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Influence of Chemical Composition of Abrasive Materials and Strength of Interlayer Boundaries on Impact and Abrasive Wear Resistance of Layered Composite Materials

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Abstract
Introduction. Parts of machines and mechanisms that operate in various conditions and come into contact with abrasive particles can quickly wear out and fail. This is especially true for the hydraulic block of a drilling pump, which, due to intense wear, must be replaced after only 5–10 hours of use when pumping heavy drilling fluids. The analysis of scientific literature and experience with drilling pump operation shows that current methods for increasing the wear resistance of structural steels against abrasive and impact-abrasive forces are ineffective. Thus, it is an urgent task to enhance these properties through improved design and manufacturing techniques for drilling pump components, which would reduce the cost of production, repairs, and maintenance. The aim of this work is to study the effect of chemical composition of abrasive particles and the strength of the interlayer boundaries of "wear-resistant steel — rubber" on the impact and abrasive wear resistance of layered composite materials.
Materials and Methods. Layered composite materials (LCMs) consisted of: a wear-resistant layer of 40X steel and a rubber layer of BK-1675N butyl rubber. The impact and abrasive wear resistance of the LCMs was studied in accordance with GOST 23.207–79 on a special installation. A mixture of silicon oxide and aluminum was used as an abrasive material. The microstructure of the SCMs surface, as well as the chemical and phase composition of the abrasive particles, were analyzed using equipment from the Common Use Center "Nanotechnology" of Platov South-Russian State Polytechnic University (NPI). The adhesive strength between the layers of the LCMs was determined using a custom-built installation.
Results. The results of the study revealed that the wear resistance of the LCMs was several times higher than that of steels used for manufacturing parts resistant to abrasive particles. During the wear process, solid particles of aluminum and silicon oxides actively embed in the surface of the LCMs, increasing the intensity of wear. In contrast, less solid particles of magnesium and calcium aluminates were destroyed and fixed in formed defects on the LCM surface, slightly reducing wear intensity. It was also found that, when SCM layers were joined by hot vulcanization under pressure with a copper concentration of 25–30% in sintered P40X steel, adhesive strength increased to 0.93 MPa.
Discussion and Conclusion. The developed SCMs make it possible not only to increase the abrasive and impact-abrasive wear resistance, but also to use cheaper grades of steels as a wear-resistant layer. The proposed method of joining the SCM layers from sintered steels eliminates the need for additional surface machining and the use of special adhesives. Such SCMs can be used in the assemblies of machine parts and mechanisms that are operated in conditions of abrasive and shock-abrasive wear.

Keywords: impact and abrasive wear resistance, layered composite material, drilling pumps, elastic-dissipative substrate, adhesive strength

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Оригинальное эмпирическое исследование

Влияние химического состава абразива и прочности межслойных границ на ударно-абразивную износостойкость слоистых композиционных материалов

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Аннотация

Введение. Детали машин и механизмов, эксплуатируемые в различных условиях, при контакте с абразивными частицами быстро изнашиваются и выходят из строя. Например, при перекачке тяжелых буровых растворов из-за интенсивного изнашивания детали гидравлического блока бурового насоса через 5–10 часов работы необходимо менять. Анализ научных публикаций и опыт эксплуатации буровых насосов указывают на то, что существующие способы повышения износостойкости конструкционных сталей при абразивном и ударно-абразивно воздействии малоэффективны. Поэтому актуальной задачей является повышение этих свойств в результате совершенствования конструкции и технологии изготовления деталей буровых насосов, что позволит снизить затраты на производство их комплектующих, ремонт и обслуживание. Целью данной работы является исследование влияния химического состава абразивных частиц и прочности межслойных границ «износостойкая сталь — резина» на ударно-абразивную износостойкость слоистых композиционных материалов.

