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NON-EQUILIBRIUM SELF-ORGANIZATION OF STEEL-BRONZE TRIBOSYSTEM ON THE BASIS OF THE ACOUSTIC EMISSION METHOD

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Abstract. Directed copper to steel mass transfer caused by tribochemical activation and heat flow optimisation is researched in this article. It allows the application of selective transfer effect for contact surfaces of tribosystems without clad metal alloy injection into the lubricant environment.

Keywords: selective transfer, friction, wear, acoustic emission, self-organization.

1. Introduction

The most researched bronze-steel selective transfer in ‘quasiwearless’ mode is the formation of specific copper retaining compound in the form of metal non-oxygenation film. It is formed in alcohol-glycine fluid at the tribological contact zone. Films have low resistance shear. This leads to an increase in the friction coefficient and reduction in the wear rate (Babak *et al.* 2006). Formation of the film was observed during the transition of the tribosystem into a state of non- equilibrium in accordance with the results of the research. It occurred due to tribochemic activation that led to the development of ‘selective’ transfer process (Brater *et al*. 2006). Efforts to apply the selective transfer effect on the other classes of tribosystem materials have not given any positive result, however. It is caused by the lack of the conditions that are required for tribochemical activation in the tribosystem lubricant environment (Brater *et al*. 2006).

At the same time, published results have showed that mass transfer is possible for steel-copper tribosystems at the expense of dynamic diffusion (Brater *et al*. 2006; Гаркунов 1989; Беркович *и др*. 2000).

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Articles of V. S Ivanova *et al.* and V. Stadychenko *et al.* point out that the occurrence and development of such diffusion is possible during the transition of the surface layer of the tribosystem into a state of non-equilibrium at certain heat flow (Иванова *и др.* 1998; Стадниченко *и др.* 2006).

It can therefore be assumed that the activation of copper on steel transition was possible not only due to the tribochemical activation process (the formation of servowitte film when clad metal alloys are injected into the lubricant) but also due to heat flow control.

2. Experimental research

Steel 0.4C and bronze 9Al-Fe friction pair specimens were used for wear rate research. These materials were chosen due to their wide application in rolling bearings of positive-displacement hydraulic machines (Иванова 1992). The dimensions, condition of working surface, and heat treatment of specimens met the requirements of DST 9490-70. The chemical composition of specimens is given in table 1.

Testing the wear resistance of specimens was carried out on a universal automated tribodiagnostic complex (Пашечко 2000). The ‘disk to disk’ set-up imitates the actual friction pair operation of a positive-displacement hydraulic machine. Sliding friction mode with stationary disk was used during research. The stationary specimen was made of bronze 9Al-Fe. A steel 0.4C specimen was used for the movable one. The dimensions of the research specimen were thus: diameter D_{sam} = 25mm, thickness L=15mm.

The load pattern applied initiated linear Hertzian contact at the beginning of research. It is well known that the nominal contact area changes considerably during the triboprocess. That can influence the regularity of wear phenomena. In order to avoid this factor, the initial breaking-in of the specimen was carried out. It is described below.

The lay-out of the preceding breaking-in of positive-displacement hydraulic machine is given in table 1. Abrasive belt 4 and bearing 3 by means of spring 5 and screw 6 were placed on the lower roller 2 (Fig 1). After the tribometer was switched on, the abrasive belt rotated together with the lower roller and aged the upper stationary roller 1. This resulted in the creation of a working surface on the upper roller. Such breaking was carried out until the contact area reached S=20 mm^2. Applied loading was P=50N, and the rotational speed of the friction machine drive shaft was 5 s^{-1}. Aviation lubricant B-3V was used.

