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Stability of Physical and Mechanical Properties of Wear-Resistant Ultrafine-Grained Surface Friction Layers under Extreme Conditions of Thermal Effects during Operation of Sliding Bearings

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As established, the transition of the friction pair composed of steel 130Cr17 and steel 20Cr13 to a stationary operating mode with minimal wear and friction coefficient occurs due to the self-organization of the wear-resistant ultra-fine-grained coatings on the contact surfaces of both solids. These coatings are formed from a qualitatively new ultradispersed and nanostructured material that can contain up to 25 at.% of oxygen and carbon. As shown, self-organizing wear-resistant coatings are composed of friction layers, each of which is the result of a separate act of layering a microvolume of metal on the working surfaces of the solids. Friction layers differ from the deformed original metal of steels in terms of their high hardness and elasticity. They prevent the formation of strong adhesive bonds between rubbing solids and facilitate the transition of the system to a stationary operating mode with a minimal coefficient of friction and wear. During operation, the material of the surface friction layers is subject to intense cyclic thermomechanical effects. Therefore, its ability to retain its unique physical and mechanical properties under extreme conditions of high temperature and pressure determines the behaviour and performance properties of friction units. To analyse the possible influence of external thermal effects on the physical and mechanical

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properties of the rubbing material, the samples obtained after friction tests are annealed in a vacuum of 0.01 MPa at temperatures of 620°C and 720°C for 1 hour. As established, these causes complete softening of the original metal that was deformed by friction. At the same time, the material of the friction layers retains high hardness and elasticity even after the samples have been annealed at 720°C. The maximal softening of the metal is observed at the beginning of the friction layers, where the structure is least fragmented, while the minimal softening is observed in the nanostructured material at the final part of the friction layers. As shown, during the formation of surface friction layers, the carbide phase dissolves and the metal is saturated with active chemical elements of the working environment. This enriches the grain boundaries of the surface friction layers with C and O atoms. Thermal treatment of samples after friction results in carbon atoms occupying octahedral interstitial sites of the b.c.c. iron–chromium alloy in the boundary regions of the grains of the surface friction layers, while oxygen atoms form a fine-dispersed oxide phase (α-Fe_2O_3). Their number at grain boundaries increases with the increased degree of metal fragmentation. The carbon atoms in the octahedral interstitial sites of the b.c.c. iron–chromium alloy form strong covalent bonds with the surrounding metal atoms. They reduce significantly the mobility of atoms and make the metal structure less sensitive to external thermomechanical influences. The presence of a fine-dispersed oxide phase at the grain boundaries also contributes to this one. This makes the physical and mechanical properties of the material of the surface friction layers significantly more resistant to external thermal influences compared to those of the deformed original metal.

Key words: sliding friction, wear resistance, nanostructured material, ultrafine-grained structure, plastic deformation, surface friction layers, physical and mechanical properties, recrystallization.

Встановлено, що перехід пари тертя криця 130Х17–криця 20Х13 у стаціонарний режим роботи з мінімальними зносом і коефіцієнтом тертя відбувається завдяки самоорганізації на поверхнях контакту обох тіл зносостійких наддрібнодисперсних покриттів. Ці покриття складаються з якісно нового ультрадисперсного та наноструктурованого матеріялу, який може містити до 25 ат.% Оксиґену та Карбону. Показано, що самоорганізовані зносостійкі покриття складаються з шарів тертя, кожен з яких є результатом окремого акту нашарування мікрооб'ємів металу на робочі поверхні тіл. Поверхневі шари тертя відрізняються від деформованого вихідного металу криць високими твердістю та пружністю. Вони перешкоджають утворенню між тілами, що труться, сильних адгезійних зв'язків і сприяють переходу системи в стаціонарний режим роботи з мінімальними коефіцієнтом тертя та зносом. Під час роботи матеріял поверхневих шарів тертя піддається інтенсивним циклічним термомеханічним впливам. Його здатність зберігати свої унікальні фізико-механічні властивості в екстремальних умовах високих температури та тиску визначає поведінку й експлуатаційні властивості вузлів тертя. Для аналізи можливого впливу зовнішніх термічних навантажень на фізичні та механічні характеристики матеріялу зон контактної взаємодії криць зразки після випробувань на тертя піддавалися відпалу у вакуумі 0,01 МПа за температур у 620°C і

720°C упродовж 1 години. Встановлено, що це викликає повне знеміцнення деформованого через тертя вихідного металу. Водночас матеріял поверхневих шарів тертя зберігає високі твердість і пружність навіть після відпалу зразків за 720°C. Максимальне знеміцнення металу спостерігається на початку шарів тертя, де структура є найменш фраґментованою, мінімальне — у наноструктурованого матеріялу кінцевої частини шарів тертя. Показано, що утворення поверхневих шарів тертя супроводжується розчиненням карбідної фази та насиченням металу активними хемічними елементами робочого середовища. Це збагачує межі зерен шарів тертя атомами C і O. Термічне оброблення зразків після тертя приводить до того, що атоми Карбону у примежових областях зерен шарів тертя займають октапори ОЦК-стопу заліза з Хромом, а атоми Оксиґену утворюють дрібнодисперсну оксидну фазу α-Fe_2O_3. Їхня кількість на межах зерен зростає разом зі збільшенням ступеня фраґментації металу. Атоми Карбону в октапорах ОЦК-стопу заліза з Хромом, утворюють міцні ковалентні зв'язки з навколишніми атомами металу. Вони істотно понижують рухливість атомів і роблять структуру металу менш чутливою до зовнішніх термомеханічних впливів. Присутність на межах зерен дрібнодисперсної оксидної фази теж сприяє цьому. Це робить фізико-механічні властивості матеріялу поверхневих шарів тертя значно більш стійкими щодо зовнішніх термічних впливів у порівнянні з деформованим вихідним металом.

Ключові слова: тертя ковзання, зносостійкість, наноструктурований матеріял, наддрібнодисперсна структура, пластична деформація, поверхневі шари тертя, фізико-механічні властивості, рекристалізація.

