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TRIBOLOGICAL CONTACT IN MATERIALS SYSTEMS "CuCrNiZrTi - M500", "CuCrNiZrTi - 5140H", "CuCrNiZrTi - 3310H"

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The limited information on the manifestation of the parameters of the molecular component of friction - the shear strength of the adhesive bond τ_0 and the piezoelectric coefficient β of the molecular component for each specific study predetermines the use of purposeful determination of parameters by modeling shear on small-sized samples in order to increase the objectivity and accuracy of the result assessment. The article poses the task of conducting definitive tribotechnical tests of the high-entropy alloy to assess its adaptability to loading and lubrication conditions during contact with steel, cast iron and to establish the nature of the manifestation of the parameters of adhesion properties by modeling shear on small samples. It was found that under conditions of drop lubrication, the surfaces of the samples of the studied materials appear to be compatible and are satisfactorily run-in. In this case, the parameters of high-speed and force loading determine the manifestation of boundary lubrication. The time reaching the steady-state friction mode is practically the same for all systems, and is observed after 7.5 minutes. The obtained graphic patterns and parameters of their mathematical approximation made it possible to determine the nature of the change in the adhesive properties of a high-entropy alloy with a change in shear rates.

***Keywords**: system of materials, coefficient of friction, piezo coefficient, shear, tangential strength, lubrication formation*

Introduction

This work is a continuation of work [1], which shows the importance of having numerical values of the parameters of adhesion properties directly for the surfaces of metals of full-scale operational friction units of machines and mechanisms with reversible movement, ie. in which there is a shear with a certain speed of movement, when the manifestation of the molecular (adhesive) component of the friction force has time to manifest itself. According to the authors of [2], a distinctive feature of high-entropy alloys (HEA) from traditional alloys is that these alloys have a high entropy of mixing, which affects the formation of structures based on solid solutions. A little over 15 years have passed since the discovery of high-entropy alloys.

1. Analysis of publications

The first review is made in the form of a complete materials science cycle "production - structure - properties" for a new class of vacuum-plasma coatings - nitrides of multi-element high-entropy metal alloys, information is given in [3]. The analysis of the current state of production of such coatings, their morphology, elemental and phase composition, structure, substructure, stress state and functional properties, depending on the main parameters of the formation: substrate temperature during deposition; the value of the applied bias voltage; substrate, as well as the composition of the gas atmosphere. Then there were many articles on the synthesis and study of various high-entropy alloys [4-10].

The last review of HEA was made in [11]. Analysis of more than 200 obtained high-entropy alloys (HEAs) made it possible to establish the relationship between the electron concentration, phase composition, lattice parameter, and properties of solid solutions based on bcc, fcc lattices. The main conditions for the appearance of high-entropy chemical compounds - the Laves phase, σ- and μ-phases, have been identified. For the formation of a 100% high-entropy σ-phase, it is necessary that all the elements that make up high-entropy alloys form the σ-phase in two-component alloys in a different combination, and the electron concentration of the alloy should be in the range of 6.7-7.3 electron/atom.

For the formation of a 100% high-entropy Laves phase, the following conditions are necessary [11]:

- total negative enthalpy of mixing of the alloy at the level of -7 kJ/mol and below;
- the presence of a pair with an atomic difference of more than 12 %;
- in the presence of two elements in the alloy with the enthalpy of mixing less than 30 kJ/mol, the average concentration of electrons should be in the range of 6-7 electron/atom.

In [11] it is shown that the ratio of the lattice parameters of a solid-state HEA, determined in the experiment, to the lattice parameter of the most refractory metal of the HEA determines the value of the elastic modulus. The values of the modulus of elasticity predetermine the manifestation of the mechanical properties of the HEA in contact with other structural materials. Revealing the features of the manifestation of the service properties of newly created materials, which include HEAs, is relevant in the development of materials science and tribological aspects of ensuring the reliability of friction pairs of various mechanical engineering objects. As an option, it is proposed to consider the feasibility of using HEAs in the manufacture and repair of parts, for example, such mechanical engineering objects as cars, tractors and others.

The purpose of this work is to conduct definitive tribotechnical tests of the high-entropy CuCrNiZrTi alloy to assess its adaptability to loading and lubrication modes during contact interaction with steel, cast iron and the manifestation of the parameters of adhesion properties by modeling shear on small samples.

2. Research methodology

To prepare the CuCrNiZrTi target, micropowders of the corresponding metals were taken and mixed in equiatomic proportions. Then the prepared powder mixture was placed in a grinding jar of a planetary ball mill made of tungsten carbide, and grinding bodies were added. Grinding bodies are balls with a diameter of 5-10 mm, also made of tungsten carbide, the mass of which was equal to 10 masses of the powder mixture.

Then the grinding bowl was filled with a gasoline galosh, the lid was tightly closed, and the planetary ball mill was turned on (rotation speed 500 min^{-1}, operating time 5 hours). The resulting homogenized composition was dried under vacuum and pressed to form the composition into a flat disc 100 mm in diameter and 5 mm thick. Then the disk was placed in a vacuum thermal furnace and baked in it for 3 hours. Next, the fabricated target of CuCrNiZrTi (Fig. 1a) was used to deposit a magnetron coating on an NNV-6.6I1 setup. The coating was carried out on prepared substrates of AISI-201 steel (hexagons with a side length of 22 mm and a thickness of 5 mm). The vacuum chamber was evacuated to a pressure of 0.003 Pa, then a hot cathode plasma source (PSWHC) was turned on, argon was injected to a pressure of 1 Pa, a negative bias potential of 1000 V was applied to the substrate, and the substrate surface was cleaned and heated for 10 minutes. After that, the argon pressure was lowered to 0.1 Pa and the magnetron was turned on. The bias potential on the substrate was reduced to 150 V, the magnetron current was kept constant at a level of 3 A. The substrate was placed in the chamber at a distance of 15 cm, and the deposition time was 1 hour.

The phase composition and structural parameters of the samples were studied on an XRD-6000 diffractometer using CuK_{α} radiation (Fig.1b). Phase composition of CuCrNiZrTi coating (table 1). Let's discuss this composition.

