and with Valena additive in both regimes of friction are presented below.

Contact system “Spheroidal graphite cast iron with 0.051% Sn – Steel”

(GJS 600-3 – C22)

Figures. 3 and 4 show wear variation for spheroidal graphite cast iron in both regimes of friction.

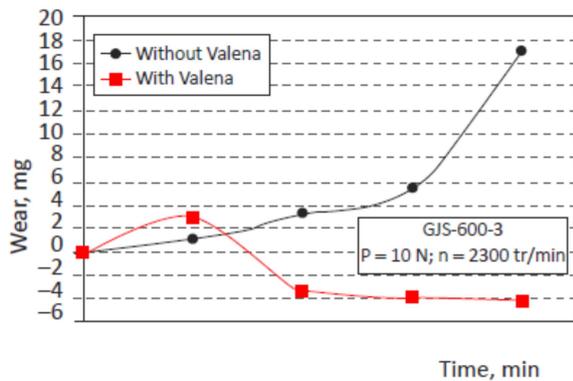


Figure 3. Influence of Valena additive on wear of GJS-600 at friction in Regime I

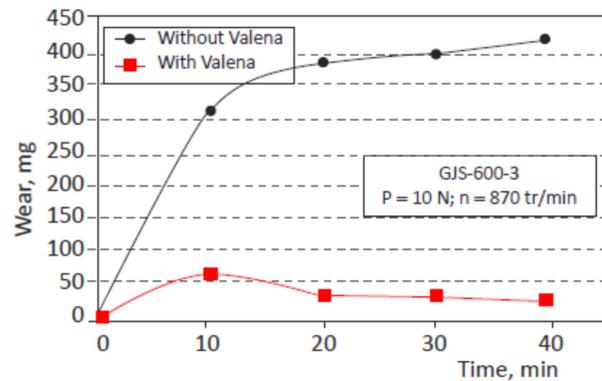


Figure 4. Influence of Valena additive on wear of GJS-600 at friction in Regime II

In the case of friction with high speed and low load (Regime I), the wear curve in the period of running-in up to the time of 10 min shows dissimilarities. The presence of Valena in grease Litol 24 leads to higher wear compared with that in grease without Valena additive. After that period, wear decreases, the specimen’s mass increases, and that is due to the film deposited on the cast iron specimen’s surface (Figure 3).

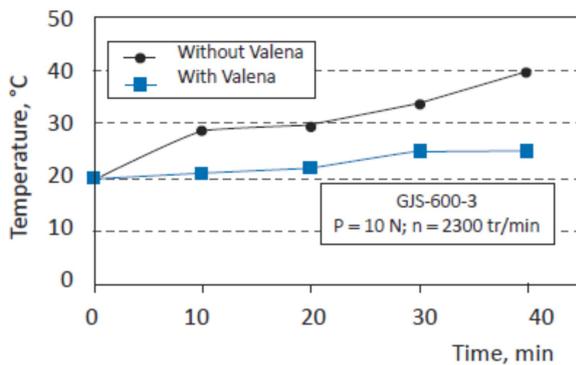


Figure 5. The temperature of the time friction in Regime I.

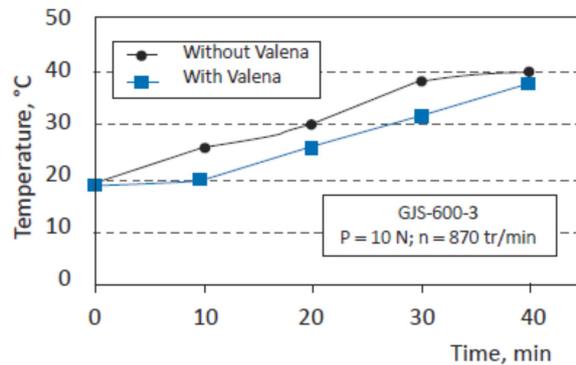


Figure 6. The temperature of the time friction in Regime II.

The temperature of lubricant material with Valena additive for the time of friction increases with 5° C only, whereas in grease without Valena – with 20° C (Figure 5). In the case of friction with twice higher load and 2.6 times higher speed (Regime II), specimen’s wear occurs in both media, however, the wear in grease with Valena is 17 times lower than that in grease without Valena additive, which is

most probably the result of the protecting copper film formed on the working surfaces (Figure 3). The temperature in both media increases with 20° C (Figure 6).

