Received: 20.08.2021
Revised: 20.10.2021
Accepted: 29.10.2021
DOI: 10.17804/2410-9908.2021.5.24-35

APPROACHES TO THE DEVELOPMENT OF WEAR-RESISTANT LAMINATED METAL COMPOSITES

R. A. Savrai[1*], S. V. Gladkovsky[1], S. V. Lepikhin[2], and Yu. M. Kolobylin[1]

[1]*Institute of Engineering Science, Ural Branch of the Russian Academy of Sciences, 34 Komsomolskaya St., Ekaterinburg, 620049, Russian Federation*
[2]*Glazov State Pedagogical Institute named after V.G. Korolenko, 25, Pervomaiskaya street, Glasov, Udmurt Republic, Russian Federation, 427621*

a) http://orcid.org/0000-0001-9873-3621 ras@imach.uran.ru;
b) http://orcid.org/0000-0002-3542-6242 gsv@imach.uran.ru;
c) http://orcid.org/0000-0002-0240-2164 lepichin@mail.ru;
d) http://orcid.org/0000-0002-7831-2624 uramk@mail.ru

*Corresponding author. E-mail: ras@imach.uran.ru
Address for correspondence: 34 Komsomolskaya St., Ekaterinburg, 620049, Russian Federation

Layered metal composites made of dissimilar metals and alloys occupy a special place among modern composite materials. In particular, their use is considered promising when high strength, fatigue resistance, and wear resistance are required. However, there are few data on the abrasive wear resistance of such composites, and further study is necessary. In this paper, an attempt is made to formulate some approaches to the development of wear-resistant laminated metal composites in order to promote more detailed research. For this purpose, the abrasive wear resistance at room (+25 °C) and cryogenic (−196 °C) temperatures of a layered metal composite consisting of low-alloy and maraging steels was studied. The composite was obtained by explosive welding. It is shown that the wear resistance of the composite is determined by the combined influence of a number of factors, namely the presence of interlayer boundaries, the structural state, hardness, and toughness of the steels. It is concluded that, for better wear resistance of a layered composite, the dissimilar layers must wear out evenly under existing environmental conditions.

Keywords: laminated metal composite, microstructure, microhardness, abrasive wear.

1. Introduction

Wear is one of the main factors limiting the service life of machine parts and structures for various purposes. The most common type of wear is abrasive wear. Abrasive particles are present in almost all natural and technological environments. The danger of abrasive wear is also due to the fact that it causes a relatively rapid failure of the working surfaces. Therefore, the reduction of losses from abrasive wear is an important scientific and practical task. For solving this task, the development of new wear-resistant materials and coatings, including composites, is constantly underway [1–16]. Among promising modern composite materials, layered metal composites made of dissimilar metals and alloys occupy a special place. The physical and mechanical properties of the composites can significantly exceed those of their constituents at room, elevated, and lowered temperatures. The use of such materials is considered promising in cases where high strength, fatigue resistance, and wear resistance are required [17–24]. However, in the literature there are few data on the abrasive wear resistance of laminated metal composite materials [12].

Thus, the aim of the research is to study the abrasive wear resistance at room (+25 °C) and cryogenic (−196 °C) temperatures of a layered metal composite consisting of low-alloy and

maraging steels and to formulate approaches to the development of wear-resistant laminated metal composites. The composite was obtained by explosive welding. The choice of parameters and the wear test scheme was due to the fact that such composites are expected to be used in parts and structural elements of transport systems operating at low climatic temperatures. It is known that the wear of road vehicles is abrasive in 60 % of cases. This is due to the negative effect of dust and fine sand particles falling into the gaps of tribological couples. Wear of this type is found in parts of running gears, pin joints, open sliding bearings, and working bodies of road vehicles. The choice of materials for the constituents of the composite was based on low carbon content in both steels (0.12 wt% in the low-alloy steel and 0.02 wt% in the maraging steel), which provides them with good deformability in a wide temperature range. It also makes it possible to conduct such heat treatment of the composite that the layers of the maraging steel become as hard as possible and those of the low-alloy steel become more ductile [19]. Besides, maraging steels have a high resistance to brittle fracture and a low cold brittleness threshold, which can have a positive effect on wear resistance at low climatic and cryogenic temperatures. However, this requires additional research.