Материалы и методы. Слоистые композиционные материалы (СКМ) состояли из износостойкого слоя стали 40Х и резинового слоя бутилкаучука марки БК-1675Н. Ударно-абразивную износостойкость СКМ рассматривали в соответствии с ГОСТ 23.207–79 на специальной установке. В качестве абразивного материала была взята смесь оксида кремния и алюминия. Изучение микроструктуры поверхности СКМ, химического и фазового состава абразивного порошка проводили на оборудовании ЦКП «Нанотехнологии» ЮРГПУ (НПИ). Адгезионную прочность межслойных границ СКМ исследовали на разработанной для этой цели установке.

Результаты исследования. В результате исследований СКМ на ударно-абразивный износ выявлено, что их износостойкость в несколько раз выше, чем у сталей, используемых для изготовления деталей, устойчивых к воздействию абразивных частиц. Выявлено, что в процессе изнашивания твердые частицы оксидов алюминия и кремния активно внедряются в поверхность СКМ, увеличивая интенсивность износа, тогда как менее твердые частицы алюминатов магния и кальция при ударе разрушаются и закрепляются в образовавшихся дефектах на поверхности СКМ, незначительно снижая интенсивность износа. Установлено, что при соединении слоев СКМ методом горячей вулканизации под давлением и концентрации меди 25–30 % в спеченной стали П40Х адгезионная прочность повышается до 0,93 МПа.

Обсуждение и заключение. Разработанные СКМ позволяют не только повысить абразивную и ударно-абразивную износостойкость, но и в качестве износостойкого слоя использовать более дешевые марки стали. Предложенный способ соединения слоев СКМ из спеченных сталей исключает необходимость в дополнительной механической обработке поверхности и в использовании специальных клеящих составов. Такие СКМ могут использоваться в узлах деталей машин и механизмов, которые эксплуатируют в условиях абразивного и ударно-абразивного износа.

Ключевые слова: ударно-абразивная износостойкость, слоистый композиционный материал, буровые насосы, упруго-диссипативная подложка, адгезионная прочность

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Для цитирования. Исмаилов М.А. Влияние химического состава абразива и прочности межслойных границ на ударно-абразивную износостойкость слоистых композиционных материалов. *Безопасность техногенных и природных систем.* 2024;8(3):88–96. https://doi.org/10.23947/2541-9129-2024-8-3-88-96

Introduction. The main reason for the decrease in the operational reliability of parts and mechanisms in mining [1], oil and gas [2], construction, road and processing industries [3] is the impact of various types of wear, such as abrasive, shock-abrasive, corrosive, and fatigue and others [4]. For example, scientific research and operational experience with drilling pumps have shown that the hydraulic block components are more susceptible to abrasive and shock-abrasive wear.

The analysis of scientific publications has shown that materials developed for operation in impact and abrasive wear conditions must have high hardness, viscosity and wear resistance [5]. However, the experience of operating drilling pumps [6] indicates that one of the reasons for the decrease in the operational reliability of valve parts is the low impact and abrasive wear resistance of structural steels [7] and sealing elastic elements [8]. Therefore, an urgent task is to develop a technology for producing layered composite materials in which one of the layers is made of a wear-resistant material, and the other is made of an elastic-dissipative one, for example, based on rubber mixtures, which allows absorbing part of the impact energy acting on the part.

Materials and Methods. Layered samples were made for testing, one layer of which was made of wear-resistant steel (Fig. 1, pos. 1), and the other, elastic layer was made of BK-1675N butyl rubber (Fig. 1, pos. 2). As wear-resistant steel, we used:

– rolled steel 40X, which was subjected to heat treatment — quenched at 860°C with oil cooling and tempered at 200 and 570°C with air cooling;

– sintered and hot-formed steel P40X.