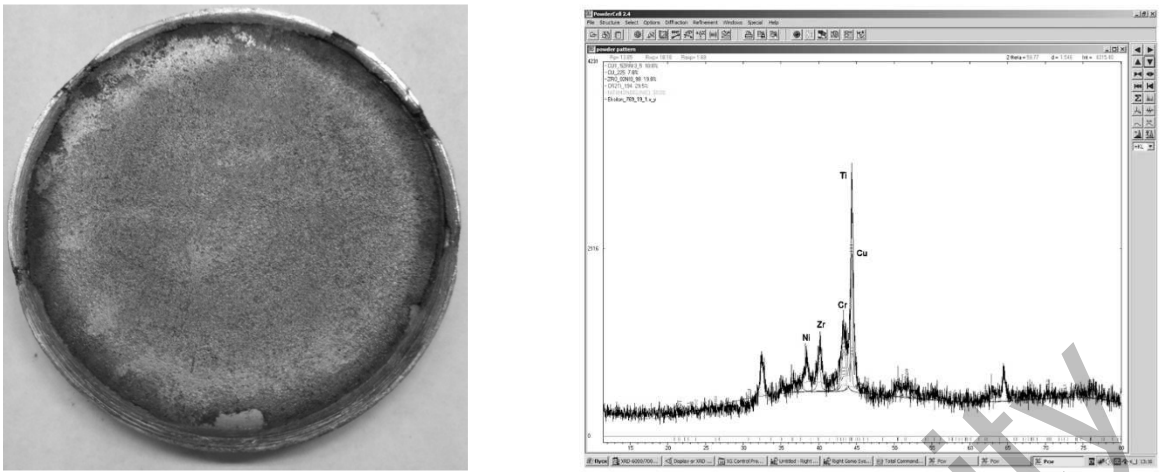
The first is $Cu_{1.5}ZrNi_{3.5}$ with a phase content of 10 at. % and with a lattice constant a = 6.7671 Å. According to [12, 13], $Cu_{1.5}ZrNi_{3.5}$ has the B2 structure, a high-temperature austenite phase ordered according to the CsCl type (Pm3m-fcc).

In second place is Cu with a phase content of 7.8 at. % and lattice constant a = 3.6178 Å. Unit cell of fcc copper.

In third place is $Zr_{0.02}Ni_{0.98}$ with a phase content of 19.8 at. % and lattice constant a = 3.3406 Å. According to X-ray spectral analysis, the main component of the eutectic is a combination of nickel and zirconium. The eutectic component is identified as a ZrNi intermetallic compound with an fcc lattice corresponding to the space group F43m (sphalerite type).

The fourth place is occupied by $TiCr_2$ with a phase content of 29.5 at. % and lattice constant a = 4.9076 Å and c = 15.9700 Å. Intermediate phases with a Laves structure are formed near the $TiCr_2$ composition [14].

In fifth place is NiTi with a phase content of 33 at. % and the lattice constant a = 2.8007 Å, b = 4.6192 Å, c = 4.1824 Å, β = 97.5793. According to [15], the results of neutron diffraction studies of quenched alloys in the initial austenitic and martensitic states show that the $Ti_{49.5}Ni_{50.5}$ alloy is in the austenitic state at room temperature.



a) b)

Fig. 1 Target CuCrNiZrTi for magnetron (a), phase composition of CuCrNiZrTi coating (b)

Table 1. The phase composition of the coating

Sample	Detected phases	The content of phases, at. %	Lattice parameters, Å
CuCrNiZrTi	$Cu_{1,5}ZrNi_{3.5}$	10	a = 6,7671
	Cu	7.8	a = 3,6178
	$Zr_{0.02}Ni_{0.98}$	19.8	a = 3,5406
	$TiCr_2$	29.5	a = 4,9076 c = 15,9700
	NiTi	33	a = 2.8007 b=4.6192 c = 4.1824 β=97.5793
	Possible phase presence ZrNi, Cu_3Ti_2		

Its crystal lattice parameter B2 (a) and the degree of long-range atomic order (η) turned out to be equal to a = 0.30125 nm; η = 1.00 ± 0.05. On the contrary, the $Ti_{50.5}Ni_{49.5}$ alloy at room temperature is in the martensitic state B19', which unambiguously follows from the interpretation of the neutron diffraction pattern and makes it possible to determine its parameters: a = 0.2903 nm, b = 0.4112 nm, c = 0.4636 nm , β = 97.25. The NiTi we observed turned out to be martensite with the B19 'structure. Thus, of the five phases of the CuCrNiZrTi coating, three have an fcc structure, $TiCr_2$ gives the Laves phase, and NiTi gives martensite with the B19'structure.

Electron microscopy was performed on a TESCAN MIRA 3 scanning electron microscope. Figure 2 shows the XPS of the coatings and Table 2 shows the chemical composition.

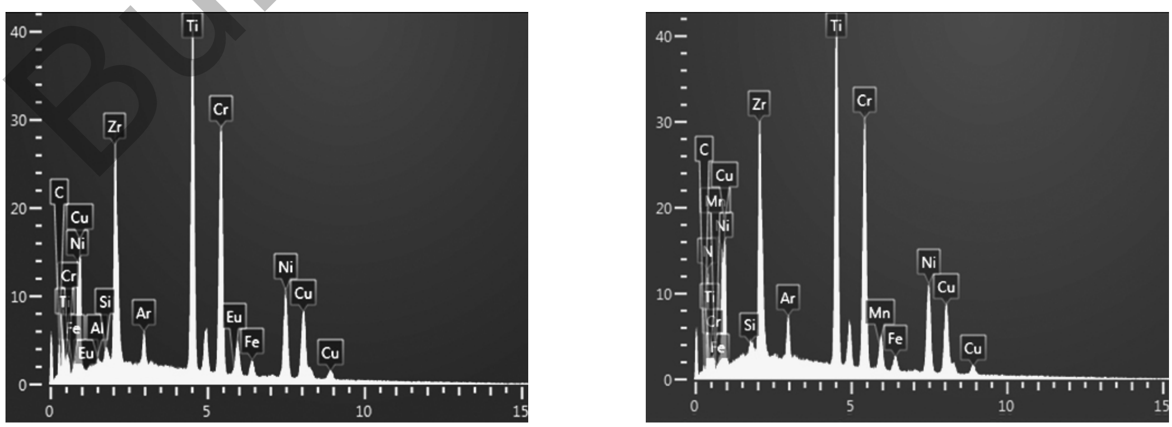


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Fig. 2. XPS of CuCrNiZrTi in argon at 2 points (no difference)