2. Experimental procedure

The structural low-alloy GOST 09G2S and maraging GOST EP678 steels were used as the constituents of the composite. Table 1 shows the chemical composition of the steels, which was determined by means of a SPECTROMAXx F optical emission spectrometer.

Table 1. Chemical composition of the steels constituting the composite, wt%

Steel	C	Si	Mn	Cr	Ni	Mo	P	S	Al	Ti	Cu	Nb
Low-alloy steel	0.12	0.68	1.32	0.07	0.07	0.01	0.020	0.010	0.04	–	0.12	–
Maraging steel	0.02	0.16	0.08	10.65	9.35	1.97	0.004	0.004	0.09	0.90	0.10	0.09

Prior to forming the composite, initial low-alloy steel sheets with dimensions of 95Ч85Ч2 mm were normalized by heating to a temperature of 860 °C and holding at this temperature for 2 hours followed by cooling in air. Maraging steel sheets with dimensions of 95×85×50 mm were quenched by heating to a temperature of 920 °C and holding at this temperature for 30 min followed by cooling in water. To form the ultrafine-grained microstructure, the sheets of maraging steel were subjected to further processing, which included multidirectional (six-fold) isothermal forging in the temperature range of 850–700 °C and at a strain rate ranging between 1×10^{-3} and $5Ч10^{-3}$ s^{-1} using a PA2638 hydraulic press, with subsequent multi-pass warm rolling at a temperature of 700 °C using a DUO-300 mill. The thickness of the sheets was 24 mm after the forging and 1 mm after the rolling.

The laminated composite was formed by explosive welding [25–28]. Welding of a package of the steel sheets was carried out in one step according to a symmetrical angular scheme (Fig. 1). The multilayer package consisted of four alternating sheets of the low-alloy steel with a thickness of 2 mm and three sheets of the maraging steel with a thickness of 1 mm, the outer sheets being the low-alloy steel ones. The maximum distance between the sheets was 7 mm. Ammonite was used as an explosive for welding. After the welding, the laminated composite was cut into two parts, one of which was left in its original state, and the other was subjected to heat treatment by heating to a temperature of 500 °C and holding at this temperature for 3 hours followed by cooling in air.

The microstructure and features of the interlayer boundaries of the laminated composite, as well as the microstructure of the steels constituting the composite, were studied using a Neophot-21 optical microscope and a Tescan Mira 3 LMH scanning electron microscope (SEM) with an electron backscatter diffraction (EBSD) analysis system. The microhardness was determined by means

of a Shimadzu HMV-G21DT instrument at a load of 0.49 N, with a loading speed of 40 мм/s and holding under load for 15 s.