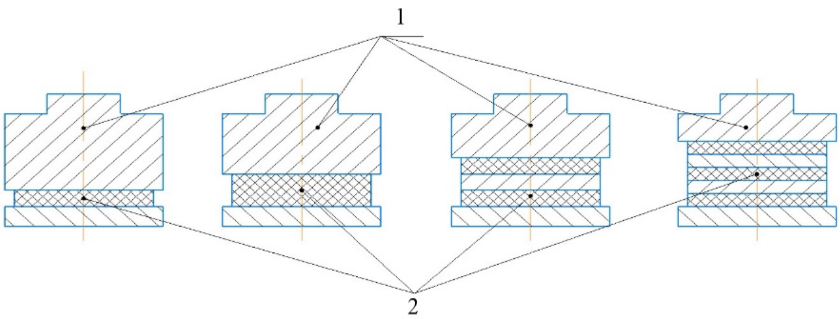


Fig. 1. Samples of LCMs for testing for impact and abrasive wear resistance:
1 — wear-resistant material; 2 — elastic-dissipative substrate

The impact and abrasive wear resistance of layered samples was tested in accordance with GOST 23.207-79[1] on a special installation [9]. The principle of operation of the installation was based on the forced impact of the sample on the counterbody through a layer of abrasive. The wear of the samples was estimated by the lost mass after 1000 strokes on analytical scales OHAUS Pioneer PA [10].

GOST 23.207–79 "Ensuring of wear resistance of products. Testing of engineering materials for impact abrasive wear" recommends to use silicon carbide as an abrasive to compare the abrasive and impact-abrasive wear resistance of various materials. However, in relation to the specific operating conditions of machines and mechanisms, GOST allows the use of an appropriate abrasive material. For example, to increase the density of drilling fluids, various weights are used, the choice of which will depend on the specific drilling conditions. In the case where weights with greater abrasiveness are required, various abrasive materials are used [11]. Therefore, a mixture of silicon and aluminum oxides was used as an abrasive when testing for impact and abrasive wear resistance.

Microstructure of the LCMs surface after testing for impact and abrasive wear resistance, X-ray studies and qualitative phase analysis of the abrasive powder were carried out at the Common Use Center "Nanotechnology" of Platov South-Russian State Polytechnic University (NPI).

To study the adhesive strength, the samples of rolled steel 40X, sintered and hot-deformed steel P40X were glued to rubber in two ways: with an adhesive based on chloroprene rubber and by hot vulcanization under pressure at a temperature of 160°C for 20 minutes without glue [12]. The adhesive strength of the interlayer boundaries of LCMs was studied using the installation developed for this purpose [13].

Results. Tests with impact energy from 3 to 23 J showed that 40X steel samples wear significantly more after improvement than samples after low tempering (Fig. 2, curves 1 and 3). At the same time, the use of elastic-dissipative substrate (UDS) reduced wear by 1.5–2 times (Fig. 2, curves 2 and 4), compared with samples that were tested without a substrate (Fig. 2, curves 1 and 3).

[1] GOST 23.207-79. *Ensuring of wear resistance of products. Testing of engineering materials for impact abrasive wear.* URL: https://docs.cntd.ru/document/1200010682 (accessed: 22.05.2024). (In Russ.)

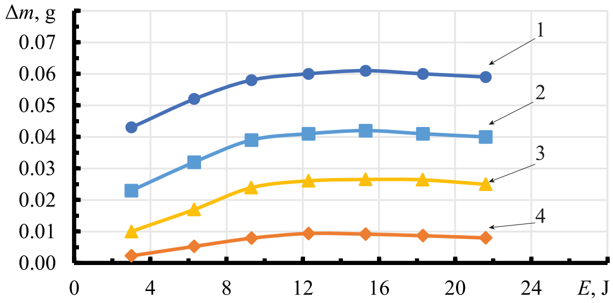
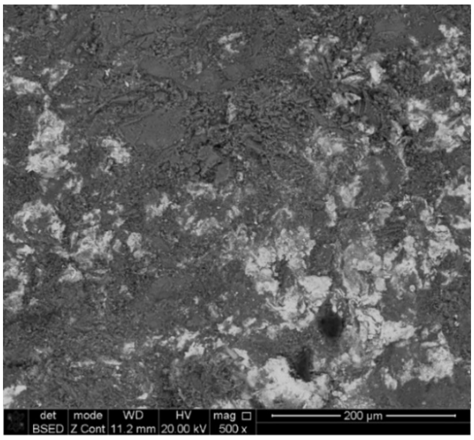
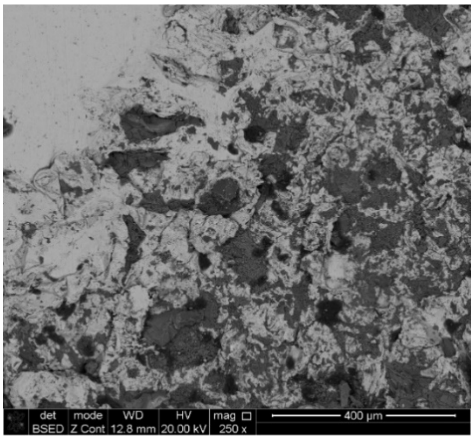