Table 1. The chemical composition of tribosystem materials

Steel 0.4C-Cr	C	Si	Mn	Ni	S	P	Cr	Cu
	0.36-0.44	0.17-0.37	0.50-0.080	up to 0.30	up to 0.035	up to 0.035	0.80-1.10	up to 0.3
Bronze 9Al-Fe	As	Sb	Sn	Si	Ni	Fe	Zn	Mn
	0.05	0.05	0.2	0.2	1.0	-	1.0	0.5

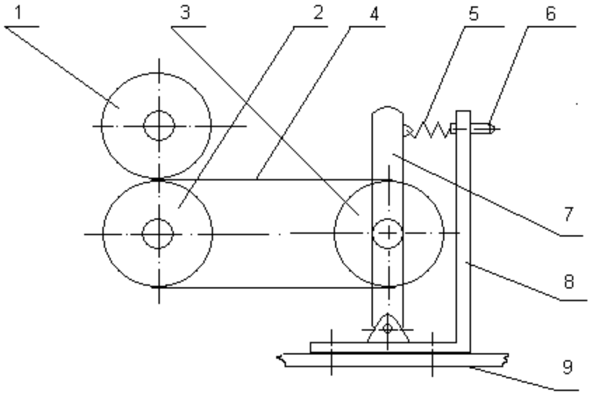


Fig 1. Lay-out of the of the tribosystem grinding specimen equipment. 1 – upper stationary roller, 2 – lower movable roller, 3 – bearing, 4 – abrasive belt, 5 – spring, 6 – screw, 7 – lever, 8 – leg, 9 – friction machine casing

Friction and wear resistance tests were held in a chamber that was a part of an automated tribodiagnostic system (ATDS) (Пашечко 2000). The ATDS allowed continuous recording of triboparameters to be carried out by means of a PC and regulated the temperature in effective volume of interworking Pyrometrical sensors were used to measure temperature. Acoustic emission (AE) recording was carried out during the friction process in accordance with the methods applied in V. Stadnychenko paper (Стадниченко 2006). The wear rate was determined by a mass method meeting the requirements of TU25-06.1131-79.

The tests were performed in two stages. At first, the tribosystem self-organisation equilibrium process was researched. Heat dissipation caused by friction from both specimens developed due to heat exchange convention. The load was changed during tests in accordance with the program and was equal to 800N, 1800N, and 800N. The tribosystem working time was 80 minutes during each load applied. The total continuous test lasted 4 hours.

In the second stage, a wear resistance testing method was chosen taking into consideration the creation of conditions for non-equilibrium self-organisation during energy mass transfer (Бабак *и др.* 2004; Стадниченко *и др.* 2007). It should be mentioned that non-equilibrium self-organisation took place after the end of tribosystem breaking-in when its condition became stable and reached equilibrium. For each series of tests, 80°C was maintained, as it was necessary for the process. Heating the lower part of the chamber and cooling the upper part of the chamber throughout all experiments achieved it. The load within the test varied and was equal to 800N, 1600N, and 800N. The tribosystem operation time was 80 minutes during each load applied. The total time for the test was 4 hours.

The recordings of friction moment M_{fr}, temperature T of tribosystem contact area, average AE signal power W_{av}, boundary layer thickness h, and wear out index I_m were carried out during both stages.

Specimen ratios of friction moment and temperature that were recorded at the first stage of research are given in figure 2. The specimen ratio of average AE power change recorded during tribosystem steel 0.4 C-Cr-bronze 9Al-Fe equilibrium self-organisation is given in figure 3.

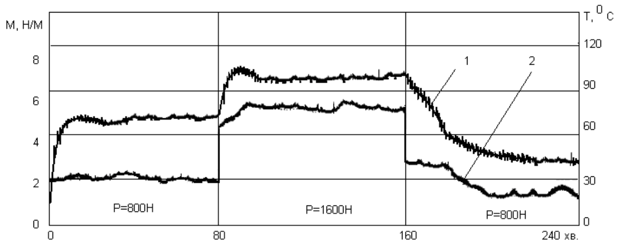


Fig 2. Ratio of friction moment and temperature (T) in contact area during steel 0.4 C-Cr-bronze 9Al-Fe tribosystem equilibrium self-organisation test. 1 – temperature, 2 – friction moment

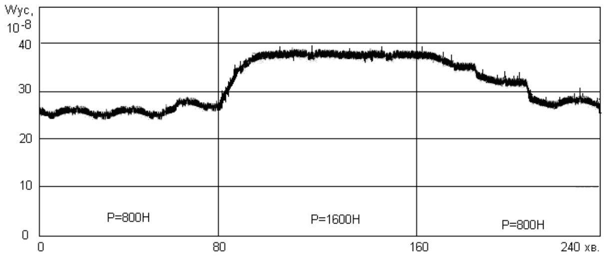


Fig 3. Ratio of average AE power change during steel 0.4 C-Cr-bronze 9Al-Fe tribosystem equilibrium self-organisation test

Specimen changes in friction moment and temperature ratio which were recorded at the second stage of research (non-equilibrium self-organisation) are shown in figure 4. The specimen ratio of average AE power change recorded during steel 0.4 C-Cr-bronze 9Al-Fe tribosystem non-equilibrium self-organisation is given in figure 5.