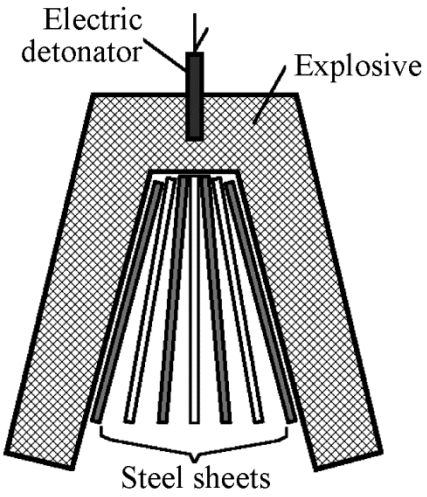


Fig. 1. Schematic formation of the laminated composite by explosive welding

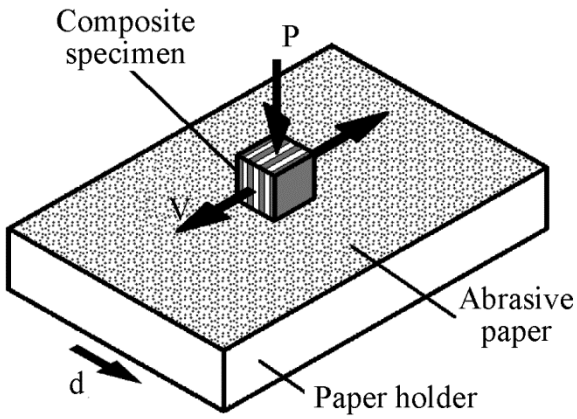


Fig. 2. Schematic abrasive wear resistance testing

Testing for abrasive wear resistance was carried out using a laboratory tribological setup according to the "pin-plate" scheme [29] in air (at a temperature of +20 °C) and in liquid nitrogen (at a temperature of −196 °C) by reciprocating sliding of the composite specimens over a fixed electrocorundum with a grain size of 160 мм (GOST 14A 16-N abrasive paper) at a load P of 20 and 50 N, an average sliding speed V of 0.175 m/s, a stroke length of 90 mm and a transverse displacement d of 1.2 mm (without unloading) after each reciprocating stroke of the specimen (Fig. 2). In this case, the total length of the friction path L was 14.2 m. The rationale for the structure of the wear test system, as well the parameters chosen, is that the "pin-plate" scheme avoids noticeable frictional heating of specimens. In this case, the effect of temperature can be clearly determined by external cooling. Prismatic specimens with dimensions of 10Ч10Ч10 mm were used. Before the testing, the specimens were rubbed until uniform contact of the specimen surface with the abrasive was achieved. The sliding of the composite specimens was performed both along (as shown in Fig. 2) and across the layers. To test the wear resistance of the steels constituting the composite, the composite was divided into separate layers. The testing of the specimens, which represented individual layers of the low-alloy and maraging steels, was conducted on the bonding area of the layers. Thus, the area S of the test surface of the composite specimens and the steels constituting the composite was 1 cm^2. Four repeats were made at each load and temperature. The specimens were weighed by means of laboratory scales with an accuracy of 0.00005 g before and after the tribological tests. As a result of weighing, the weight loss of the specimens Q was determined. The rate of abrasive wear was calculated by the formula [30]

$$I_h = \frac{Q}{\rho SL}, \quad (1)$$

where I_h is wear rate, dimensionless; Q is weight loss, g; c is the average density of the specimen material, g/cm^3; S is the geometric contact area of the specimen with the abrasive, cm^2; L is the total length of the friction path, cm.

3. Results and discussion

3.1. Structure and microhardness

As a result of explosive welding of the sheets of the low-alloy and maraging steels, a seven-layer composite is formed (Fig. 3). Note that almost diffusionless bonding of metals occurs during explosion welding [31, 32]. This is confirmed by a sharp difference in the chemical composition between the layers of the five-layer composite obtained from similar steels [19]. Figure 3 also shows that the interlayer boundaries are practically free of non-metallic inclusions or welding defects, such as pores, incomplete penetrations and discontinuities. Besides, both wavy and plane interlayer boundaries are formed, which may contain vortex zones with local molten areas (indicated by arrows in Fig. 3). This is typical for explosive welding and primarily due to the collision velocity of the welded sheets [32]. However, for each combination of the materials and the collision angle, there are critical values of the collision velocity, at which the shape of the interlayer boundary changes from plane to wavy. It is believed that the shape of the boundary does not significantly affect the quality of the joints produced by explosive welding, but the presence of complexly shaped interlayer boundaries somewhat increases the bonding strength of the welds [32].