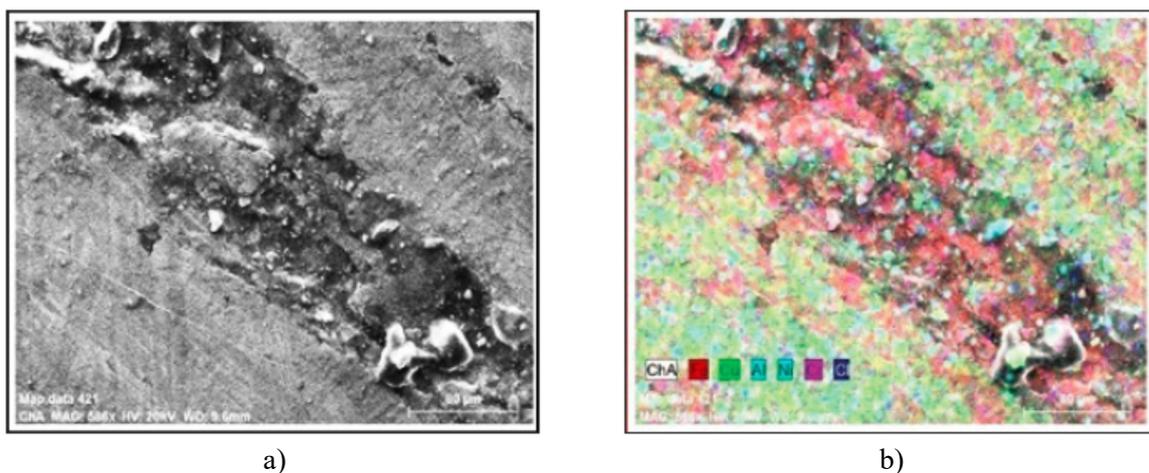
Visual observation shows clearly metal-plating film with reddish colour on the surface of the spheroidal graphite cast iron specimen and on the surface of the steel counter body (Figure 7a, b).



Figure 7. Specimens pictures of the spheroidal graphite cast iron (GJS) with 0.051% Sn (a); and of the counter body of steel (C22) (b) after friction duration 40 min at $P = 10\text{ N}$ and $n = 2300\text{ min}^{-1}$.

The microstructure and the composition of the metal-plating film on specimens' surfaces are studied by scanning electronic microscope EVO MAX 10 ZEISS. Figure 8 shows the microstructure and the composition of the deposited metal-plating film on the surface of spheroidal graphite cast iron GJS 600-3 specimen.

The composition of the deposited film shows presence of the following elements: iron, copper, aluminum, nickel, chromium and chlorine.



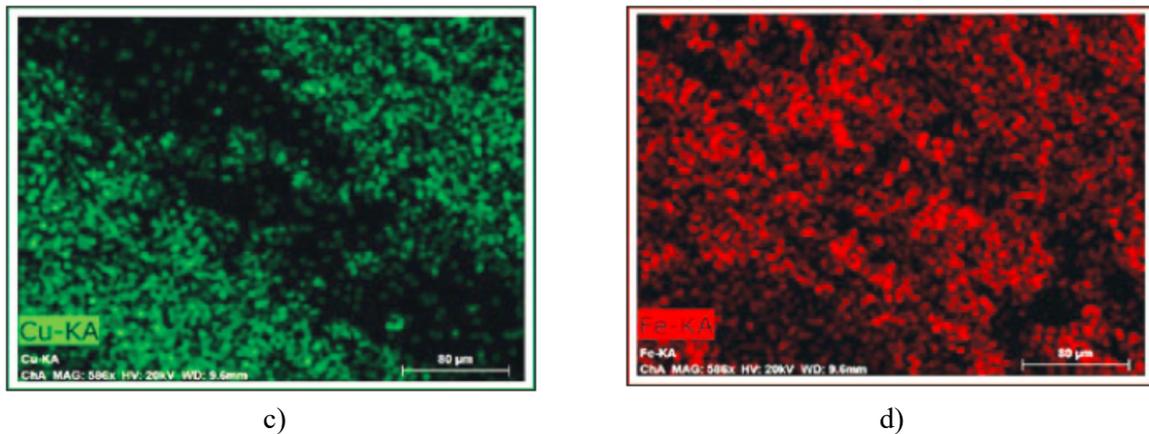


Figure 8. Microstructure (a), composition (b), microstructure with Cu (c), and Fe (d) in metalplating film on the surface of spheroidal graphite cast iron GJS 600 – 3 with 0.051% Sn specimen, after friction process at $P = 10 \text{ N}$; $n = 2300 \text{ min}^{-1}$.