Table 2. Quantitative chemical composition of CuCrNiZrTi, %

Element	Zr	Ti	Cr	Ni	Cu
Nominal	20	20	20	20	20
in argon	23.2	21.2	19.9	17.1	6.8
in nitrogen	22.8	20.8	19.7	16.9	7.0

Tribotechnical tests were carried out on a friction machine SMTs-2 in two stages on small-sized samples according to the friction pattern "movable disk - fixed block", Figure 3. At the first stage, the surfaces were run-in at a rotational speed of the movable disk n = 300 min-1, a stepwise loading of the contact with a normal force of 22 N, 45 N, 90 N, 140 N, 180 N, 230 N and holding at each of the loads for 3 min. The oil was fed into the friction zone by a drop method. In this case, both the micro-profile of the contact zones of the surfaces of the materials and the lubricating formations screening them were formed. At the second stage, the assessment of the manifestation of the properties of lubricating formations was carried out without oil supply. The rotational speed of the movable disk was n = 300 min^{-1}. The stepwise loading of the contact was carried out with a normal force of 22 N, 45 N, 90 N, 140 N, 180 N, 230 N, 275 N, 320 N and holding at each of the loads for 2 min. At the same time, abundant grease was preliminarily removed from the surfaces of both samples. Thus, conditions were created for modeling the operation of the contact zones of the surfaces of materials through the formed lubricating formations. With a clear increase in resistance to movement, recorded by the recorder, the test was suspended. In case of manifestation of pathological wear accompanied by noise effects, oil was supplied to the friction zone, and the surfaces were again run-in to steady friction.

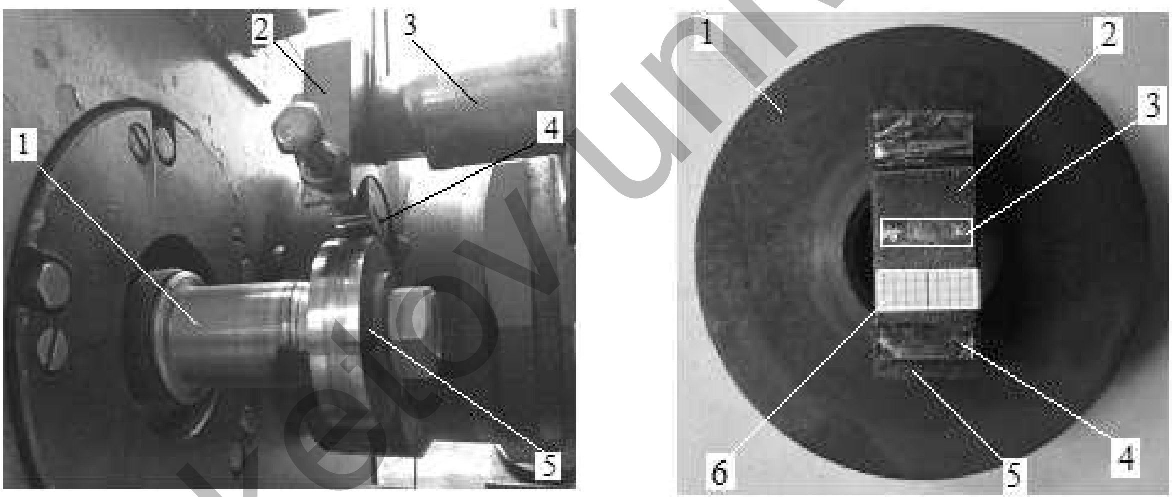

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Fig. 3. Methodological support of tribotechnical tests: a - model interface "movable disk - fixed block": 1 - lower shaft; 2 - upper shaft holder; 3 - upper shaft; 4 - sample - block; 5 - sample - disk; b - samples: 1 - disk; 2 - block; 3 - wear mark; 4 - sealant; 5 - shoe holder; 6 - measuring ruler

Transmission oil TAD-17I 85W90 with dynamic viscosity μ = 0.106 Pa•s at 50 ºC was used as a lubricant. Samples - disks d = 50 mm, b = 12 mm were made of the following materials:

- steel 5140H, 229 HV;
- steel 3310H, 116 HV;
- cast iron M500, 200 HV.

Samples - pads 9x15x3 were made of high-entropy alloy CuCrNiZrTi (890 HV). The assessment of the wear of the pads was carried out according to the energy intensity of wear Im(mg•J^{-1}), taking into account the determination of the work of friction forces at each stage of tribotechnical tests in accordance with the procedure described in [17]. In this case, the values of the wear of the pads by weight and the values of the coefficient of friction at each of the test stages were used. Taking into account the fact that the weight loss of the block samples was determined at the end of the second stage, the energy intensity of wear was presented as a generalized average.