Fig. 2. Dependence of wear (Δm) on impact energy (E) without (1, 3) and with a rubber substrate (2, 4) LCMs with a working layer of 40X steel after improvement (1, 2) and low tempering (3, 4)

In Figure 2, it can be seen that with an increase in the impact energy, the wear intensity of the samples changed, and two sections could be distinguished. At the first stage, with an increase in the impact energy to 12 J, the wear of the samples increased as a result of the introduction of abrasive particles into their surface (Fig. 3 *a*) and into the grain boundaries (Fig. 3 *b*), which contributed to intensive chipping of micro-volumes of metal. In the second section, with a further increase in the impact energy, as a result of plastic deformation, the upper layer of the sample was strengthened, and abrasive particles, collapsing, loaded its surface, resulting in a slight slowdown in the intensity of wear.



a)



b)

Fig. 3. Microstructure of the working layer surface made of improved 40X steel:
a — in the steady state of wear; *b* — at the stage of intensive wear

X-ray phase analysis showed that the abrasive powder mainly consisted of aluminum and silicon oxides, magnesium and calcium aluminates (Fig. 4). Phase composition of the abrasive did not change after wear resistance tests.

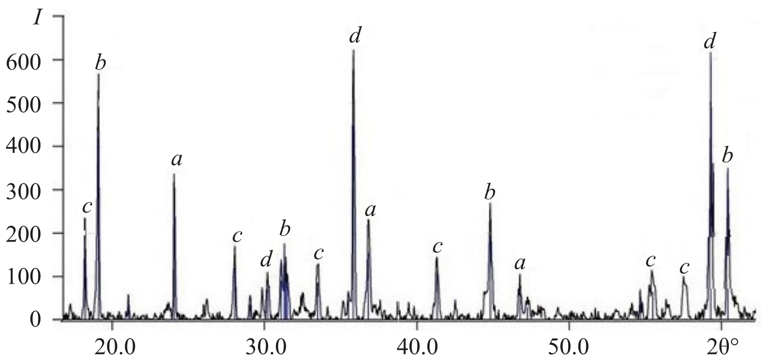
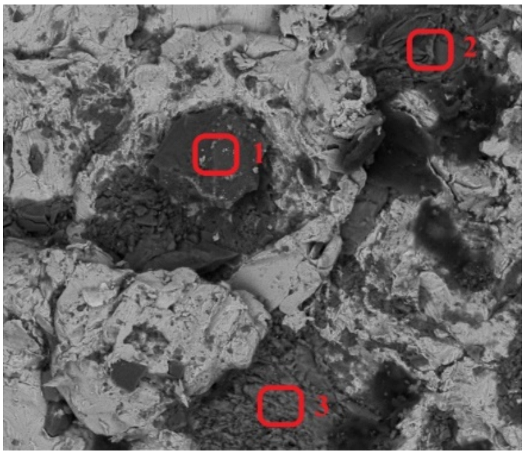


Fig. 4. Phase composition of the abrasive powder used in tests for impact and abrasive wear:
a — SiO_2; *b* — $MgAl_2O_4$; *c* — $CaAl_2O_4$; *d* — Al_2O_3