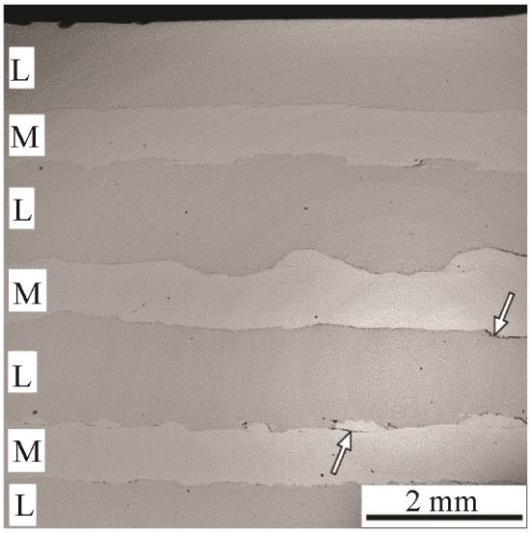
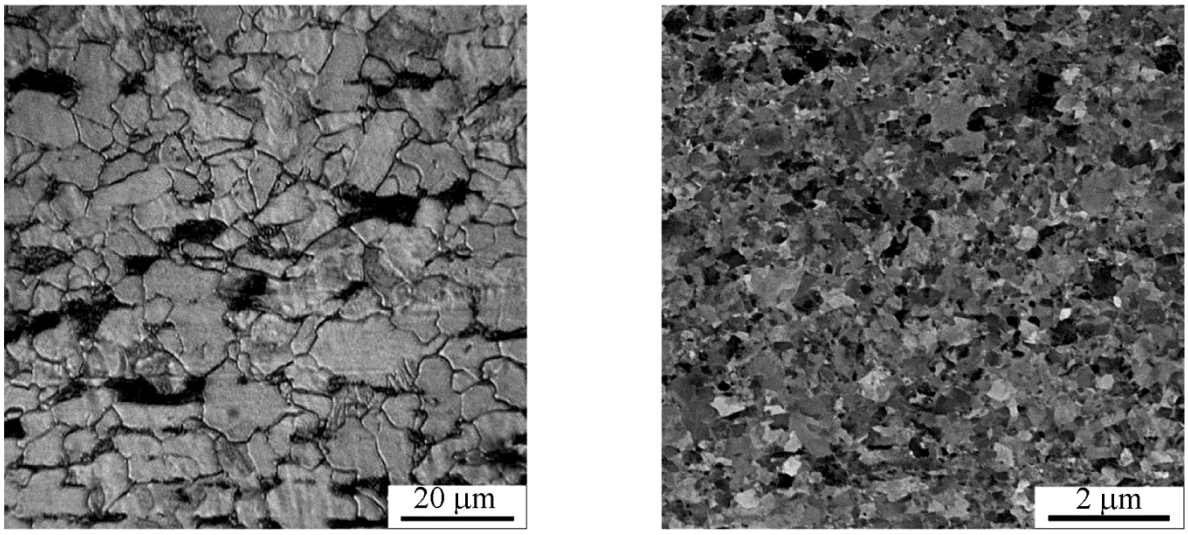


Fig. 3. The structure of the seven-layer composite obtained by explosive welding:
L – the low-alloy steel layers; M – the maraging steel layers. The arrows indicate vortex zones with local molten areas

The study of the microstructure of the as-welded laminated composite by optical and scanning electron microscopy has shown that the low-alloy steel layers have a ferrite-pearlite structure with a pearlite content of 10 % and an average size of ferrite grains of 10–12 мм (Fig. 4a). The maraging steel layers have a homogeneous ultrafine-grained structure (Fig. 4b) with an average crystallite size of 187±47 nm according to the results of EBSD analysis (Fig. 5). It contains fragmented batch martensite, some amount of retained austenite (up to 10 %), and a small fraction of primary carbonitrides, this being consistent with the available data [33]. Near the interlayer boundaries, the mixing of the steels is observed, and on the side of the low-alloy steel layers there is an up to 5 мм wide dispersed zone with a crystallite size of 0.5 to 2 мм (see Fig. 5). The microstructure of the maraging steel layers is homogeneous over the entire width of the layers.



a b

Fig. 4. The microstructure of the low-alloy (a, optical microscopy) and maraging (b, SEM) steel layers constituting the as-welded composite