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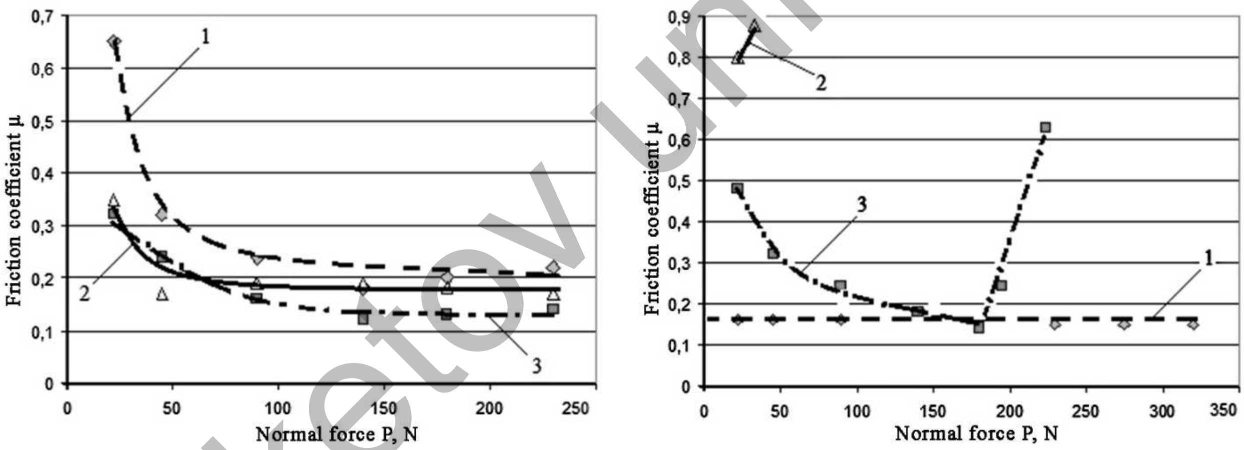
The parameters of the adhesive bond were evaluated on a friction machine SMTs-2 with additional equipment in accordance with the procedure described in [1]. To estimate the pressure in the contact zone and the tangential shear strength, we used the average values of the contour areas, which were determined from the indentations. The values of the areas for tribosystems of materials at the end of the second stage of testing were: "CuCrNiZrTi - 5140H" S_1 = 9.5±0.5 mm^2; "CuCrNiZrTi - 3310H" S_2 = 7.5±0.5 mm^2; "CuCrNiZrTi - M500" S_3 = 12.5±0.5 mm^2. To assess the parameters of adhesion without lubricant, the surfaces were thoroughly degreased with gasoline "Kalosha".

3. Research results and their discussion

The results of tribotechnical tests of the investigated high-entropy alloy and the manifestation of the properties of lubricating formations are presented in the form of the constructed regularities of the change in the friction coefficient from the normal force in the contact zone, Fig. 4. During the tests, the system of materials "5140H - CuCrNiZrTi" worked stably at both stages. The system of materials "3310H -CuCrNiZrTi" did not work at the second stage, for 15 seconds there was a breakdown of the frictional contact with a jump in the friction coefficient from 0.8 to 2.13. After that, the system was run-in again with a load of 22 N and 45 N. At the same time, for 2 minutes at each of the loads, the system showed a stable coefficient of friction of 0.35. At the second stage, the system of materials, the M500 - CuCrNiZrTi system, worked for 8.5 minutes. During this time, a decrease in the friction coefficient from 0.48 to 0.14 was observed. However, at a load of 180 N for 45 seconds, a jump in the friction coefficient to 0.24 appeared, followed by an increase within 3 seconds to 0.64. After that, the system was run-in again with a load of 45 N and 90 N. At the same time, for 2 minutes at each of the loads, the system showed a stable coefficient of friction of 0.16 and 0.12, i.e. there was a decline.



a) b)

Fig. 4. Dependence of the dynamic coefficient of friction on the normal force:
a - 1st stage, running-in; b - 2nd stage, friction on residual lubricating formations;
1 - "CuCrNiZrTi - 5140H" system; 2 - system "CuCrNiZrTi - 3310H"; 3 - "CuCrNiZrTi - M500" system

The analysis of the obtained graphical dependencies in general indicates the following. Under conditions of drop lubrication, the surfaces of the samples of the studied materials appear to be compatible and are satisfactorily running in. In this case, the parameters of high-speed and force loading determine the manifestation of boundary lubrication. The time reaching the steady-state friction mode is practically the same for all systems, and is observed after 7.5 minutes. In this case, the systems of materials were equally stable in the range of normal loading forces from 140 to 230 N:

- the smallest coefficient of friction μ = 0.13 was observed in the system of materials " CuCrNiZrTi - M500";
- the highest coefficient of friction μ = 0.22 - in the system of materials " CuCrNiZrTi - 5140H";
- an intermediate place was taken by the system of materials "CuCrNiZrTi - 3310H" with a coefficient of friction μ = 0.17.

It is possible to explain such a tribological state based on the stiffness of the contact between the surfaces, due to the correlation of the hardness of the interacting materials and the presence of free carbon in cast iron.

Free carbon causes a decrease in the shear resistance between the tops of the micro-profile irregularities, thereby intensifying the effect of increasing the lubricating effect of the transmission oil molecules. Carbon in carbides of steels 5140H and 3310H does not exhibit such an effect. However, with a relative equality of the hardness of steels 5140H and M500, the hardness of steel 12X2H4 is two times less. In this regard, the possibility of the formation of stable bonds of oil molecules on a less hard surface is greater, which was indirectly manifested in the system of materials "5140H - CuCrNiZrTi". However, this system turned out to be more susceptible to deformation of the surface layer of steel 3310H when it was loaded with a harder surface of the CuCrNiZrTi alloy in the absence of abundant lubrication, which manifested itself at the second stage of testing. As a result of processing tribograms and evaluating the weight loss of the samples-pads, the values of the energy intensity of wear Im were calculated, the data are given in Table 3.