After the impact resistance test, there were areas with particles of silicon and aluminum oxides on the surface of 40X steel rings, which, penetrating into the surface of the sample, formed wells and activated the destruction process at the initial stage (Fig. 5 *a*). Magnesium aluminate particles (Fig. 5 *a*, pos. 2) due to the lower hardness (Mohs scale hardness 7.5–8), compared with aluminum oxide particles (Mohs scale hardness 9), with increasing impact energy, partially penetrated into the surface of the sample, and most of them were destroyed. Calcium aluminate particles

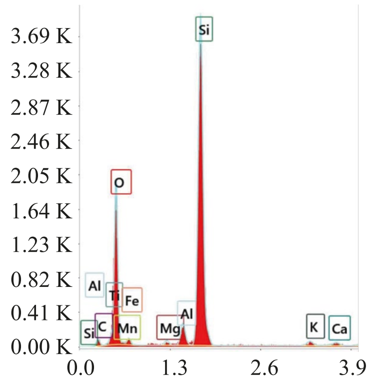
(Fig. 5 *a*, pos. 3) due to low hardness, at all values of the impact energy, actively loaded the LCMs surface (Fig. 3 *a*). Figures 5 *b–g* provide chemical composition of the test surface in the abrasive particles area.



a)

Element	Weight %	MDL	Atomic %	Error %
C K	3.4	2.30	5.8	31.7
O K	45.8	0.35	59.5	10.3
Mg K	0.7	0.15	0.6	17.0
Al K	2.7	0.13	2.1	8.9
Si K	38.1	0.11	28.2	5.1
K K	1.0	0.25	0.5	19.3
Ca K	0.9	0.24	0.5	21.2
Ti K	1.0	0.34	0.4	18.2
Mn K	0.8	0.38	0.3	29.0
Fe K	5.6	0.41	2.1	7.1

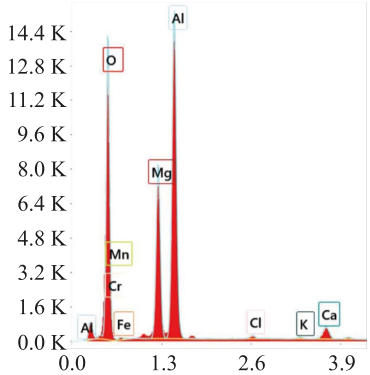
b)



c)

Element	Weight %	MDL	Atomic %	Error %
O K	42.8	0.08	57.0	9.2
Mg K	15.4	0.06	13.5	7.0
Al K	31.9	0.07	25.2	6.7
Cl K	0.4	0.08	0.2	19.7
K K	0.3	0.10	0.1	21.8
Ca K	2.1	0.11	1.1	5.5
Cr K	4.6	0.16	1.9	4.2
Mn K	0.3	0.20	0.1	35.0
Fe K	2.2	0.19	0.8	6.5

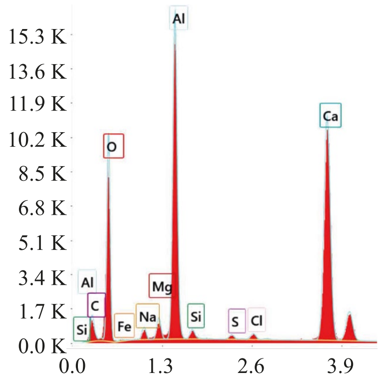
d)



e)

Element	Weight %	MDL	Atomic %	Error %
C K	6.1	0.34	10.5	12.7
O K	45.5	0.12	58.8	10.5
Na K	1.4	0.09	1.3	11.4
Mg K	1.5	0.05	1.2	9.1
Al K	18.6	0.05	14.2	6.3
Si K	0.6	0.05	0.4	10.6
S K	0.3	0.05	0.2	15.7
Cl K	0.4	0.05	0.3	11.4
Ca K	24.7	0.07	12.7	2.4
Fe K	0.9	0.12	0.3	8.7

f)



g)

Fig. 5. Microstructure (*a*) and distribution of components in abrasive particles on the surface of improved 40X steel at the stage of intensive wear: *b, c* — silicon oxide; *d, e* — magnesium aluminate; *f, g* — calcium aluminate

Studies showed that the operational reliability of LCMs was significantly affected by the adhesive strength of the interlayer boundaries. The adhesive strength of the interlayer boundaries of LCMs "steel — rubber" bonded with glue based on chloroprene rubber (Fig. 6, *1*) and hot vulcanization (Fig. 6, *2*) differed significantly.