The wear rate of steel and bronze specimens is given in table 2 together with the total tribosystem wear rate with various surface layer self-organisation states.

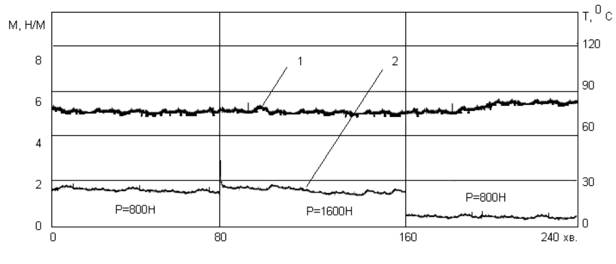


Fig 4. Specimen ratios of friction moment (M_{fr}) and temperature (T) in contact area during steel 0.4 C-Cr-bronze 9Al-Fe tribosystem non-equilibrium self-organisation test. 1 – temperature, 2 – friction moment

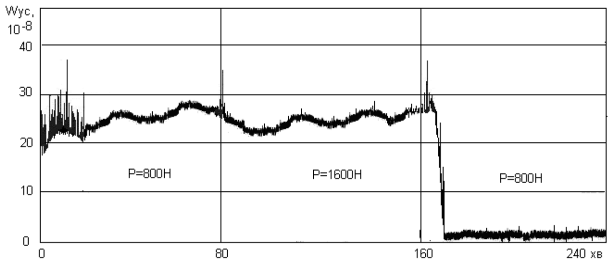


Fig 5. Average power ratio of AE during steel 0.4 C-Cr-bronze 9Al-Fe tribosystem equilibrium self-organisation test

Table 2. Linear wear rate of tribosystem elements

Self-organisation mechanism	Total wear ratio	Steel specimen wear ratio	Bronze wear ratio
Equilibrium self-organisation	288×10^{-10} m/m	70×10^{-10} m/m	218×10^{-10} m/m
Non-equilibrium self-organisation	54×10^{-10} m/m	12×10^{-10} m/m	42×10^{-10} m/m

Results of the equilibrium self-organisation tests proved that the regularity of changes of contact area friction moment, temperature, and average AE power ratio is repeated with the change in the operating load. Stages that correspond to friction pair working stages during different working loads are clearly shown in all diagrams (Figs 2, 3). When the working load applied to the tribosystem increased from 800N to 1600N, a significant increase in average M_{fr}, T, and W_{av} was therefore observed. Stabilisation of all abovementioned parameters took place when secondary breaking-in of the tribosystem was carried out. With further working load decrease from 1600N to 800N, the average parameters dropped to a level that is lower than it was with initial 800N applied. M_{fr}, T, and W_{av} average value at the stages of stabilisation were given in table 3.

Results of the non-equilibrium self-organisation tests proved that the regularity of changes in contact area friction moment, temperature, and average AE power is repeated with the change in working load. Essential increase in M_{fr} and W_{av} parameters was observed upon the change in applied load. Average value of M_{fr} and W_{av} did not however change considerably with applied load increase from 800N to 1600N. This concerns not only the moments when the load increases, but also the stabilization stage of this value when secondary breaking-in was finished (Figs 4, 5). Secondary breaking-in time with change in applied load was considerably less, than secondary breaking-in time of the tribosystem during contact area equilibrium self-organisation (Tab 4). With further working load decrease from 1600N to 800N, the average ratio of these parameters dropped to a level that was lower than it was with initial 800N applied. Insignificant change in temperature was observed, though. At the same time, M_{fr} had considerably less value than M_{fr} during the same stage of friction pair equilibrium self-organisation. M_{fr}, T, and W_{av} average value at their stages of stabilisation are given in table 4.