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1. INTRODUCTION

In many cases, the efficiency of machines and process equipment depends on the characteristics of the sliding bearings used in the manufacture of these machines and equipment. They determine the technical characteristics of products, their efficiency and durability. In most cases, sliding bearings are manufactured using friction pairs made of steel and copper-based alloys, such as bronze or brass. However, they are not capable of operating under high loads in aggressive environments. Therefore, for extreme friction conditions, pairs of friction elements based on chromium steels were developed. High-chromium steels have been proven wear-resistant materials with a range of essential mechanical and special properties. The choice of chemical composition of steels was determined by the conditions of their operation [1–12]. In particular, the friction pair of steel 120Cr15 and steel 20Cr13 has demonstrated good performance. The use of it in sliding bearings of pumps for heavily loaded equipment in the energy, mining and food industries provides significant economic benefits. In this regard, further scientific research and development of technical

solutions to improve the antifriction properties of these alloys are of great importance.

Almost any load applied to the friction components is transmitted through their working surfaces. Therefore, the properties of the surface friction layers in each friction element typically determine the overall behaviour and operational characteristics of the friction unit. It has been demonstrated in works [7–11] that, under conditions of sliding friction in environments with active chemical elements, the transition of friction pairs composed of steels 130Cr17 (120Cr15) and 20Cr13 to a stationary operating mode with minimal wear and friction coefficient occurs due to the self-organization of qualitatively new, wear-resistant ultra-fine-grained coatings on the contact surfaces of both bodies. These coatings differ from the deformed original metal of the steels in their high hardness and elasticity. They localize plastic deformation processes in a thin surface layer, which prevents the formation of strong adhesive bonds between rubbing bodies and facilitates the system's transition to a stationary operating mode with a minimum coefficient of friction and wear.

During the operation of the friction unit, the material of the wear-resistant ultra-fine-grained coatings is subjected to intense cyclic thermomechanical effects. Today, there are many theoretical methods for calculating the actual temperatures and pressures, which occur during friction at the points of real contact between metal surfaces [13–17]. According to them, individual sections of the friction surfaces of the working pair consisting of steel 130Cr17 (120Cr15) and steel 20Cr13 can experience extreme conditions of high normal pressure (3 GPa), flash temperature (450°C), and relative shear rate. Therefore, the ability of the material of wear-resistant ultra-fine-grained coatings to maintain its unique physical and mechanical properties under extreme conditions of high temperature and pressure determines the behaviour and performance characteristics of friction units.

This work studies the influence of external thermal effects on the physical and mechanical properties of the material in the contact interaction area of a friction pair composed of steels 130Cr17 and 20Cr13. This will enable us to compare the resistance to external thermal effects of a qualitatively new material of wear-resistant ultra-fine-grained coatings with that of the original metal deformed by friction, and to understand how the degree of fragmentation of the structure and its saturation with impurity atoms affect the stability of the materials' physical and mechanical properties.

This study will be useful for developing the physical foundations for obtaining qualitatively new wear-resistant nanostructured and ultra-dispersed alloys on the contact surfaces of friction units, which will ensure a reduction in wear and the coefficient of friction by 2 to 3 times under extreme operating conditions.

2. RESEARCH OBJECTS AND METHODS

The object of the study was a friction contact pair consisting of steel 130Cr17 (pad) and steel 20Cr13 (disk). The metal used for the research was obtained from an open induction furnace with a capacity of 12 kg. Metal samples were collected from each smelting for chemical analysis. The carbon content was analysed through combustion in an oxygen stream, while the concentration of alloying elements was determined using an x-ray fluorescence spectrometer. The results of the chemical analysis of the steels are presented in Table 1.

The alloys under study in the cast state possess a metallic matrix predominantly characterized by an austenitic structure. As known [4], such a structure is not always optimal in terms of wear resistance and mechanical processing. There are numerous ways to alter the structure of the metal matrix in alloys through heat treatment, which can achieve the desired physical and mechanical properties. Therefore, the alloys obtained after casting were subjected to additional heat treatment. Steel 130Cr17 was subjected to heat treatment, which included the following steps: heating to 950°C (held for 2 hours), cooling to 680°C (held for 2 hours), cooling in a furnace, quenching in oil from 1020°C and subsequent tempering at 600°C for 1 hour. The heat treatment of 20Cr13 steel consisted of heating to 1020°C (held for 45 minutes), quenching in oil, and tempering at 520°C for 1 hour.

The test of the contact pair consisting of steel 130Cr17 (pad) and steel 20Cr13 (disk) under sliding-friction conditions was conducted using a standard friction machine (model 2070CMT-1). Friction between the steels according to the pad-disk scheme occurred under a normal load of $5 \cdot 10^6$ N/m^2 and a sliding speed of 1 m/s (Fig. 1). The ratio of the pad area to the disc area, known as the mutual overlap coeffi-

TABLE 1. The average chemical composition of steels 130Cr17 and 20Cr13 (the total concentration of other impurity atoms did not exceed 0.05 wt.%).

	Steel 130Cr17		Steel 20Cr13	
	wt.%	at.%	wt.%	at.%
Fe	80.47	75.57	86.30	84.37
Cr	17.23	17.37	12.42	13.04
Si	0.36	0.68	0.50	0.97
Mn	0.51	0.49	0.41	0.41
Ti	0.01	0.02	0.01	0.01
Cu	0.06	0.05	0.09	0.08
P	0.02	0.03	0.02	0.04
S	0.02	0.03	0.02	0.04
C	1.32	5.76	0.23	1.04

cient, is approximately $\kappa \cong 0.08$. The root-mean-square errors in measuring the weight wear of steels did not exceed $5 \cdot 10^{-6}$ g/m. The testing scheme for steels under friction conditions is illustrated in Fig. 1. Friction tests were performed in a water-air environment.

After friction testing, steel samples were subjected to heat treatment at 620°C and 720°C for one hour in a vacuum of 0.01 MPa. For this purpose, a laboratory LHTM muffle vacuum furnace was utilized. Based on the phase diagrams of Fe–Cr–C-system alloys [17, 18], the $\alpha \rightarrow \gamma$-transformation in the metal of the steels under investigation can occur at temperatures above 780°C. Therefore, such heat treatment of steels ensured the most severe conditions of external thermal influences without phase transformations of the metals, which could have an additional effect on the physical and mechanical properties of materials.