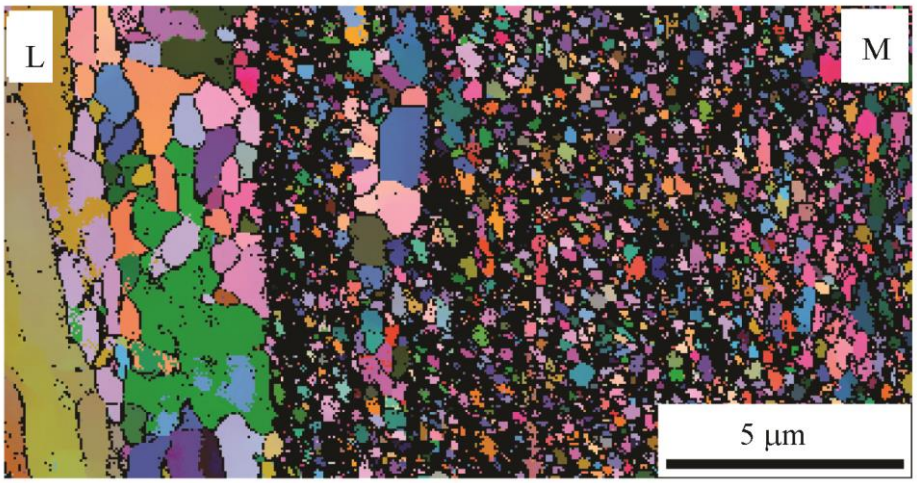


Fig. 5. The EBSD grain map of the interlayer boundary formed within the as-welded composite: L – the low-alloy steel layer; M – the maraging steel layer

After additional heat treatment of the composite (heating at 500 °C), the microstructure of the low-alloy steel layers remains unchanged according to the optical microscopy; however, carbon redistribution and coarsening of carbides must occur in the steel [19]. No visible changes in the microstructure of the maraging steel layers were also observed by optical microscopy; however, the formation of intermetallic phases must occur in the steel heated above 400 °C [34–36]. At the aging temperature of 500 °C, the main hardening phase is the Ni_3Ti intermetallide with an h.c.p. structure. The retained austenite, which is present in the structure of the maraging steel, becomes depleted of alloying elements during the heat treatment due to the formation of new phases and partially turns into martensite when the aged steel is cooled to room temperature. This reduces the content of retained austenite to about 5 %. Consequently, after additional heat treatment, the microstructure of the maraging steel mainly consists of batch martensite and dispersed particles of intermetallic phases.

Figure 6 shows the microhardness of the laminated composite. It can be seen that, for the as-welded composite, the average microhardness of the low-alloy steel layers is 250 HV0.05, and that of the maraging steel layers is 460 HV0.05. As expected, the hardness of the maraging steel with an

ultrafine-grained structure is significantly higher than that of the low-alloy steel with a ferrite-pearlite structure. After the additional heat treatment of the composite, the microhardness of the low-alloy steel layers decreased to 220 HV0.05, and that of maraging steel layers, on the contrary, increased to 520 HV0.05. The observed change in the hardness of the heat-treated composite is caused by the corresponding structural changes, namely carbon redistribution and coarsening of carbides for the low-alloy steel and the formation of intermetallic phases and the austenite to martensite transformation for the maraging steel. Note that the heat treatment of the composite increases the difference in the hardness of the layers.

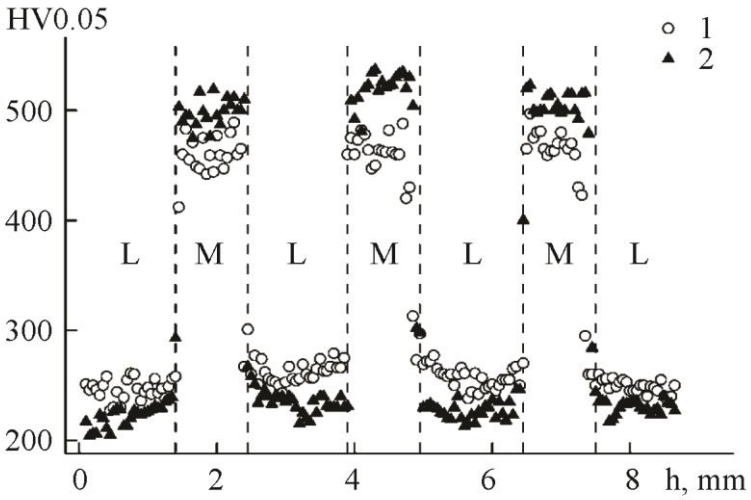


Fig. 6. Distribution of microhardness HV0.05 over the cross section of the as-welded (1) and heat-treated (2) composite: L – the low-alloy steel layers; M – the maraging steel layers

3.2. Abrasive wear resistance

Table 2 and Figs. 7 and 8 show the results of testing the laminated composite and its constituents for abrasive wear resistance. Note that testing along and across the layers reveal no significant difference in the specimen properties. Therefore, the results of testing along the layers are given.