Table 3. Average value of tribosystem parameters during equilibrium self-organisation

Applied load	Friction moment Mfr N/m	Tribocontact area temperature T^0C	Average AE power $W_{av}\ 10^{-8}$ W
800	2.0	68	26
1600	5.7	104	38
800	1.6	36	26

Table 4. Average value of tribosystem parameters during non-equilibrium self-organisation

Applied load	Friction moment Mfr N/m	Tribocontact area temperature T^0C	Average AE power $W_{av}\ 10^{-8}$ W
800	1.8	80	26
1600	1.8	80	26
800	0.4	80	2

The result obtained confirmed that the contact area changes into ‘quasiwearless’ state during non-equilibrium self-organisation. This was proved by metallographic examination and chemical analysis.

3. Factographic research of friction contact areas

Factography and chemical analysis of the friction area showed the following results. Chemical composition of both steel 0.4 C-Cr and bronze 9Al-Fe differed from the original specimens insignificantly in terms of percentage correlation (Tab 5). $CH+O_2$ percentage in the specimens’ superficial layers was measured by means of a Link 860 microanalyzer in the normalisation mode of operation.

From the results received, we can see that the lead from the bronze specimen surface layer diffused. An increase in the percentage of sulphur in the steel specimen from 0.035 % to 0.141 % was observed. CH hydroxyl group specified the standard mechanochemical friction area wear and oxygen enrichment of tribosystem surface layers occurs upon tribosystem equilibrium self-organisation.

For steel and bronze, CH and O_2 were 5.324 % and 2.184 % correspondingly (Tab 5). The bronze specimen of tribosystem equilibrium self-organisation in the surface layer showed a higher wear rate than the steel specimen. The wear rate for the bronze specimen was 3.142 times higher than it was for the steel specimen.

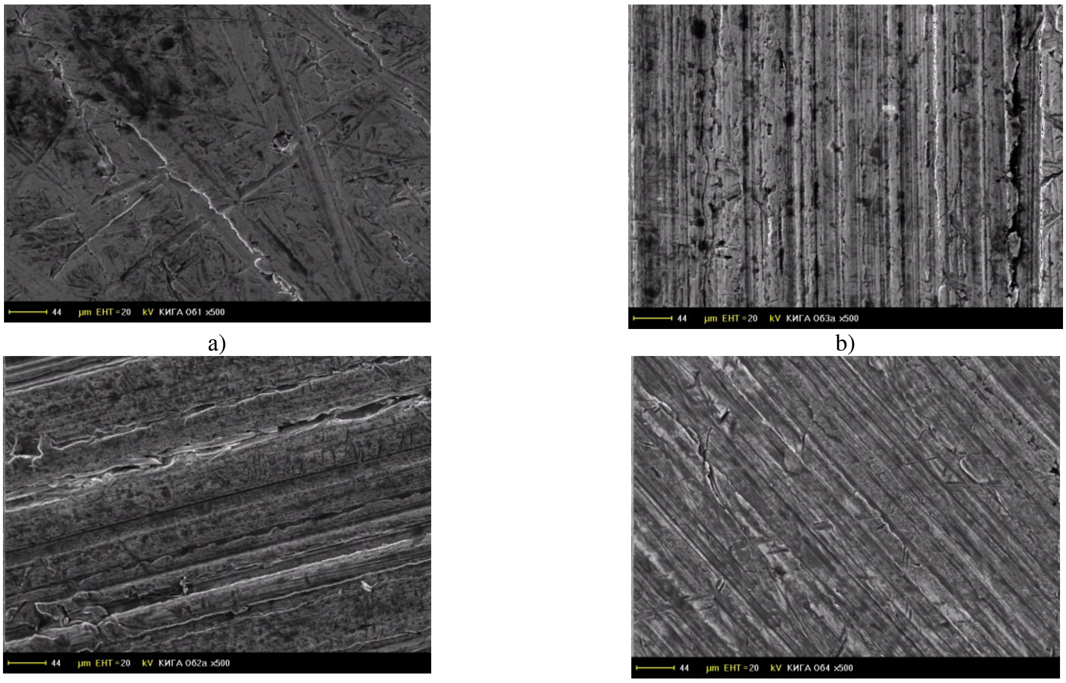
Steel 0.4 C-Cr - bronze 9Al-Fe friction contact area factographies in different self-organisation mechanisms were given at figure 6. Analysis of the bronze specimen surface in equilibrium self-organisation state indicated the charging of its surface with wear particles of the steel specimen (Fig 6, c). The mechanochemical form of abrasive wear occurred.