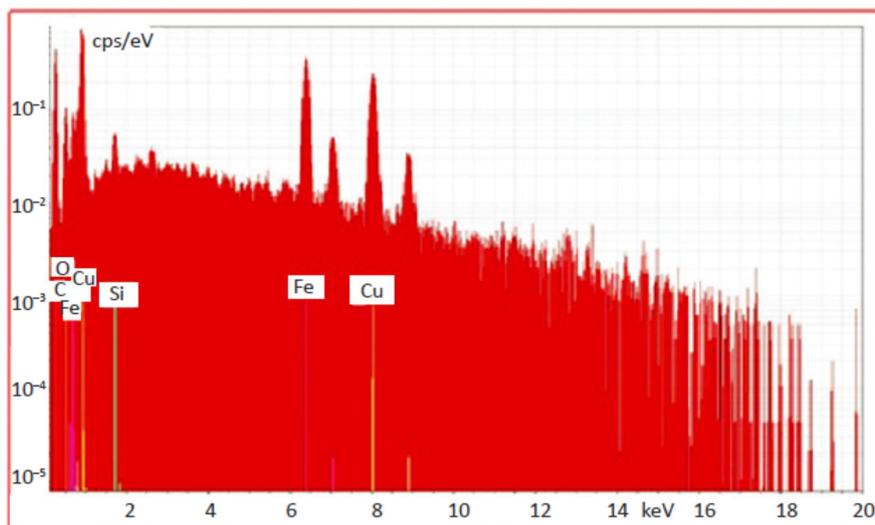


Figure 9. Chemical elements spectrum in metal-plating film on the surface of spheroidal graphite cast iron GJS 600 – 3 with 0.051% Sn, after friction at $P = 10 \text{ N}$; $n = 2300 \text{ min}^{-1}$.

Figure 9 shows the chemical elements spectrum in the composition of the metal-plating film. The wear curve of the counter body of steel C22 at friction in Regime I and the wear curve of the specimen of spheroidal graphite cast iron in the same regime of friction are similar (Figure 10).

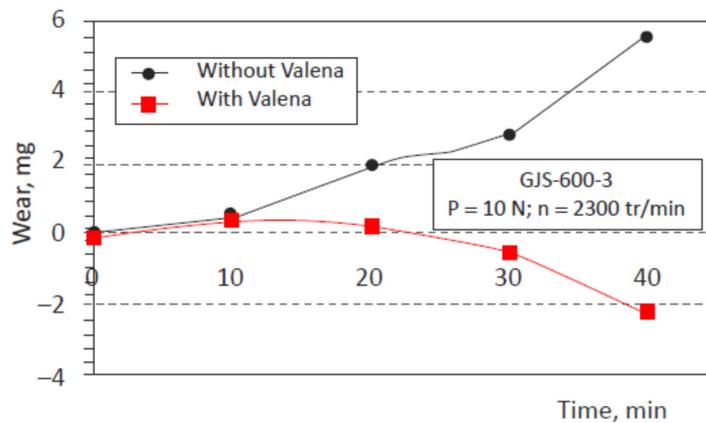


Figure 10. Influence Valena additive on the wear of the counter body of steel (C22).

Metal-plating copper films on the specimen of spheroidal graphite cast iron and on the counter body of steel form almost simultaneously. Figure 11 shows the microstructure and the composition of the metal-plating film on the surface of the counter body (C22).