Figure 6 shows that LCMs bonded with glue had greater adhesive strength with rubber than LCMs connected by hot vulcanization under pressure. The adhesive strength of the samples made of P40X steel with rubber was almost the same when using both bonding methods and amounted to 0.21 and 0.2 MPa, respectively (Fig. 6 *c* and Fig. 6 *d*).

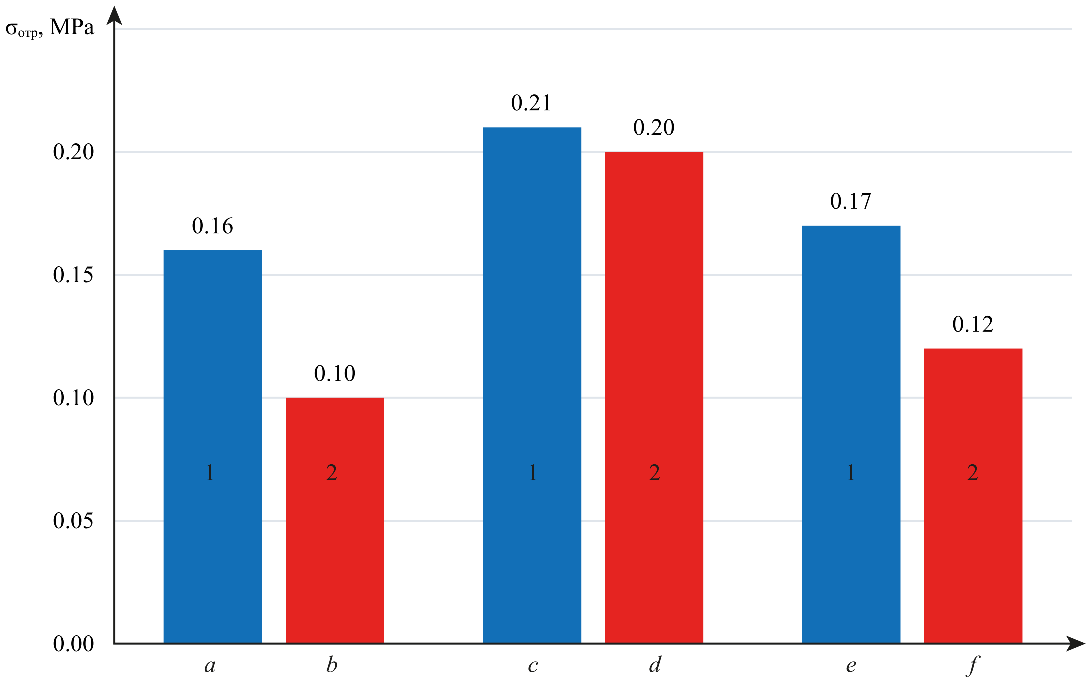


Fig. 6. Dependence of the adhesive strength of LCMs on the technology of obtaining steel samples:
a, b — rolled 40X; *c, d* — sintered P40X; *e, f* — hot-deformed P40X

When tested for impact and abrasive wear resistance, LCMs bonded with glue were destroyed due to overstress along the metal-rubber boundary, due to their significantly different stiffness, degree of deformation and the complex stress state that occurred as shear deformations developed [14].

Therefore, further research was aimed at increasing the adhesive strength of sintered P40X steel with rubber connected by hot vulcanization. One of the ways to increase the adhesive strength was to add copper to the charge (Fig. 7), which, when sintered above its melting point, spread over the free surface of the particles and interparticle boundaries under the influence of surface tension forces. This helped to increase the surface porosity of the compacts.