The morphology and chemical composition of the surface friction layers were investigated with a JSM-6490LV scanning electron microscope produced by JEOL Ltd. It was additionally equipped with an INCA Energy 350 Premium energy-dispersive spectrometer featuring a silicon drift detector and an INCA Wave 500 wave-dispersive spectrometer. It also included an HKL Channel 5 EBSD electron backscatter diffraction detector, manufactured by OXFORD Instruments (UK). The studies were carried out using an accelerating voltage of 20 kV and a beam current set at 7 nA. Images of friction surfaces were obtained in secondary electron mode. The calculation of element concentrations from the obtained spectra was conducted using the matrix correction method. For this purpose, the most advanced matrix effect correction scheme, XPP, from OXFORD Instruments Analytical Ltd. was employed.

The local chemical composition of wear-resistant surface friction

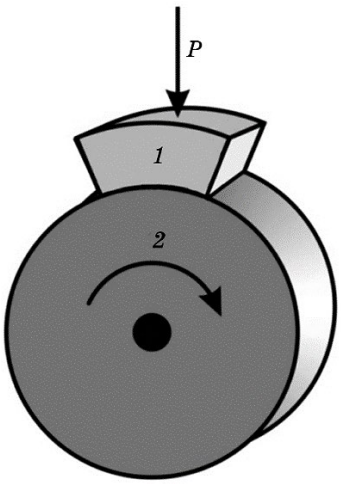


Fig. 1. The testing scheme for steels under friction conditions: *1*—pad, *2*—disc.

layers was further analysed using an MS-46 X-ray microprobe from CAMECA. The chemical composition was quantitatively analysed on oblique sections at specified points using a probe mode with settings of 20 kV and 13 nA. The ZOND program [19] was used to calculate concentrations and to make corrections for absorption, fluorescence, and atomic number. The total error in calculating the concentrations of metal atoms in the surface friction layers did not exceed 0.2 wt.%.

Metallographic studies were conducted using a Neophot-30 optical microscope manufactured by Carl Zeiss. Layers of nickel approximately 300 μm thick were preliminarily electrolitically deposited on the friction surfaces to protect them from potential damage during the preparation of the sections.

Transmission electron microscopy studies of the microstructure and phase composition of the surface friction layers were conducted using a JEM-200CX electron microscope (JEOL Ltd.) at an accelerating voltage of 200 kV. To prepare thin foils, which enable the study of the metal throughout the entire depth of the contact interaction zone in steels, a specially developed technique is employed, as described in detail in Ref. [20].

Rockwell hardness measurements were conducted using a UT5011 device in accordance with State Standard 9013-59 (ISO 6508-86). Microhardness measurements were performed using a PMT-3 microhardness tester in accordance with ГОСТ 2999-75. A Vickers diamond tip was used with an indenter load of 0.5 N.

Micromechanical tests of the material in the contact interaction zones in steels were conducted using the indenter dynamic penetration method with the УМП-11 device. The technique for recording indenter penetration diagrams in coordinates of indenter load (P) and mutual approach (h) of the indenter and the sample was employed. The development of this technique is detailed in works [21–23]. The indenter and the sample approached each other at a constant speed of 1 m/s. To enable a comparison of the microhardness values calculated from the diagrams (based on the size of the diagonal of the residual plastic imprint) with the measurement data from the PMT-3 device, the maximum load applied to the indenter was set to 0.5 N in both cases. The proportion of the work of elastic deformation (A_E) in the total work of elastic–plastic deformation (A) during the penetration of the indenter was determined by the ratio of the areas under the unloading and loading curves of the indenter penetration diagrams.

3. RESULTS AND THEIR DISCUSSION

The dependences of the friction coefficient and weight wear of a contact pair consisting of 130X17 steel (pad) and 20X13 steel (disk) on the friction path are illustrated in Figs. 2 and 3.

From these figures, it is evident that the friction process of the contact pair can be conditionally divided into two stages: the running-in stage (section 1 in Fig. 2) and the stationary operation stage, character-

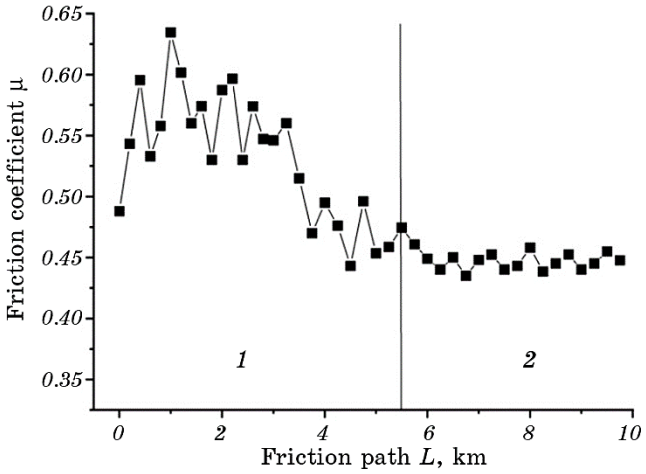


Fig. 2. Dependence of the friction coefficient on the friction path for the contact pair made of steel 130Cr17 and steel 20Cr13: *1*—the stage of running-in of the friction unit, *2*—the stage of stationary operation.