Table 3. Parameters for assessing the energy intensity of wear

Roller material	Friction force work A_{tr}, J	Mass pad wear Δm, mg	Wear rate $Im \bullet 10^{-8}$, $mg \bullet J^{-1}$
5140H	41184.4	0.0016	7.7
M500	23380.4	0.0025	21.3
3310H	21343.2	0.0033	30.9

Analysis of the data in Table 3 indicates the following. First, the smallest wear value per unit of friction force work is characteristic of the frictional interaction with steel 40X. Moreover, in accordance with the data in Figure 2, wear accumulated mostly evenly throughout both stages of testing, for which steady-state friction was characterized by dynamic coefficients of friction of 0.22 and 0.16. Secondly, significantly higher values of the wear rate were observed when interacting with M500 cast iron - by a factor of 2.8, and with steel 3310H - by a factor of 4, respectively. Moreover, as can be seen from Figure 4, a large proportion of the total wear was formed for M500 at the second stage of testing, since at the first stage the friction coefficient was the smallest and amounted to 0.13. Almost all of the wear at the first stage was formed by interaction with steel 3310H, the steady-state dynamic coefficient of friction was 0.17. From it follows that the mechanical wear of the CuCrNiZrTi material under boundary friction conditions was influenced by:

- microrelief of surfaces on the actual area of frictional contact, formed by both phase components 3310H, M500 and 3310H and CuCrNiZrTi with a characteristic distribution of their microhardness, which was formed by the process of destruction of cohesive and adhesive bonds between them under the action of normal and tangential loading forces of microvolumes of materials;
- layer thickness and properties of lubricants formed under the action of the forces of adhesive interaction of TAD-17I oil molecules with active metal centers. Moreover, the ratio of such centers based on the chemical composition of the materials of the tested systems is ambiguous. Large heterogeneity is characteristic of the "3310H - CuCrNiZrTi" system. For this system, such an inhomogeneity, together with a lower surface hardness, did not at all ensure the stability of the bonds without supplying components to the friction zone, and predetermined their greater destruction than restoration with abundant lubrication of the contact zone. Based on the results of modeling the shear of surfaces, a graphical approximation of the averaged data of changes in the tangential strength of their frictional bond in a limited area with multiple distributed contact of microroughnesses in the form of linear dependencies was performed, fig. 5-7. The surface microrelief was previously formed by contact interaction during friction at the second stage of tribotechnical tests. At the same time, according to the parameters of the trend lines in the Excel program, their equations and the reliability of the approximation R2 were determined, the results are shown in table 4, 5.

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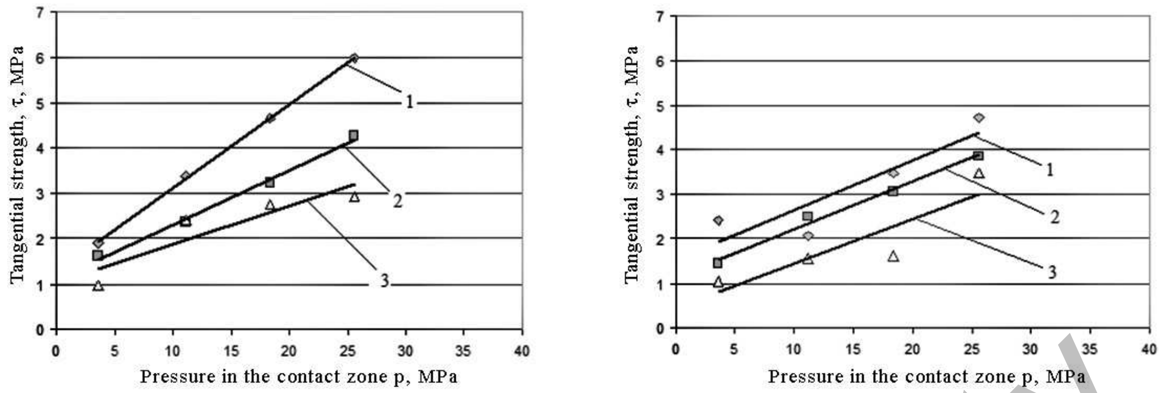

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Fig. 5. Tangential strength of adhesive bond in contact of materials "CuCrNiZrTi - M500":
a - in the environment of TAD-17I transmission oil; b - without lubricant; 1 - mm/s; 2 - mm/s; 3 - shear rate mm/s.

Analysis of the results obtained indicates the following. The high values of the reliability of the approximation of the experimental data results confirm the correctness of the graphic expression of the described processes and indicate once again the binomial nature of the law of molecular friction in the studied systems of materials. In all systems of materials under study, the parameter τ_0 occurs at p = 0 MPa, both during lubrication and during dry contact. From which it follows that in the absence of a load in the distributed contact zone, the molecular component of the forces of contact interaction between the elements "surface No. 1 - lubricating formations - surface No. 2" appears.

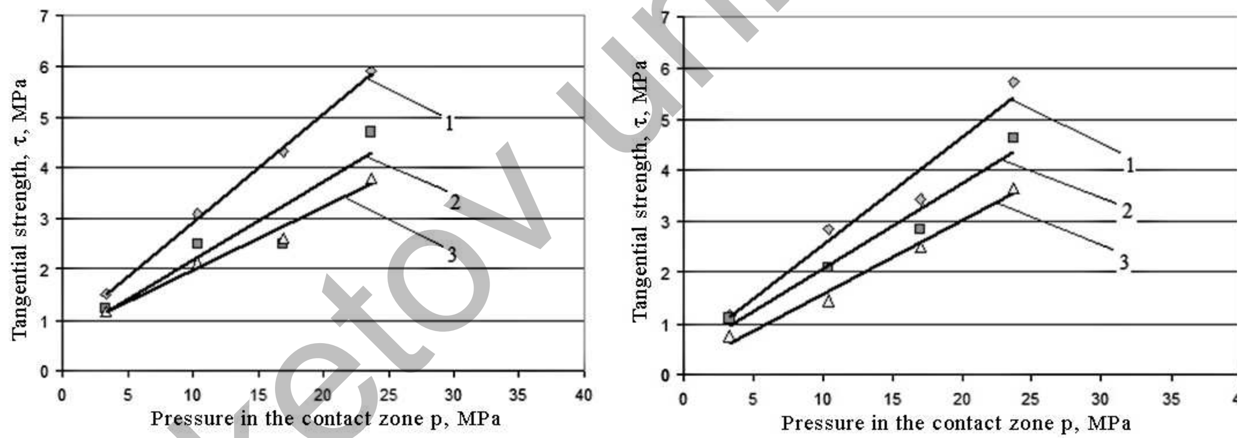

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Fig. 6. Tangential strength of adhesive bond in contact of materials "CuCrNiZrTi - 3310H":
a - in the environment of TAD-17I transmission oil; b - without lubricant; 1 - mm/s; 2 - mm/s; 3 - shear rate mm/s

The largest values of the parameter τ0 during lubrication are characteristic for the system of materials "CuCrNiZrTi - 5140H", the smallest values are characteristic for the system "3310H - CuCrNiZrTi", and the system "M500 - CuCrNiZrTi" occupies an intermediate position. At the same time, the β parameter for the system of materials "CuCrNiZrTi - 5140H" when lubricated is the smallest, while for the system "3310H - CuCrNiZrTi" it is the largest.