Physicochemical research of tribosystem surface layers in equilibrium and non-equlibrium self-organisation state have demonstrated essential differences in the chemical composition of friction surfaces before and after the beginning of wear resistance testing.

Silicon in the surface layer of steel specimen after its non-equilibrium self-organisation decreased from 0.37 % to 0.137 %. At the same time, sulphur concentration increased from 0.035 % to 0.430 %. This was caused by EP additives in the B-3Vlubricant. Copper concentration on the surface of the steel specimen increased considerably: from 0.123 % to 8.425 %. It surpassed copper concentration on the surface of the steel specimen in equilibrium self-organisation state considerably (0.220 %). The appearance of zinc (0.250 %) on the surface of the steel specimen in non-equilibrium self-organisation state should be mentioned.

Table 5. Tribosystem chemical composition at the initial stage of investigation and with the change in the self-organisation mechanism of the surface layers

<table>
<tr><td colspan="11">Initial chemical composition of tribosystem elements</td></tr>
<tr><td rowspan="2">Steel 0.4C-Cr</td><td colspan="2">C</td><td>Si</td><td>Mn</td><td>Ni</td><td>S</td><td>P</td><td>Cr</td><td colspan="2">Cu</td></tr>
<tr><td colspan="2">0.36-0.44</td><td>0,17-0,37</td><td>0,50-0,080</td><td>Up to 030</td><td>Up to 0.035</td><td>Up to 0,035</td><td>0,80-1.10</td><td colspan="2">0.123</td></tr>
<tr><td rowspan="2">Bronze 9Al-Fe</td><td colspan="2">As</td><td>Sb</td><td>Sn</td><td>Si</td><td>Ni</td><td>Fe</td><td>Zn</td><td>Mn</td><td>Cu</td></tr>
<tr><td colspan="2">0.05</td><td>0.05</td><td>0.2</td><td>0.2</td><td>1.0</td><td>-</td><td>1.0</td><td>0.5</td><td>97</td></tr>
<tr><td colspan="11">Chemical composition of tribosystem elements in equilibrium self-organisation state</td></tr>
<tr><td rowspan="2">Steel 0.4C-Cr</td><td colspan="2">CH+O₂</td><td>Si</td><td>Mn</td><td>Ni</td><td>S</td><td>P</td><td>Cr</td><td colspan="2">Cu</td></tr>
<tr><td colspan="2">5.324</td><td>0.29</td><td>0.521</td><td>0.184</td><td>0.141</td><td>0.000</td><td>0.927</td><td colspan="2">0.220</td></tr>
<tr><td rowspan="2">Bronze 9Al-Fe</td><td>As</td><td>CH+O₂</td><td>Sb</td><td>Sn</td><td>Si</td><td>Ni</td><td>Fe</td><td>Zn</td><td>Mn</td><td>Cu</td></tr>
<tr><td>0</td><td>2.184</td><td>0.000</td><td>0.737</td><td>0.186</td><td>0.730</td><td>-</td><td>0.970</td><td>0.384</td><td>95.124</td></tr>
<tr><td colspan="11">Chemical composition of tribosystems elements in non-equilibrium self-organisation state</td></tr>
<tr><td rowspan="2">Steel 0.4C-Cr</td><td colspan="2">CH+O₂</td><td>Si</td><td>Mn</td><td>Ni</td><td>S</td><td>P</td><td>Cr</td><td>Cu</td><td>Zn</td></tr>
<tr><td colspan="2">24.446</td><td>0.137</td><td>0.448</td><td>0.772</td><td>0.430</td><td>0.052</td><td>0.841</td><td>8.425</td><td>0.250</td></tr>
<tr><td rowspan="2">Bronze 9Al-Fe</td><td>As</td><td>CH+O₂</td><td>Sb</td><td>Sn</td><td>Si</td><td>Ni</td><td>Fe</td><td>Zn</td><td>Mn</td><td>Cu</td></tr>
<tr><td>0</td><td>25.373</td><td>0.000</td><td>1.354</td><td>0.176</td><td>0.312</td><td>-</td><td>1.123</td><td>0.386</td><td>91.384</td></tr>
</table>



a) b)

c) d)