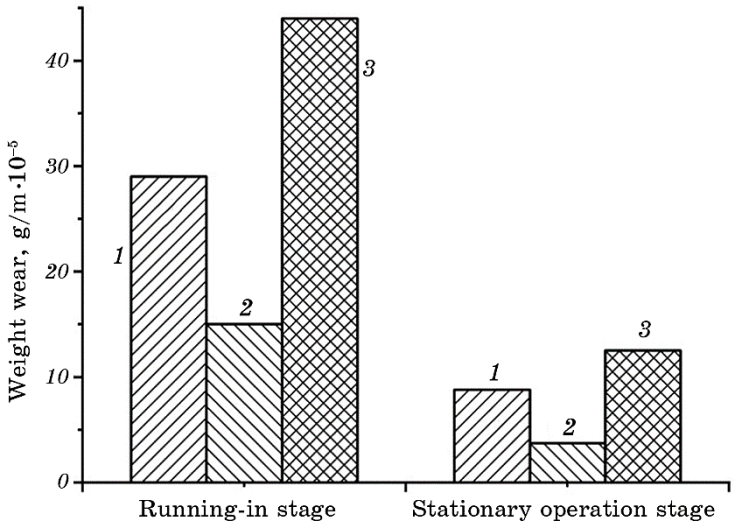


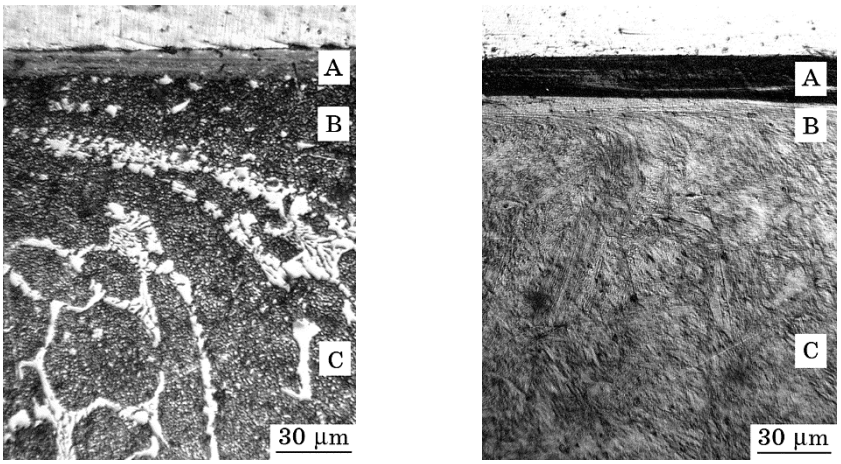
Fig. 3. Weight wear of the contact pair (steel 130Cr17 and steel 20Cr13) during the breaking-in stage and under stationary operating conditions: *1*—wear of the pad (steel 130Cr17), *2*—wear of the disc (steel 20Cr13), *3*—total wear of the friction unit.

ized by minimal wear and a low friction coefficient (section *2* in Fig. 2).

The analysis of the dynamics of structural–phase transformations in the contact interaction zones of steels during friction indicates that the transition of the friction pair to a stationary operating mode, characterized by minimal wear and a low coefficient of friction, occurs due to the self-organization of wear-resistant coatings on the contact surfaces of both components. In this context, the amount of these coatings must be sufficient to shield completely the initial metals that were deformed during the running-in stage. Self-organized wear-resistant coatings are formed as a result of the physical and chemical processes occurring in the contact zone of the bodies during the running-in stage, and these coatings can occupy between 45% and 90% of the working surface of each rubbing body.

Figure 4 shows photographs of the structure of the contact interaction zone of steels (cross-sections) after the friction tests. The self-organized wear-resistant coatings in the photographs correspond to zone A. They are situated above the deformed original metal of the steels (zone B), have a clear boundary with it, and differ in their degree of etching. Zones C in the figure correspond to the undeformed original metal located deep within the rubbing parts.

A more detailed study of the structure of wear-resistant self-organizing coatings (zone A) was conducted on oblique sections of samples prepared at an angle of 30 degrees to the friction surface (Fig. 5). It can be observed that these coatings consist of distinct friction

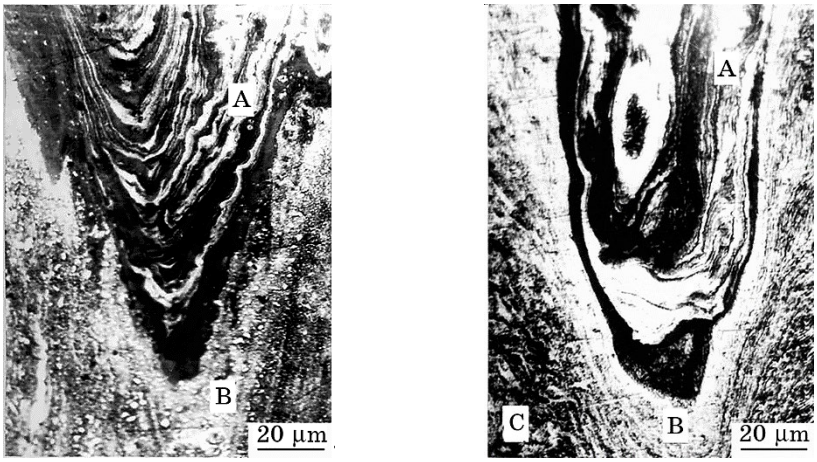


a *b*

Fig. 4. The structure of the contact interaction zone of steels 130Cr17 (*a*) and 20Cr13 (*b*) after the friction test. Cross-section: A is wear-resistant self-organizing coatings, B is deformed original metal, C is undeformed original metal.

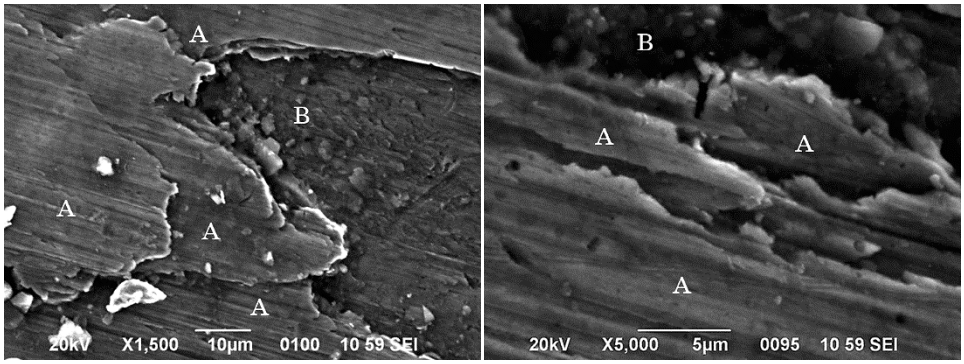
layers with a clear boundary between them, the total number of which varies along the working surface.

Studies using scanning electron microscopy of the morphology of friction surfaces confirm the previous results. Figure 6 illustrates typical areas of the working surfaces of 130Cr17 and 20Cr13 steels after the friction pair has transitioned to a stable operating mode characterized by a minimum coefficient of friction and wear. The structure of the lateral boundaries of the wear-resistant self-organizing coatings



a *b*

Fig. 5. The structure of the contact interaction zone of steels 130Cr17 (*a*) and 20Cr13 (*b*) after the friction test. Oblique section at an angle of 30°: A is wear-resistant self-organizing coatings, B is deformed original metal, C is undeformed original metal.



a *b*

Fig. 6. The structure of the friction surfaces of steels 130Cr17 (*a*) and 20X13 (*b*): A is wear-resistant self-organizing coatings; B is deformed original metal.