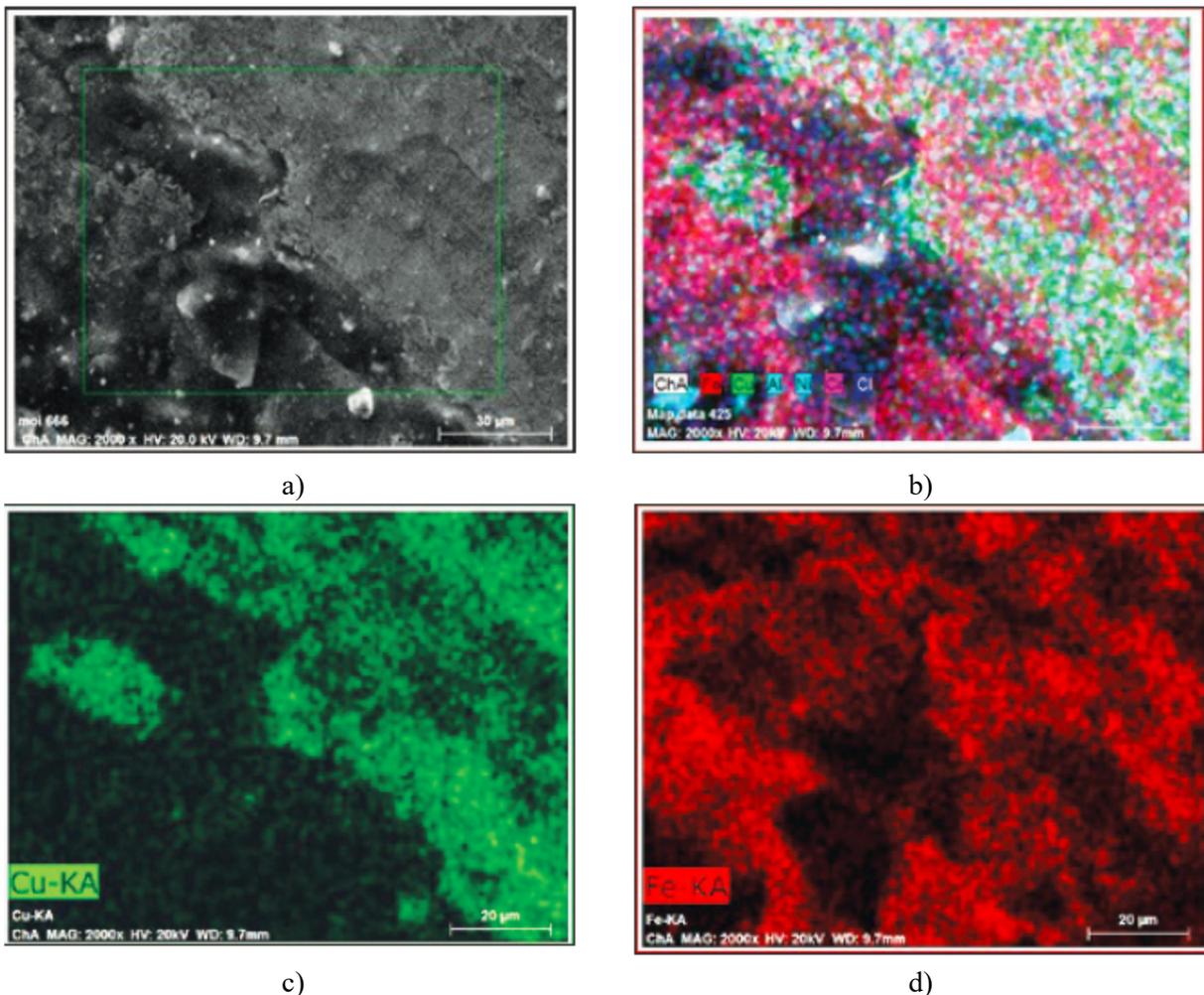


Figure 11. Microstructure (a), composition (b), microstructure with elements Cu (c), and Fe (d) in the metalplating film on the surface of the counter body (C22), after friction at $P = 10 \text{ N}$; $n = 2300 \text{ min}^{-1}$.

Roughness profiles of the surface before and after friction are obtained in radial direction of annular copper film (Figures 12, 13). The roughness of the surface before friction is $R_a = 0.466 \mu\text{m}$, and after friction the roughness of the deposited copper film is $R_a = 0.196 \mu\text{m}$.