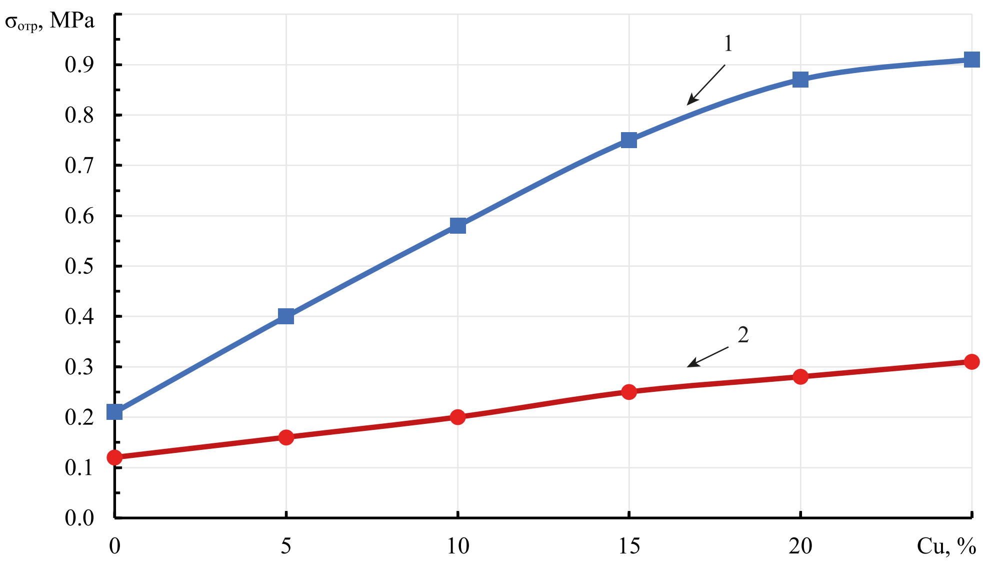
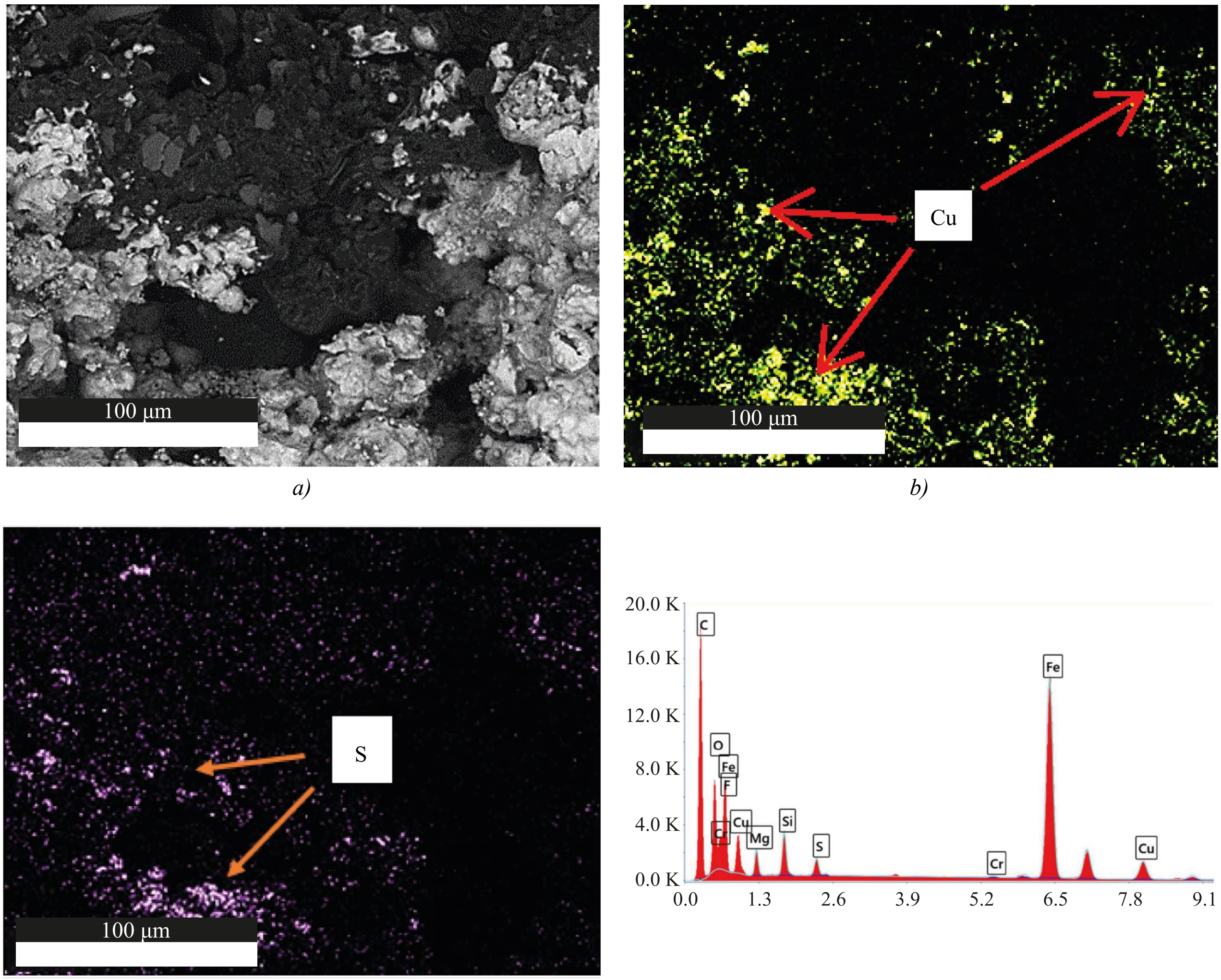