(zone A, Fig. 6) indicates that they are composed of individual layers, resulting from the multiple layering of metal microvolumes on the friction surfaces. Analysis of the cross-sectional structure of the contact interaction zone of steels during friction indicates that each friction layer of self-organizing wear-resistant coatings results from a separate act of layering metal microvolumes on the friction surfaces. These metal microvolumes are formed through the adhesive interaction of contacting bodies during the running-in stage of the friction units.

The data presented above clearly indicate that the physical and mechanical properties of wear-resistant self-organizing coatings have a significant impact on the tribological characteristics of friction units. However, for the successful operation of friction units, it is equally important that these coatings retain their unique properties under long-term cyclic thermomechanical loads experienced during operation. Therefore, to analyse the potential influence of external thermal effects on the material properties in the contact interaction zones of steels, samples tested under friction were annealed in a vacuum of 0.01 MPa at temperatures of 620°C and 720°C.

Each of the friction layers in the self-organizing wear-resistant coatings is created from a distinct process of metal layering on the working surfaces of the components. As one moves along the individual friction layers in the direction of metal layering, there are significant changes in the mechanical properties, microstructure, and chemical and phase composition of the material [7–9]. Therefore, to understand the mechanism of the potential influence of external thermal effects on the physical and mechanical characteristics of self-organizing wear-resistant coatings, it is crucial to conduct a comprehensive study of the material in the individual friction layers. This study should focus on how heat treatment affects the chemical and phase composition, microstructure, and mechanical properties of various regions within these layers.

Research findings presented in works [7–11] indicate that the nature of structural–phase transformations in the contact interaction zones of both friction pair components largely coincides. To streamline our discussion and avoid unnecessary repetition, we will henceforth focus on the processes taking place in the friction layers of steel 130Cr17.

After conducting friction tests on the contact pairs both before and after annealing the samples, we performed micromechanical tests and local x-ray spectral analysis on the materials in the contact interaction zones of the steels. Using the Vickers diamond tip of the PMT-3 device, we marked various areas of the oblique sections of the friction layers and the original metal. Subsequently, local x-ray spectral analysis and micromechanical testing of the material were conducted in the speci-

fied areas. Therefore, the mechanical properties and chemical composition of the material in the friction layers (zone A), the deformed original metal (zone B), and the undeformed original metal (zone C) of the steels were analysed in the same locations.

Table 2 presents the average mechanical characteristics of the various parts of the friction layers (zone A), along with the deformed (zone B) and undeformed (zone C) original metal of 130Cr17 steel. The measurements were conducted immediately after the friction tests of the contact pair and the subsequent annealing of the samples at tempera-

TABLE 2. Average values of mechanical characteristics for the friction layers (zone A), along with the deformed (zone B) and undeformed (zone C) initial metal of 130Cr17 steel, following the testing of the friction pair consisting of 130Cr17 steel and 20Cr13 steel in a water–air environment. The measurements were conducted immediately after the friction tests of the contact pair and the subsequent annealing of the samples at temperatures of 620°C and 720°C for duration of 1 hour.

	Zone C	Zone B	Zone A. Friction layer		
			beginning	middle	end
Immediately after the friction tests of the contact pair					
H_d^m, GPa	3.7	5.5	6.5	8.4	10.2
H_d^c, GPa	3.6	5.5	6.6	8.3	10.1
H_h, GPa	3.2	4.6	5.5	6.5	7.7
$H_d^c - H_h$, GPa	0.4	0.9	1.1	1.8	2.4
A_{el}/A	0.09	0.12	0.16	0.24	0.29
A_{pl}/A	0.91	0.88	0.84	0.76	0.71
After the friction tests of the contact pair and the subsequent annealing of the samples at temperature of 620°C for a duration of 1 hour					
H_d^m, GPa	3.4	3.6	5.1	7.4	9.5
H_d^c, GPa	3.5	3.6	5.2	7.3	9.6
H_h, GPa	3.2	3.2	4.4	5.9	7.4
$H_d^c - H_h$, GPa	0.3	0.4	0.8	1.4	2.2
A_{el}/A	0.08	0.09	0.11	0.20	0.28
A_{pl}/A	0.92	0.81	0.89	0.80	0.72
After the friction tests of the contact pair and the subsequent annealing of the samples at temperature of 720°C for a duration of 1 hour					
H_d^m, GPa	3.3	3.4	3.7	7.0	9.4
H_d^c, GPa	3.3	3.3	3.6	7.0	9.3
H_h, GPa	3.0	3.0	3.2	5.7	7.1
$H_d^c - H_h$, GPa	0.3	0.3	0.4	1.3	2.2
A_{el}/A	0.08	0.08	0.09	0.19	0.28
A_{pl}/A	0.92	0.92	0.91	0.81	0.72

tures of 620°C and 720°C for duration of 1 hour.

The data presented in this table were obtained by averaging measurements collected from five different friction layers. The correlation between the microhardness values determined by the diagonal size of the residual plastic imprint (H_d^c), as derived from the dynamic penetration diagrams of the indenter, and the microhardness measurements obtained with the PMT-3 device (H_d^m) corroborates the validity of the micromechanical tests conducted on the metal.

Micromechanical tests of the materials in the contact interaction zones of the steels (Table 2) indicate that heat treatment of the samples following friction tests results in complete softening of both the undeformed and friction-deformed original metal (Fig. 4, zones B and C). Meanwhile, the material of the friction layers, from which self-organizing wear-resistant coatings are formed (Fig. 4, zone A), retains high hardness and elasticity. The data presented in the table reveal that the influence of external thermal effects on the mechanical properties of the friction layer material depends on both the annealing temperature and the degree of fragmentation of the metal structure. Maximum softening of the material is observed at the beginning of the friction layers. In these regions, there is a significant dependence of the mechanical properties on the annealing temperature. Increasing of the annealing temperature of the samples from 620°C to 720°C leads to complete nearly the softening of the material at the onset of friction layers.