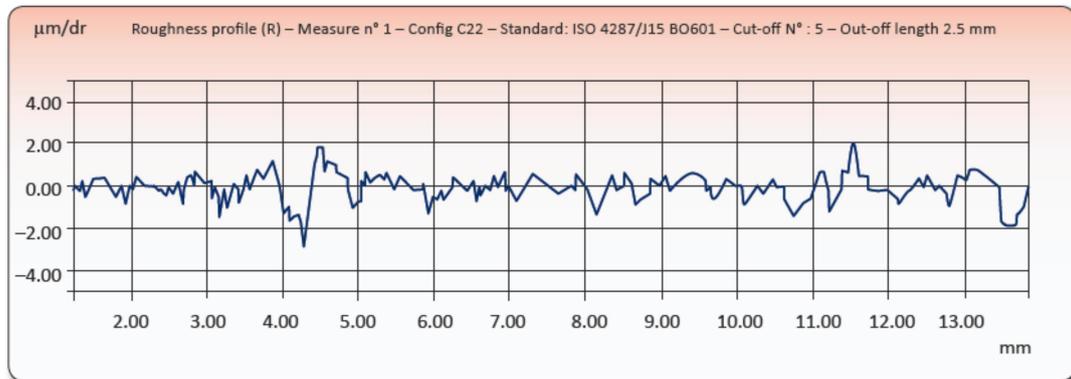


Figure 12. Profilogram of the counter body surface (C22) before wear: $R_a = 0.466 \mu\text{m}$.

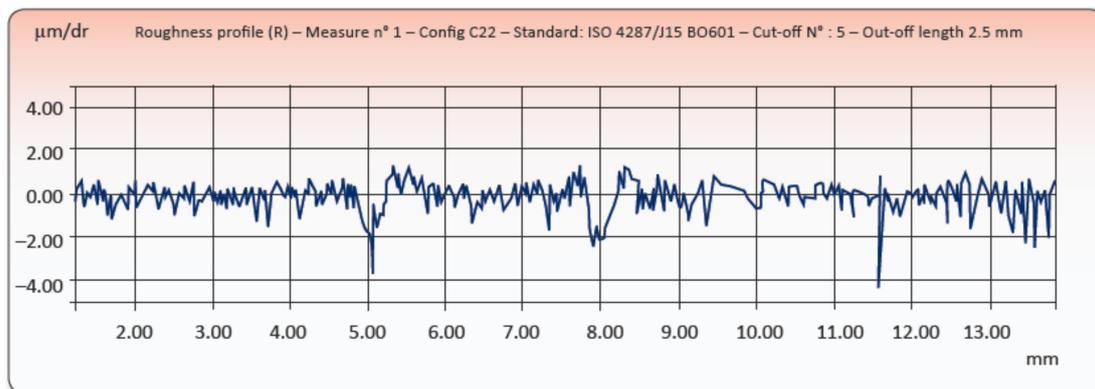


Figure 13. Profilogram of the counter body surface (C22) after wear: $R_a = 0.196 \mu\text{m}$ at friction in regime $P = 10 \text{ N}$; $n = 2300 \text{ min}^{-1}$.

The width of the copper film is determined by the profilogram. It is 6 mm, i.e., twice larger than the width of the ring. The process of selective transfer occurs not only in the contact between the specimens, but also out of the contact zone. This fact is also found in other authors' studies [20, 30, 35, 38]. It is seen in the profilogram's indication from 5 to 11.5 mm.

Copper film thickness is not uniformly distributed both in radial direction and along the length of the trail. The average thickness film value is $3 \mu\text{m}$.

Contact system "Steel – Steel" (Ст4кп – C22)

Figures 14 and 15 give the wear curves for specimen of steel Ст4кп in both regimes of friction. The influence of Valena on the character of variation is almost analogous with that in the case of spheroidal graphite cast iron micro alloyed by tin. In both regimes of friction is observed deposition of metal plating copper film upon the specimen and the counter body, which shows the presence of selective transfer process.

For the lighter regime of friction – $P = 10 \text{ N}$; $n = 2300 \text{ min}^{-1}$, effect of no-wear effect is observed, as it is in the case of spheroidal graphite cast iron specimens. The copper film thickness on the counter body is $2.5 \mu\text{m}$.