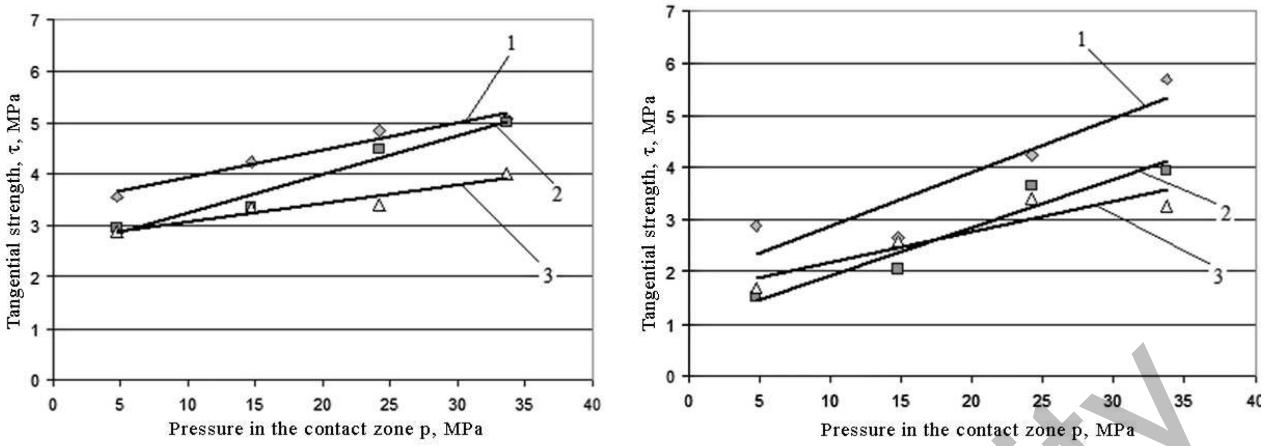

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Fig. 7. Tangential strength of adhesive bond in contact of materials "CuCrNiZrTi - 5140H": a - in the environment of TAD-17I transmission oil; b - without lubricant; 1 - mm/s; 2 - mm/s; 3 - shear rate mm/s

A graphic illustration of the nature of the change in the parameters of the adhesive bond according to the Table. 4, 5 for a more informative presentation is shown in Fig. 6-8. Interpreted in this way, graphical dependencies clearly display the following.

First, there is practical independence:

- parameter β on the shear rate at dry contact, which was observed for the system “CuCrNiZrTi - M500, Fig. 6 a, pos. 2, the value was β = 0.1 ± 0.006, and when lubricated for the "CuCrNiZrTi - 5140H " system, Fig. 8 a, pos. 1, the value was β = 0.05 ± 0.014;

- parameter τ_0 on the shear rate during lubrication for the "CuCrNiZrTi - 3310H" system, Fig. 7 b item 1, the value of which was τ_0 = 0.72 ± 0.06 MPa.

Table 4. Parameters of approximation of experimental data for tribological systems of materials in the environment of TAD-17I transmission oil

Parameter	5140H – CuCrNiZrTi			M500 – CuCrNiZrTi			3310H – CuCrNiZrTi		
	υ_1	υ_2	υ_3	υ_1	υ_2	υ_3	υ_1	υ_2	υ_3
Equation type	$\tau=\beta\cdot p+\tau_0$			$\tau=\beta\cdot p+\tau_0$			$\tau=\beta\cdot p+\tau_0$		
Approximation reliability R^2	0.96	0.95	0.93	0.99	0.99	0.82	0.99	0.87	0.97
Piezo coefficient β	0.053	0.075	0.036	0.185	0.12	0.085	0.21	0.15	0.12
Tangential strength τ_0, MPa	3.39	2.48	2.71	1.26	1.09	1.02	0.79	0.63	0.74

Table 5. Parameters of approximation of experimental data for tribological systems of materials in dry contact

Parameter	5140H – CuCrNiZrTi			M500 – CuCrNiZrTi			3310H – CuCrNiZrTi		
	υ_1	υ_2	υ_3	υ_1	υ_2	υ_3	υ_1	υ_2	υ_3
Equation type	$\tau=\beta\cdot p+\tau_0$			$\tau=\beta\cdot p+\tau_0$			$\tau=\beta\cdot p+\tau_0$		
Approximation reliability R^2	0.84	0.93	0.84	0.79	0.98	0.78	0.95	0.96	0.98
Piezo coefficient β	0.1	0.09	0.06	0.11	0.107	0.09	0.21	0.17	0.14
Tangential strength τ_0, MPa	1.87	1.0	1.6	1.51	1.14	0.45	0.41	0.38	0.13