Fig 6. Microphotography of friction surfaces. Steel 0.4 C-Cr - bronze 9Al-Fe tribosystem: a) steel 0.4 C-Cr in equilibrium self-organisation; b) steel 0.4 C-Cr in non-equilibrium self-organisation; c) bronze 9Al-Fe in equilibrium self-organisation; d) bronze 9Al-Fe in non-equilibrium self-organisation

The abovementioned change in the chemical composition of the steel specimen friction area indicated copper and zinc mass transfer from the surface of the bronze specimen. For such a wear mechanism occurring during the abovementioned mass transfer, it was impossible to refer to the first or the second capturing wear type because this friction area was considerably smoothed (Fig 6 b, d).

Analysis of the steel specimen friction area also indicated a considerable increase in the percentage of CH and O_2 in the surface layer: from 5.324 % in equilibrium self-organisation state to 24.446 % in non-equilibrium self-organisation state (Tab 5). Similar changes were typical for the ratio of CH and O_2 on the surface of the bronze specimen. In this case, CH and O_2 ratio increased from 2.184 % to 25.373 % in non-equilibrium self-organisation state (Tab 5).

Thereby the porosity of friction areas in both steel and bronze specimens in non-equilibrium self-organisation state increased. Porosity has the capacity to deform without destruction. In addition to that, such structure can absorb lubricant due to capillarity effects (Пашечко *и др*. 2001). It should be mentioned that considerable porosity of friction contact area structure is also typical for surface layers of friction pairs during selective mass transfer (Радин *и др*. 1989). Mass transfer and porosity increase explained the absence of M_{fr} and W_{av} (wear ratio) increase of loading from 800N to 1600N in the non-equilibrium self-organisation state of the tribosystem. It also explained the further considerable decrease in these values during tribosystem not loading to the initial level of 800N (Figs 4, 5).

4. Conclusion

Thereby conditions for directed bronze to steel mass transfer could be created not only by means of controlling the tribochemical activation process, but also by heat flow optimisation. This gives the opportunity to apply the selective mass transfer effect for materials in the friction contact area of tribotechnical systems without clad metal alloy injection into the lubricant.

In this case, tribosystem self-organisation could be applied by means of consecutive transfers (Fig 7).

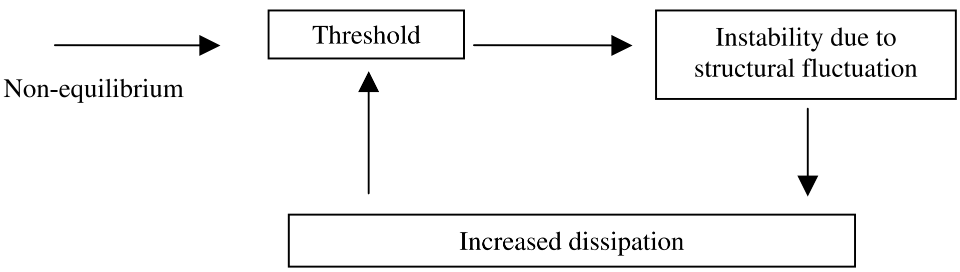


Fig 7. Development of energy dissipation mechanism during tribosystem change into quasiwearless state

This implies that the occurrence of excessive dissipation of energy determines the type of tribosystem durability P[δS]. It should also be mentioned that marking for excessive dissipation of the energy ratio could be determined by conditions of energy dissipation at the friction contact surface.

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PLIENO-BRONZOS TRIBOSISTEMOS NEPUSIAUSVYROS SAVAIMINIS SUFORMAVIMAS AKUSTINIU SPINDULIAVIMO METODU

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Santrauka

Darbe pateiktas kryptinių vario masės mainų tyrimas, kai varis pernešamas link plieno ne tik dėl tribocheminio aktyvinimo, bet ir dėl šilumos srauto oprtimizavimo. Tai leidžia pritaikyti „rinktinių mainų” efektą nepanardinant tribosistemos kontakto paviršiaus medžiagos į aliejinių mišinių, skirtų metalo padengimui, terpę.

Reikšminiai žodžiai: rinktiniai mainai, trintis, nusidėvėjimas, akustinė emisija, savaiminis susiformavimas.