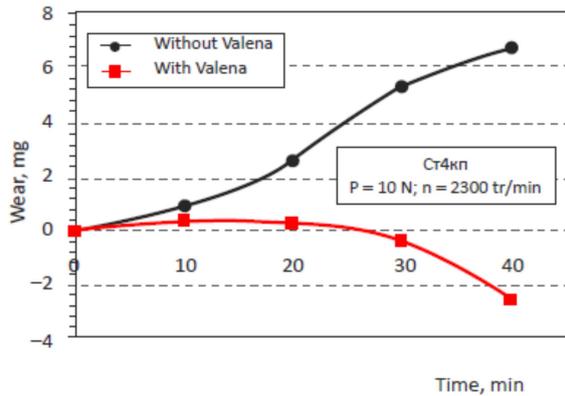


Figure 14. Influence of Valena additive on wear for Ст4кп under friction in Regime I.

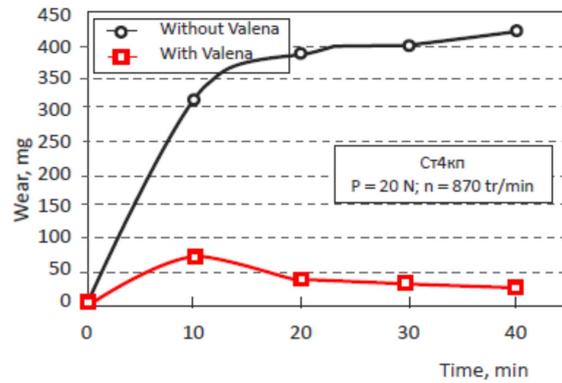


Figure 15. Influence of Valena additive on wear for Ст4кп under friction in Regime II.

The influence of Valena additive on lubricant temperature in both regimes of friction is shown in Figures 16 and 17. The increase of the temperature in both regimes decreases in the presence of Valena more than twice compared with the case without Valena additive.

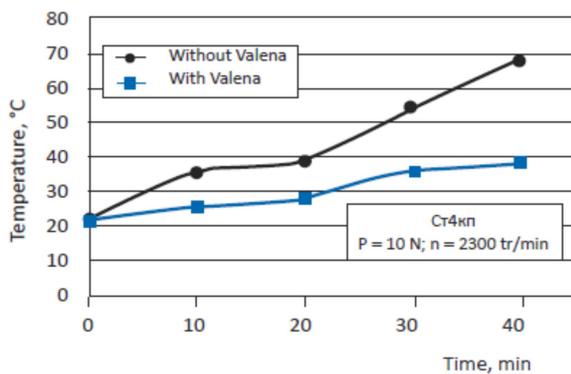


Figure 16. Variation of the temperature with time under friction in Regime I.

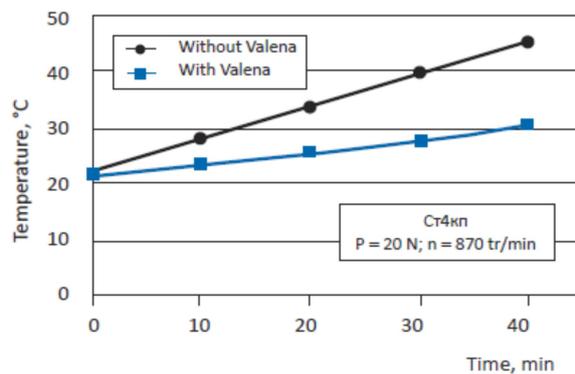


Figure 17. Variation of the temperature with time under friction in Regime II.

Contact system “Bronze – Steel” (БрАЖ9-4 – С22)

Significant wear decrease is observed during friction of bronze-steel couple in the first regime $P = 10$ N; $n = 2300 \text{ min}^{-1}$, there is, however, no effect of specimen’s mass increase as it was in the first two cases. Small wear of the bronze specimen is indicator that a selective transfer process. The thin copper film protects the surface from oxidation and destruction (Figure 18).