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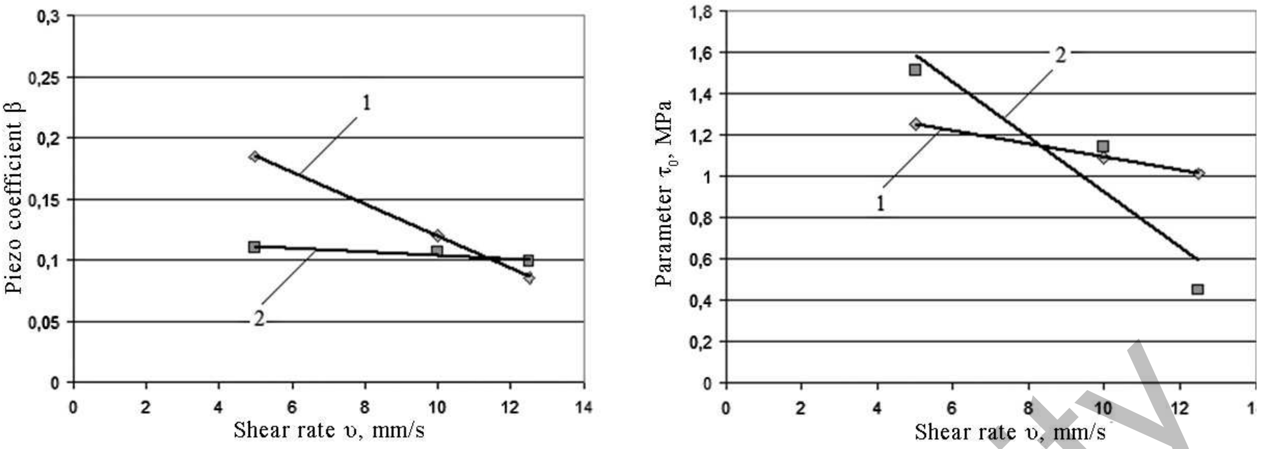

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Fig. 8. Changing the parameters of the adhesive bond in the contact of materials "CuCrNiZrTi - M500" depending on the shear rate: a - piezoelectric coefficient; b - parameter τ_0; 1 - in the environment of TAD-17I transmission oil; 2 - without lubricant.

Second, there is an explicit dependence of the parameter τ0 on the shear rate for the systems of materials "CuCrNiZrTi - 3310H" and "CuCrNiZrTi - 5140H ". Moreover, for these systems, lubricant formations formed in the friction zone increase the values of the parameter τ_0 through lubricant formations by an average of 2 times.

Thirdly, for the system of materials "CuCrNiZrTi - M500" there is a change in the mechanism of manifestation of the adhesive bond, caused by the presence of lubricant formations at a shear rate of 8 mm/s, Fig. 6 b. At $\upsilon \approx 8$ mm/s, the value of the parameter τ_0 is the same for both dry contact and contact through lubricating formations and is $\tau_0 = 1.1 \pm 0.05$ MPa. This can be explained by the fact that at $\upsilon \approx 8$ mm/s, the parameter τ_0 through the lubricating formations is less than at dry contact, due to the action of free carbon additionally released into the thinnest layers of lubricant from the disk surface. Without lubrication, the parameter τ_0 is larger due to the metal bond and a smaller amount of carbon, which is insufficient to reduce the shear resistance. In this case, the time spent on overcoming the adhesion forces is less than the time for the manifestation of the action of these forces. And lubrication reduces the effect of these forces. At $\upsilon > 8$ mm/s, the lubricating formation saturated with additional carbon continues to maintain adhesion forces due to its molar mass increased by the additional carbon.

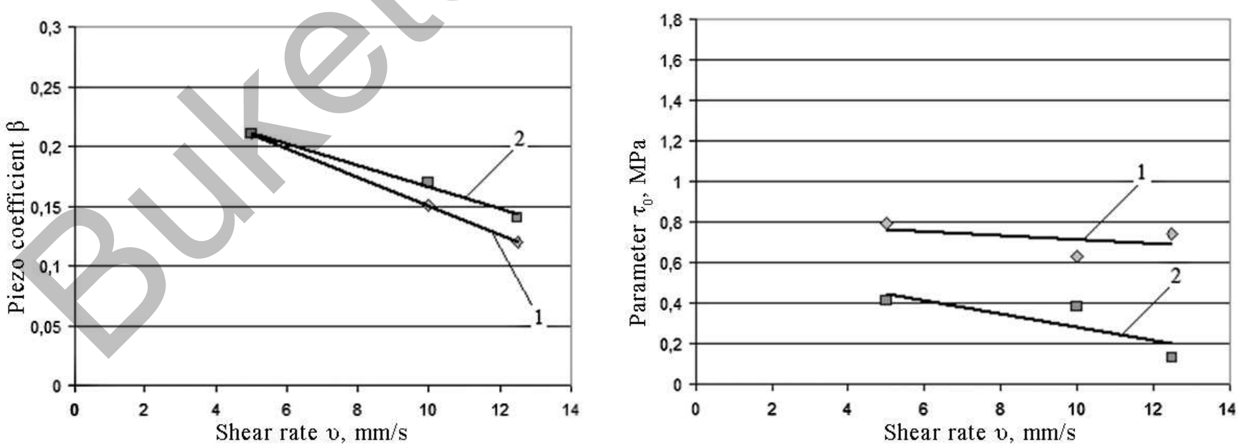

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Fig. 9. Changing the parameters of the adhesive bond in the contact of materials "CuCrNiZrTi - 3310H" depending on the shear rate: a - piezoelectric coefficient; b - parameter τ_0; 1 - in the environment of TAD-17I transmission oil; 2 - without lubricant.

In this case, the time spent on overcoming the adhesion forces through the lubricant continues to be conditionally insufficient for their destruction, which cannot be said for the time spent for the destruction of the metal bond forces.