Table 2. Wear rate I_h of the composite and its constituents during abrasive wear testing under different conditions

Specimen	I_h, 10^{-6}			
	T = +25 °C		T = −196 °C	
	P = 20 N	P = 50 N	P = 20 N	P = 50 N
Low-alloy steel	4.4±0.2	10.6±0.1	2.9±0.1	7.4±0.1
Maraging steel	4.6±0.1	10.6±0.1	2.1±0.1	6.1±0.1
As-welded composite	3.9±0.1	9.3±0.1	3.3±0.1	7.5±0.1
Heat-treated composite	3.5±0.1	8.8±0.1	3.5±0.1	8.0±0.1

It can be seen from Table 2 that, at the test temperature of +25 °C, the wear rate of the low-alloy and maraging steels does not differ significantly and that the wear rate of the seven-layer composite is lower (wear resistance is higher) than that of the steels constituting the composite. Specifically, the decrease of I_h is 11 to 15 % under a load of 20 N and 12 % under a load of 50 N

i.e. it is approximately the same (see Table 2). This may be due to the influence of the interlayer boundaries, which complicate the separation of wear products from the specimen surface. Besides, the dispersed structure of the low-alloy steel near the interlayer boundaries (see Fig. 5) also contributes to the increased wear resistance of the composite since the increase in the length of grain boundaries can lead to additional local hardening of the material under wear due to blocking the motion of dislocations [37].