The chemical composition of the friction pair was analysed using localized x-ray spectroscopy. Table 2 presents the average chemical composition of the various parts of the friction layers (zone A), along with the deformed (zone B) and undeformed (zone C) original metal of 130Cr17 steel. The measurements were conducted immediately after the friction tests of the contact pair and the subsequent annealing of the samples at temperatures of 620°C and 720°C for duration of 1 hour. The values of the chemical composition for the friction layers were obtained by averaging measurements taken from five different layers. As the annealing temperature had virtually no impact on the chemical composition of the friction layers, the table includes data for only one instance of heat treatment to prevent repetition.

Analysis of the data presented in the table indicates that the annealing of samples after friction tests has a negligible effect on the chemical composition of the metal across the entire depth of the contact interaction zones of the steels. A significant distinguishing feature of the chemical composition of the friction layers is the presence of a substantial number of oxygen atoms within them.

The intensive plastic deformation of microvolumes of metal during the formation of friction layers results in the saturation of their ultradispersed structure with oxygen atoms from the working environ-

ment, due to the thermomechanical breakdown of water molecules at the contact points of microprotrusions. When traversing individual friction layers in the direction of metal layering, the concentration of oxygen in the material can vary from 1 at.% to 21 at.%. As the number of oxygen atoms in the friction-layer material increases, the impact of heat treatment on its hardness and elasticity diminishes (see Tables 2 and 3).

Electron transmission microscopy was employed to investigate the effect of heat treatment on the microstructure and phase composition of the material in surface friction layers. Utilizing this technique, a

TABLE 3. Average values of the chemical composition for the friction layers (zone A), as well as for the deformed (zone B) and undeformed (zone C) initial metal of 130Cr17 steel, following the testing of the friction pair consisting of 130Cr17 steel and 20Cr13 steel in a water–air environment. The measurements were conducted immediately after the friction tests and the subsequent annealing of the samples at a temperature of 620°C for duration of 1 hour.

Chemical composition, at.%	Zone C	Zone B	Zone A. Friction layer		
			beginning	middle	end
Immediately after the friction tests of the contact pair					
Fe	78.07	76.56	75.62	69.17	63.76
Cr	15.62	16.70	15.75	14.71	13.87
Si	0.66	0.69	0.73	0.68	0.63
Mn	0.50	0.47	0.46	0.43	0.39
Ti	0.02	0.01	0.01	0.01	0.01
Cu	0.04	0.05	0.06	0.05	0.04
P	0.03	0.03	0.02	0.02	0.02
S	0.03	0.02	0.03	0.02	0.01
O	0.00	0.00	2.81	10.69	16.95
C	5.03	5.47	4.51	4.22	4.32
After the friction tests of the contact pair and the subsequent annealing of the samples at temperature of 620°C for a duration of 1 hour					
Fe	78.34	76.87	75.36	68.77	63.58
Cr	15.51	16.52	15.82	14.90	14.03
Si	0.68	0.66	0.77	0.70	0.61
Mn	0.46	0.49	0.44	0.46	0.36
Ti	0.02	0.02	0.01	0.01	0.01
Cu	0.06	0.04	0.07	0.05	0.05
P	0.03	0.02	0.02	0.02	0.01
S	0.02	0.02	0.02	0.03	0.01
O	0.00	0.00	2.92	10.75	17.06
C	5.08	5.36	4.57	4.31	4.28

detailed analysis of the microstructure and phase composition of the friction layers in the working pair of steel 130Cr17 and steel 20Cr13 was conducted after friction tests without subsequent annealing of the samples [8]. It has been demonstrated [8] that the fragmentation level of the structure in different parts of individual friction layers is not constant. This level can vary significantly when transitioning between adjacent layers. Less fragmented friction layers are entirely composed of an ultrafine crystalline structure formed by spatially disoriented grains with a body-centred cubic (b.c.c.) iron crystal lattice. The grains' size of these layers varies smoothly in the direction of the layering of metallic microvolumes on the friction surfaces: from 160 nm to 20 nm. As the degree of fragmentation of the structure increases, the azimuthal splitting of iron reflections in microdiffraction patterns also increases, indicating a greater spatial disorientation of the grains. The grain boundaries of friction layers are predominantly composed of dislocation clusters and exhibit a spatially extended morphology. With an increase in the degree of structural fragmentation and spatial disorientation of its grains, the volume fraction of boundary regions increases significantly. More fragmented friction layers differ from their predecessors primarily in that their final part consists of nanostructured crystalline–amorphous material with a grain size ranging from 2 to 8 nm. The crystalline–amorphous nanostructure has a well-defined boundary with the ultrafine material.

In the microdiffraction patterns of friction layers from self-organizing wear-resistant coatings, reflections corresponding to body-centred cubic (b.c.c.) iron, as well as reflections from Me7C3-type carbides, are observed. However, the number of reflections from the carbide phase gradually decreases as ones move along each layer in the direction of friction. This indicates that the intense plastic deformation of metal microvolumes during their layering on the friction surface leads to the dissolution of the carbide phase. This is confirmed by the data from Auger electron spectroscopy obtained from the grain boundaries of the surface friction layers and the original metal of 130Cr17 steel [9]. The shape of the carbon Auger electron peak suggests that the carbon atoms at the grain boundaries of the friction layers predominantly exist in a solid solution, whereas in the original metal, the carbon atoms at the grain boundaries are primarily present in the carbide phase. The dissolution of the carbide phase during intense plastic deformation of iron is further corroborated by data from publications [24, 25].