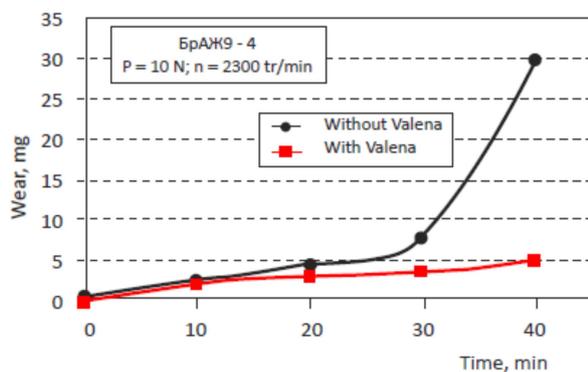


Fig. 18. Influence of Valena additive on wear of БрАЖ9-4 under friction in Regime I.

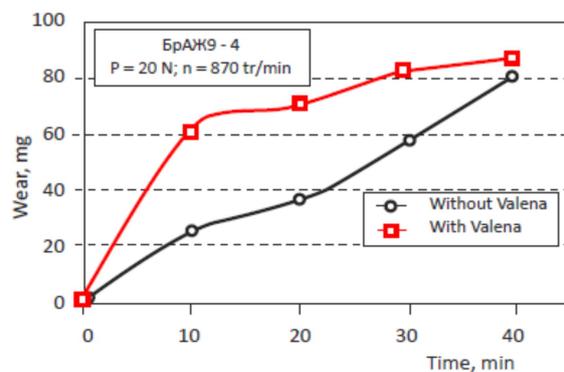


Fig. 19. Influence of Valena additive on wear of БрАЖ9-4 under friction in Regime II.

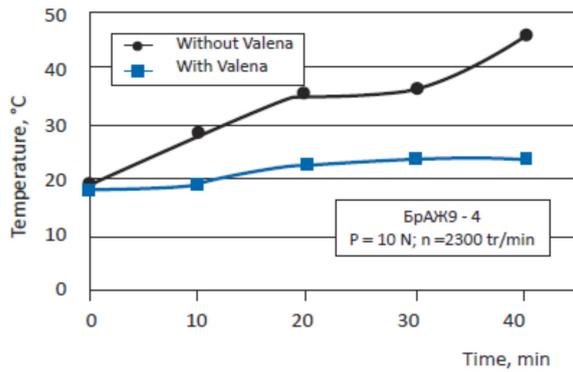


Figure 20. Variation of the temperature in time under friction in Regime I.

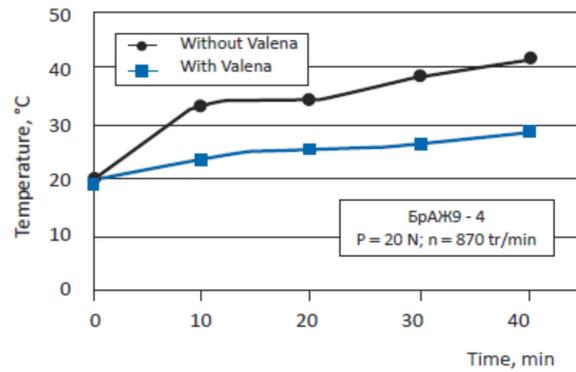


Figure 21. Variation of the temperature in time under friction in Regime II.

In the case of the second regime of friction $P = 20 \text{ N}$; $n = 870 \text{ min}^{-1}$, quite high value of bronze wear is observed in the process of running-in when Valena additive available (Figure 19). In that case, there are no favourable conditions for selective transfer occurrence. The wear increase with load increase is explained with the character of the electrochemical contact processes. Microscopic study of the surface shows that cavities with liberated hydrogen are formed in some sections under the cathode copper, which causes detachment of copper flakes. As other authors' studies also show, saturation of the surface with hydrogen takes place under these conditions, which causes brittleness in some sections of the surface. The process of extraction of alloying elements from bronze and steel is more intensive at higher load. The extracted copper transferred to the steel surface does not succeed to crystallize, and forms crumbly copper film, which is not able to protect surfaces from wear [1, 3, 14]. One more feature affects the processes in the above considered case. The plastic deformation of the surface film increases under higher pressure, the real contact area increases, and respectively, the contact interstices decrease. Lubricant penetration in contact is hindered and direct mechanical interaction between asperities occurs. So, lubricant and additive lose their functional ability. Boundary friction and intensive wear take place.