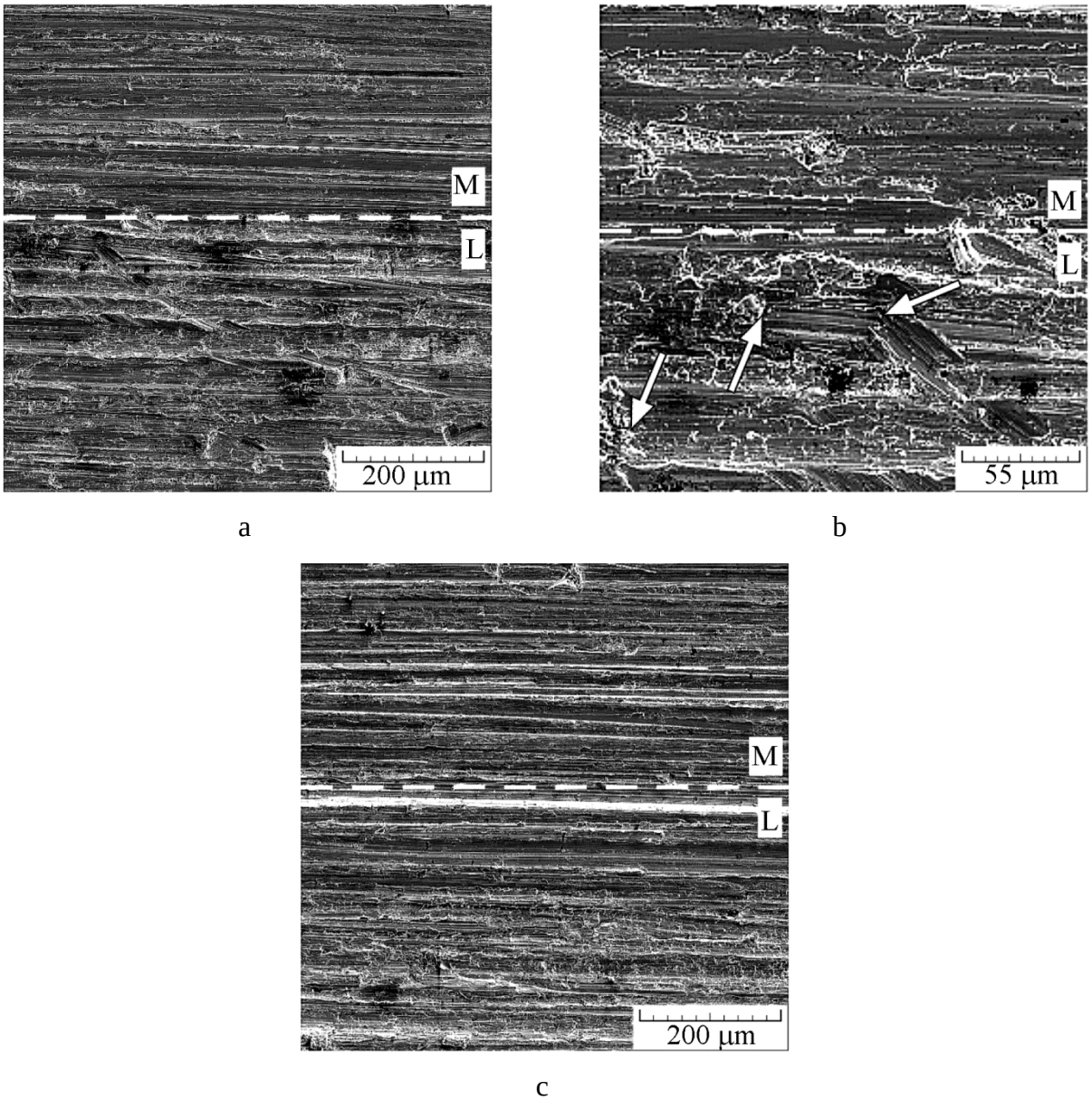


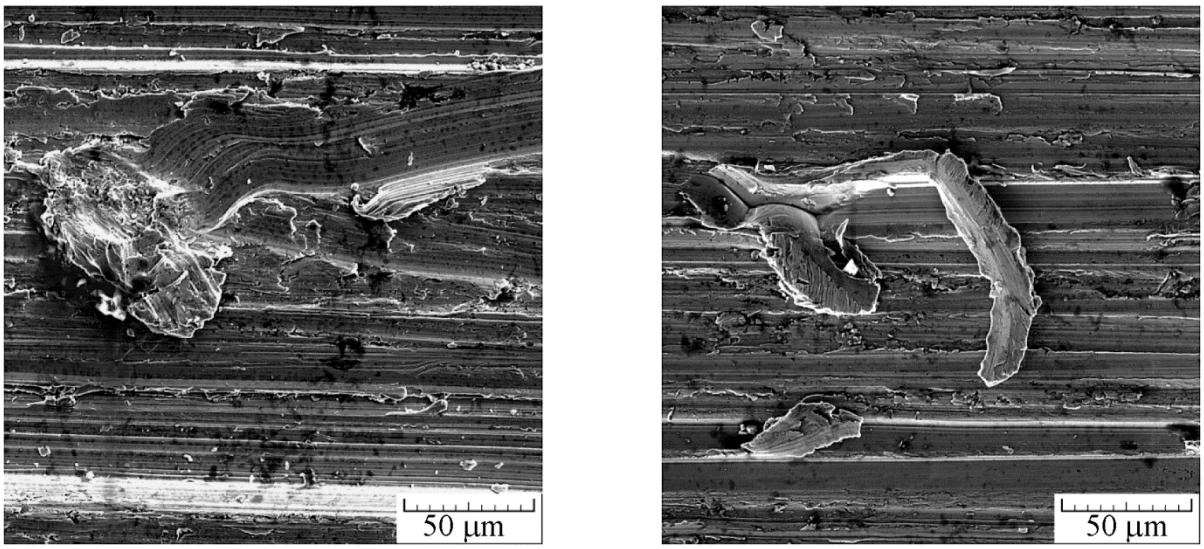
Fig. 7. Worn surfaces (SEM) after the testing of the as-welded composite for abrasive wear resistance under a load of 50 N at temperatures of +25 °C (a, b) and −196 ° C (c): L – the low-alloy steel layer; M – the maraging steel layer. The dashed line denotes the interlayer boundary, and the arrows in (b) indicate the terminated wear grooves

SEM investigation has shown that the worn surfaces have an oriented roughness with wear grooves, which is typical of abrasive wear. The predominant wear mechanism is microcutting, as evidenced by the sharp edges of the wear grooves (Fig. 7). As a rule, microcutting is observed when the hardness of the abrasive is more than 1.3 times as high as that of the tested material [38], and the hardness of the electrocorundum, which is about 2000 HV, is more than 3 times as high as that of

the steels constituting the composite (see Fig. 6). However, the low-alloy steel is characterized by wide wear grooves compared to the maraging steel, this being due to a significant difference in the dispersity of their structure (see Figs. 4 and 5). It should also be noted that some wear grooves (indicated by arrows in Fig. 7b) terminate near the interlayer boundary. This confirms the earlier assumption that the interlayer boundaries complicate the separation of wear products from the surface of the specimen under wear. In the absence of the interlayer boundaries, this process could continue and lead to a greater wear of the specimen. It is also important to emphasize that the interlayer boundaries affect the wear resistance of the composite when tested both along and across the layers, and this may be due to the presence of wavy boundaries (see Fig. 3).