As one moves along each of the friction layers toward the layering of metal microvolumes on the working surfaces, reflections from ultrafine Fe_2O_3-type oxides are also observed in the microdiffraction patterns. In the initial sections of the friction layers, these reflections are nearly absent. Ultradispersed Fe_2O_3 oxides emerge during the final

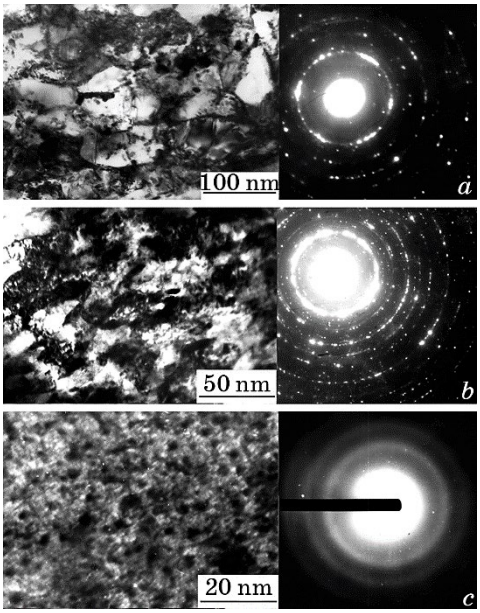


Fig. 7. Microstructures and electron diffraction patterns of different sections of the friction layer of 130Cr17 steel located along the direction of friction in the sequence $a \rightarrow b \rightarrow c$. Section '*a*' corresponds to the beginning of the friction layer, while section '*c*' corresponds to the end.

stage of metal microvolume layering, which corresponds to the middle and final sections of the friction layers.

The microstructure and electron diffraction patterns of the initial, middle, and final parts of one of the friction layers of 130Cr17 steel are presented in Fig. 7. The studies were conducted following friction tests of the contact pair, without any subsequent annealing.

Electron-microscopic studies indicate that heat treatment of samples conducted after friction tests significantly affects only the microstructure of the initial region of the friction layers, which exhibits the least fragmented structure. Therefore, future describing of the investigations will concentrate on the structural transformations occurring in these sections of the friction layers.

Figure 8 illustrates the microstructure and electron diffraction pattern of the initial section of the friction layer of 130Cr17 steel, obtained after friction testing of the contact pair and subsequent heat treatment of the tested samples at 720°C for one hour.

It is evident that the heat treatment of samples subjected to friction tests results in a modification of the microstructure in the initial region of the friction layers. This modification is significantly influenced by the annealing temperature. In regions of the friction layers

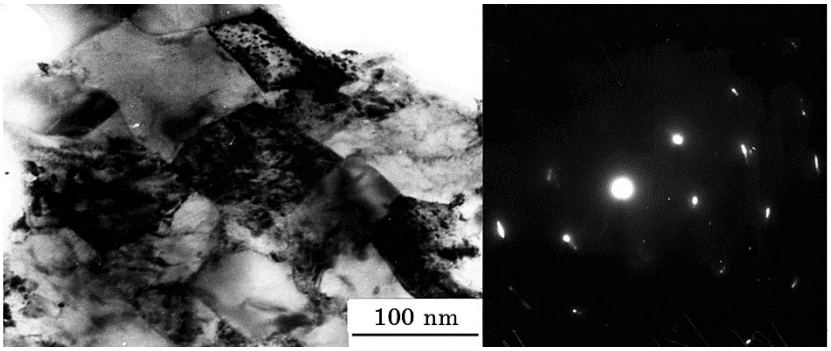


Fig. 8. Microstructure and electron diffraction pattern of the initial section of the friction layer of 130Cr17 steel obtained after friction testing of the contact pair comprising 130Cr17 steel and 20Cr13 steel and subsequent heat treatment of the tested samples at 720°C for one hour.

exhibiting the least fragmented microstructure, the process of primary recrystallization occurs intensely during the heat treatment of samples at 720°C. In the deformed material, new undistorted crystals are formed that grow in size through the absorption of grains that have been distorted by deformation. During the heat treatment of samples at 620°C, the structural changes observed in the regions of the friction layers with the least fragmented structures are not so significant. In this case, the recrystallization rate is slower. Although the grain boundaries exhibit a more regular shape, their spatial disorientation remains evident.

The microstructure of the more fragmented regions in the middle and end sections of the friction layers remains largely unchanged following the annealing of friction-tested samples. However, there is a noticeable increase in the number of reflections from ultra-dispersed oxides, such as Fe_2O_3, as observed in the electron diffraction patterns.

Thus, the data presented above indicate that each friction layer within the self-organizing wear-resistant coatings results from a distinct process of metal layering on the working surface of the components. The layering of metal microvolumes on the friction surface results in the dissolution of the carbide phase and the saturation of the metal with oxygen from the working environment. In works [8, 9], it was demonstrated that the majority of oxygen and carbon atoms in the friction layers are located within structurally disorganized grain boundary regions as a solid solution. In contrast, the carbon atoms at the grain boundaries of the original metal exist in the carbide phase. It was found in Ref. [9] that carbon atoms in the friction layers occupy two distinct positions within the crystal structure. The first position corresponds to the octahedral interstitial sites of the body-centred cu-

bic (b.c.c.) iron–chromium alloy, while the second position involves an atomic cluster of Fe–O–C, which exhibits an octahedral geometry with oxygen at the centre and two iron atoms at the vertices substituted by carbon atoms. Atomic clusters of Fe–O–C form at the grain boundaries of friction layers due to intense high-speed plastic deformation of metal microvolumes layered on the friction surfaces. They are metastable and, upon annealing of the samples, undergo disintegration, resulting in the formation of a finely dispersed oxide phase (α-Fe_2O_3) and the transition of carbon atoms into octahedral interstitial sites of the body-centred cubic (b.c.c.) iron–chromium alloy.

Zone calculations [9, 25] regarding the influence of impurity atoms on the electronic structure and interatomic bonding reveal that carbon atoms located in the octahedral interstitial sites of body-centred cubic (b.c.c.) iron–chromium alloys establish strong covalent bonds with the surrounding metal atoms. They significantly impede atomic mobility, thereby preventing any structural transformations within the metal. Conversely, regions of reduced electron density are formed between the metastable Fe–O–C atomic clusters and the surrounding metal atoms. Consequently, the limited participation of valence electrons in bond formation between the clusters atoms and the surrounding metal atoms leads to the relatively easy breakage of these bonds when grains shift along the boundaries. This destabilizes the structure and may contribute to the formation of dynamic systems at grain boundaries, which can plasticize the metal, when layered on friction surfaces.

The results of the presented studies elucidate the physical mechanisms underlying the differing reactions to external thermal effects in deformed during the running-in stage metal, as well as in the qualitatively new material of the friction layers. Additionally, these studies facilitate an understanding of how the fragmentation of the structure of surface friction layers affects the stabilization of the materials' physical and mechanical properties in response to external thermal influences.