The parameter wear intensity is announced below as criterion of comparative assessment for the tested materials. It is determined by the formula:

$$i = h / L, \tag{1}$$

where $h = m/\rho.Aa$ is thickness of the worn film during friction way $L = 1 \text{ m}$. Experimental results about wear intensity of the three materials are given in Table 7.

Table 7. Wear intensity [m/m] of materials in both regimes of friction without and with Valena.

Material	Regime I $P = 10 \text{ N}$; $P_a = 0.22 \text{ MPa}$ $n = 2300 \text{ min}^{-1}$		Regime II $P = 20 \text{ N}$; $P_a = 0.45 \text{ MPa}$ $n = 870 \text{ min}^{-1}$	
	Wear Intensity			
Steel Ст4кп	Litol 24	Litol 24 with Valena	Litol 24	Litol 24 with Valena
	7×10^{-9}	No-wear <i>Copper film</i>	1.2×10^{-6}	6.6×10^{-9}
Spheroidal graphite cast iron +0.051%Sn GJS-600-3	Litol 24	Litol 24 with Valena	Litol 24	Litol 24 with Valena
	17.8×10^{-9}	No-wear <i>Copper film</i>	0.11×10^{-6}	0.04×10^{-6}
Bronze БрАЖ9-4	Litol 24	Litol 24 with Valena	Litol 24	Litol 24 with Valena
	32×10^{-9}	5.3×10^{-9}	0.2×10^{-6}	0.2×10^{-6}

Figure 22 shows diagram of wear intensity for the materials at friction Regime I.

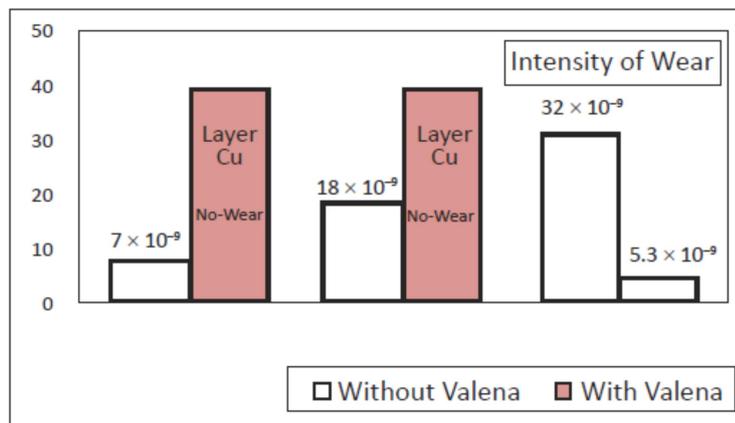


Figure 22. Wear intensity [m/m] of specimens at friction Regime I:
 $P = 10 \text{ N}$; $n = 2300 \text{ min}^{-1}$

4. Conclusions

The basic results of the present paper are:

1. Experimental data are gathered for the influence of metal-plating additive Valena on the contact characteristic of 3 types of: „GJS 600-3 - C22” (Spheroidal graphite Cast iron with 0.051%Sn – Steel), „Ст4кп - C22” (Steel - Steel) и „БрАЖ9-4 - C22” (Bronze – Steel) and their functioning at 2 friction regimes.
2. It has been found out that the additive Valena in grease Litol 24 in all three tribosystems the intensity of wear decreases and processes of selective transfer of the occur in both friction regimes.
3. In tribosystems „GJS 600-3 - C22” and „Ст4кп - C22” in friction regime at a contact pressure of $P_a=0.22 \text{ MPa}$ and revolutions of $n = 2300 \text{ min}^{-1}$ (Regime I) is observed a *no-wear effect under friction*. This effect is due to a proceeding mechanism of self-organization, where a dissipative structure is build up in the form of protective servovitic film with thickness of $2.5\div 3 \mu\text{m}$. The servovitic protective film is formed on the contact surfaces of the body and antibody of the tribosystem. The microstructure investigations of the microstructures and the chemical composition of the protective film with scanning electronic microscope shows the presence of the chemical element copper (Cu). The contact temperature decreased 2 to 4 times compared to the one in friction where there is no additive “Valena”.

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