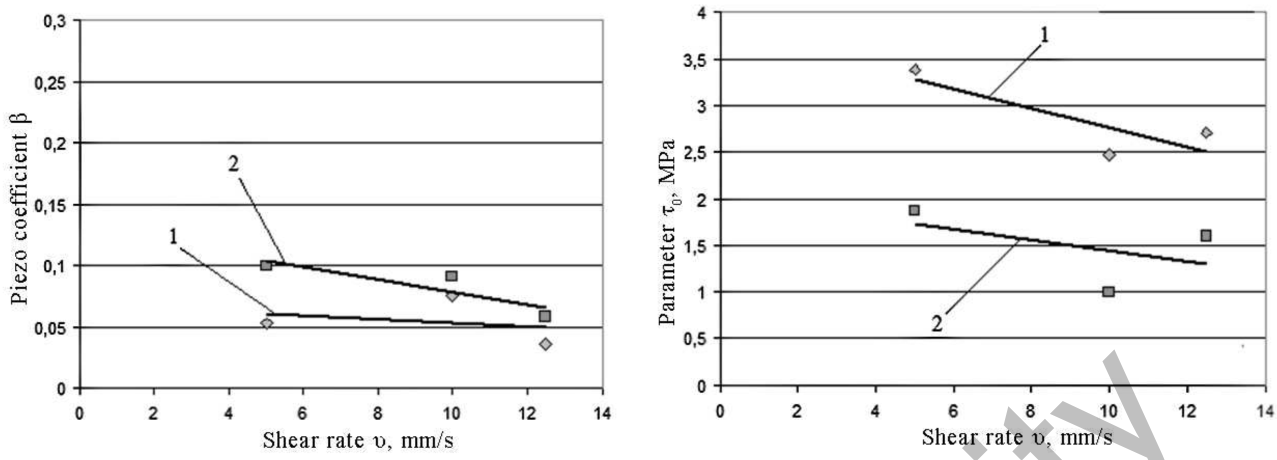

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Fig. 10. Changing the parameters of the adhesive bond in the contact of materials "CuCrNiZrTi - 5140H" depending on the shear rate: a - piezoelectric coefficient; b - parameter τ_0;
1 - in the environment of TAD-17I transmission oil; 2 - without lubricant.

We have shown above that during lubrication the dynamic coefficient of friction was 0.13; 0.17; 0.22. From which it follows that the displayed antifriction properties of the HEA of the CuCrNiZrTi system are not inferior to the antifriction properties of bronzes, brass, aluminum alloys and antifriction gray cast irons (Table 6).

Table 6. Characteristics of antifriction materials

Material	Coefficient of friction on steel
Babbits	
B83, B16, BK2	0.07-0.12
Bronze	
Br010F1, Br05TS5S5, BrS30	0.1-0.2
Brass	
LTs16K4, LTs38bts2S2	0.15-0.24
Aluminium alloy	0.1-0.15
Anti-friction gray cast irons	
AChS-1, AChS-3	0.12-0.23

Lead bronze BrS30, containing 30 % lead, and aluminum alloys with a soft structure of lead or tin are the most widely used antifriction materials. The antifriction properties of these alloys, especially aluminum alloys, are quite high, since under boundary friction, soft metals are capable of forming a thin anti-seize film that prevents direct contact between the matrix and the steel counter body. Due to the good thermal conductivity, the lubricant layer on these alloys is maintained at high sliding speeds and high pressures. Lead bronzes (like tin ones) are distinguished by high thermal conductivity (four times higher than that of other bronzes), good fatigue resistance, withstand very high specific loads, and are widely used as an antifriction layer for heavily loaded bearings with high specific pressures. As follows from the table 6, antifriction alloys of the Al-Sn system are capable of operating at the highest specific friction power.

The specific resistance of the CuCrNiZrTi alloy is $\rho = 3.1\ 10^{-8}$ (Ohm•m), and for aluminum Al it is $\rho = 2.7\ 10^{-8}$ (Ohm•m), that is, our alloy has high thermal conductivity. The microhardness of the CuCrNiZrTi coating (890 HV) is not inferior to high-entropy equiatomic alloys. Tests have shown that the wear resistance of the CuCrNiZrTi coating is ~ $3•10^{-4}$ g/min, which corresponds to the wear-resistant coatings. At the same time, the calculated energy intensity of wear obtained in this work with an order of 10^{-8} also confirms the high class of wear resistance of the coating under study. Based on the above, high-entropy coatings of the CuCrNiZrTi system turn out to be

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antifrictional, which leads to energy savings and, along with a low coefficient of friction (0.13-0.22), can compete with bronzes and aluminum alloys, which are more expensive than our coatings.

Conclusion

The results obtained in this work revealed the features of the manifestation of friction and wear of the HEA of the CuCrNiZrTi system during contact interaction with structural materials - alloyed steels 5140H, 3310H and cast iron M500, as well as the parameters of adhesion properties when modeling shear on small samples. It was found that under conditions of drop lubrication, the surfaces of the samples of the studied materials appear to be compatible and are satisfactorily run-in. In this case, the parameters of high-speed and force loading determine the manifestation of boundary lubrication. The CuCrNiZrTi system demonstrated the best antifriction properties during lubrication when interacting with steel 3310H, and without lubrication with steel 5140H. At the same time, the lowest wear resistance was observed when working with 5140H steel. The CuCrNiZrTi system showed average properties when working with cast iron M500.

The obtained graphic patterns and the parameters of their mathematical approximation made it possible to determine the nature of the change in the adhesive properties of the CuCrNiZrTi system with a change in shear rates. It was found that the highest values of the parameter $\tau 0$ during lubrication are characteristic for the system of materials "CuCrNiZrTi - 5140H " and depend on the shear rate, the smallest values of τ_0 are characteristic for the system "3310H - CuCrNiZrTi", the system " M500 - CuCrNiZrTi" occupies an intermediate position. At the same time, the β parameter for the system of materials "CuCrNiZrTi - 5140H" when lubricated is the smallest, while for the system "3310H - CuCrNiZrTi" it is the largest and depends on the shear rate. It was also found that the β parameter does not depend on the shear rate at dry contact for the "CuCrNiZrTi - M500" system and during lubrication for the "CuCrNiZrTi - 5140H " system.

The character of manifestation of the adhesive properties of the CuCrNiZrTi system in contact with alloyed steels 5140H, 3310H and M500 cast iron with a change in shear rates has been established. At the same time, it was determined that the parameter τ_0 manifests itself in the entire simulated pressure range regardless of the lubrication conditions and depends on the shear rate, while the β parameter turned out to be independent of the shear rate during dry contact for the system of materials "CuCrNiZrTi - M500" and during lubrication for systems "CuCrNiZrTi - 5140H ". New information on the numerical values of the dynamic coefficient of friction and the parameters of the adhesion properties of the HEA of the CuCrNiZrTi system expands the information on alloys of this kind. At the same time, it is recommended to use it in the selection of materials for joint work with it in friction pairs of mechanical engineering objects, as well as in the performance of analytical calculations for the predictive assessment of the effect of the adhesion component of friction on the state of the tribological contact of the surfaces of parts, taking into account their loading conditions and operating conditions.

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