During the initial stage of friction, plastic deformation of the surface layers of steels disrupts the carbide network of the eutectic component in 130Cr17 steel, resulting in the fragmentation and dispersion of its constituents (see Fig. 4, zone B). In this case, fragmentation of the structure of both steels occurs with minimal spatial disorientation of their grains [8]. At this stage of the friction process, the plastic deformation of the metal does not induce the dissolution of the carbide phase or the saturation of the metal with active chemical elements from the working environment, specifically oxygen atoms. The grain boundaries of the deformed original metal exhibit a relatively regular shape and contain a minor amount of impurity atoms that do not significantly affect the physical and mechanical properties of the material.

Intensive plastic deformation of microvolumes of metal during its layering process on friction surfaces results in significant fragmentation of the structure and spatial disorientation of its grains. In this case, grain boundaries are formed by dislocation clusters and have an extended spatial shape. During the formation of surface friction layers, the carbide phase dissolves, and the metal becomes saturated with active chemical elements from the working environment. This enriches the grain boundaries of the friction layers with carbon (C) and oxygen (O) atoms. These atoms are located in three positions within the crystal structure: Fe–O–C atomic clusters, a fine-dispersed oxide phase (Fe_2O_3), and the octahedral interstitial sites of body-centred cubic (b.c.c.) iron–chromium alloys. It was noted earlier that Fe–O–C atomic clusters are metastable. Annealing of the samples after friction leads to their decomposition, causing carbon atoms to transition into octahedral interstitial sites and resulting in the formation of an oxide phase by oxygen atoms. Therefore, heat treatment of samples after friction results in carbon atoms in the boundary regions of grains being located solely in the octahedral interstitial sites of the b.c.c. iron–chromium alloy, while oxygen atoms form an exclusively finely dispersed oxide phase, α-Fe_2O_3. Their amount at the grain boundaries increases with the degree of fragmentation of the metal structure as ones move along the friction layers in the direction of metal layering. Carbon atoms located in the octahedral interstitial sites of body-centred cubic (b.c.c.) iron–chromium alloys form strong covalent bonds with the surrounding metal atoms. They significantly reduce atomic mobility and enhance the metal-structure resistance to external thermal influences. The presence of a finely dispersed oxide phase at the grain boundaries also contributes to this effect. This alters the physical and mechanical properties of the friction layer material, significantly enhancing its resistance to external thermal influences in comparison to the deformed original metal. In this case, the influence of heat treatment on the strength and elastic characteristics of the metal diminishes as the degree of fragmentation in the structure of the friction-layer material increases (Table 2).

4. CONCLUSIONS

The transition of the friction pair to a stationary operating mode, characterized by minimal wear and a low coefficient of friction, occurs as a result of the self-organization of wear-resistant coatings on the contact surfaces of both components. The quantity of these coatings must be sufficient to shield entirely the original metals that were deformed during the running-in stage. These coatings are composed of a novel ultradispersed and nanostructured material containing up to 25 at.% of oxygen and carbon.

The self-organized wear-resistant coatings consist of distinct friction layers. Each friction layer is formed as a result of a separate act of layering metallic microprotrusions on the friction surfaces. These microprotrusions arise from adhesive interactions between the bodies during the running-in phase of friction. Friction layers differ from the deformed original metal of steels in terms of their high hardness and elasticity. They prevent the formation of strong adhesive bonds between the rubbing bodies, facilitating the transition of the system to a stationary operating mode with a minimum coefficient of friction and wear.

During the operation of sliding bearings, the material of the surface friction layers is subject to intense cyclic thermomechanical effects. Therefore, its ability to retain its unique physical and mechanical properties under extreme conditions of high temperature and pressure determines the behaviour and performance properties of friction units. To analyse the potential influence of external thermal effects on the materials' physical and mechanical properties of the contact interaction zones of steels, samples obtained after friction tests were annealed in a vacuum at 0.01 MPa and at temperatures of 620°C and 720°C during 1 hour. This process resulted in the complete softening of the original metals that were deformed during the running-in stage. Meanwhile, the material of the friction layers maintained high hardness and elasticity, even after annealing at 720°C.

The resistance of the physical and mechanical properties of the surface friction layers to external thermal influences is determined by both the annealing temperature and the degree of material fragmentation. Maximum softening of the metal occurs at the onset of the friction layers, where the microstructure is least fragmented. In contrast, minimal softening is observed in the nanostructured material located at the final section of the friction layers.

The layering of microvolumes of metal on the friction surface induces intensive plastic deformation, leading to significant fragmentation of the microstructure and spatial disorientation of the grains. This explains why the grain boundaries within the surface-friction layers are formed by dislocation clusters and exhibit a spatially extended morphology. During the formation of these layers, the carbide phase dissolves, and the metal becomes saturated with oxygen (O) atoms, which are active chemical elements from the working environment. Consequently, the grain boundaries of the surface friction layers become enriched with carbon (C) and oxygen (O) atoms. Heat treatment of samples following friction results in carbon atoms located solely in the octahedral interstitial sites at the grain boundaries of the surface friction layers in the b.c.c. iron–chromium alloy, while oxygen atoms at these grain boundaries form an exclusively fine-dispersed oxide phase α-Fe_2O_3. The concentration of these elements at the grain bound-

aries increases with the degree of fragmentation of the metallic structure as one moves along the friction layers in the direction of metal layering. Carbon atoms located in the octahedral interstitial sites of body-centred cubic (b.c.c.) iron–chromium alloys form strong covalent bonds with the surrounding metal atoms. They significantly reduce atomic mobility and enhance the metal structure's resistance to external thermal influences. The presence of a finely dispersed oxide phase at the grain boundaries also contributes to this effect. This makes the physical and mechanical properties of the surface friction layers material significantly more resistant to external thermal influences compared to the deformed original metal.

The ability of wear-resistant ultra-fine-grained coatings to maintain high hardness and elasticity under extreme friction conditions in sliding bearings localizes plastic deformation processes to a thin surface layer. This reduces the likelihood of strong adhesive bonds forming between rubbing bodies and facilitates the system transition to a steady-state operating mode with minimal friction and wear.

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