Fig 7. Effect of copper on the adhesive strength of LCMs made of sintered (1) and hot-deformed steel P40X (2)

Figure 7 shows that an increase in the concentration of copper in sintered P40X steel led to an increase in the adhesive strength of LCMs from 0.1 to 0.93 MPa, while the strength of the interlayer boundaries of LCMs with hot-formed steel increased slightly (from 0.05 to 0.3 MPa) due to the fact that during dynamic hot pressing, the surface was smoothed and most pores closed.

During hot vulcanization under pressure, crude rubber was pressed into the pores on the surface of sintered steel P40X (Fig. 8 *a*) and copper and iron sulfidation occurred in the process, and intermediate copper sulfide films of nonstoichiometric composition of Cu_xS type were formed between copper particles and rubber [15], which increased the adhesion of rubber to the matrix of sintered steel.



a) *b)* *c)* *d)*

Fig. 8. Microstructure of the LCM transition zone:
a — sintered steel — rubber; *b* — distribution of copper; *c* — sulfur; *d* — other elements

The analysis of the results of mapping the interlayer boundary of the sintered steel—rubber LCM revealed the distribution zones of copper (Fig. 8 *b*) and sulfur (Fig. *8 c*) elements. Thus, in the areas enriched with copper, due to the formation of copper sulfides, the concentration of sulfur increased, which led to an increase in the LCMs adhesion.

Discussion and Conclusion. The studies have shown that the intensity of impact-abrasive wear depends on the structure of 40X steel, the impact energy and the chemical composition of abrasive particles. It was found that with an increase in the impact energy from 3 to 9 J, the intensity of abrasive wear of 40X steel samples increases and does not depend much on the type of heat treatment. This is due to the fact that at these values of impact energy, abrasive solids are actively embedded in the surface of the sample, triggering the mechanism of impact-abrasive wear. An increase in the impact energy from 9 to 22 J leads to a decrease in the intensity of wear due to the fact that solid abrasive particles of silicon and aluminum oxide, magnesium aluminate, without having time to penetrate into the surface of the sample, break down into smaller parts and form smaller wells, and calcium aluminate particles actively break down, fixing themselves in the formed wells, micropores and other defects.

It was found that when adding from 5 to 20% of copper to the charge, the adhesive strength of the interlayer boundaries of the steel—rubber LCM increased by 3–4 times as a result of the spreading of copper under the influence of surface tension forces over the free surface of particles and interparticle boundaries, as well as the formation of Cu_xS copper sulfides during hot vulcanization under pressure.

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