Heat treatment at 500 °C for three hours additionally decreases the composite wear rate determined at a test temperature of +25 °C; this is due to the increasing microhardness of the maraging steel layers (see Fig. 6). Specifically, the decrease in the I_h is 10 % at a load of 20 N and only 5 % at a load of 50 N (see Table 2). Since the heat treatment decreases the microhardness of the low-alloy steel layers (see Fig. 6), a decrease in the wear resistance of these layers is also expected. Apparently, as the test load increases, the influence of low-alloy steel layers on the wear rate of the composite becomes more significant.

At the test temperature of −196 °C, there is a substantial difference in the wear rate of the steels constituting the composite, with the wear rate of the maraging steel being significantly lower than that of the low-alloy steel. Specifically, the value of I_h of the maraging steel is lower than that of the low-alloy steel by 28 % at the load of 20 N and by 18 % at the load of 50 N (see Table 2). The predominant wear mechanism is microploughing, as evidenced by the blunted edges of the wear grooves, and low-cycle fatigue microcracking (see Fig. 7c). It is known that the abrasive wear resistance of a material is determined by both its hardness and toughness since the embrittlement of the material facilitates the separation of wear products from the specimen surface [39]. Obviously, at a temperature of −196 °C, the low-temperature embrittlement of the low-alloy steel is much more pronounced. It can therefore be concluded that, at low temperatures, the abrasive wear resistance of the maraging steel exceeds that of the low-carbon steel. Note that, as the test load increases, the difference in the wear rate of the steels constituting the composite slightly decreases.



a b

Fig. 8. The worn surfaces (SEM) of the maraging steel layers near the interlayer boundary after the testing of the as-welded (a) and heat-treated (b) composite for abrasive wear resistance at a load of 50 N and a temperature of −196 °C

In contrast to the tests at room temperature, the wear rate of the seven-layer composite at a temperature of −196 °C is higher (wear resistance is lower) than for the steels constituting the composite. Specifically, the increase in I_h is 14–57 % at the load of 20 N and 1–23 % at the load of 50 N (see Table 2). It can be seen that the wear rate of the composite is close to, but exceeds that of the low-carbon steel. Since the wear resistance differs substantially for the dissimilar layers of the composite at the test temperature of −196 °C (see Table 2), there takes place uneven wear, when the low-carbon steel layers wear out faster than the maraging steel ones. SEM investigation of the worn surfaces has shown that this may lead to tearing off the protruding microvolumes of the maraging steel by abrasive particles under further wear (Fig. 8a). This is what seems to cause a higher wear rate of the composite. Apparently, as the test load increases, the effect of uneven wear becomes less pronounced since the difference in the wear rate of the dissimilar layers decreases (see Table 2).

The heat treatment at 500 °C leads to an additional increase in the wear rate of the composite determined at a test temperature of −196 °C, which is due to the increased difference in the hardness of the dissimilar layers (see Fig. 6). This enhances the uneven wear and relevant tearing off of protruding microvolumes of the maraging steel by abrasive particles (Fig. 8b). In this case, the increase in the value of I_h is 6 % at the load of 20 N and 7 % at the load of 50 N; i.e. it is approximately the same (see Table 2).

The results of abrasive wear resistance testing at different temperatures have also shown that the wear rate of the laminated composite and its constituents at a temperature of −196 °C is lower (wear resistance is higher) than at +25 °C. This is observed at loads of both 20 and 50 N and is due to a change in the predominant wear mechanism from microcutting to microploughing (see Fig. 7). It is well known that microploughing decreases wear rate. The reason is the low-temperature hardening of the steels constituting the composite. This decreases the ratio of the hardness of the abrasive and the tested material [38]. It should also be noted that the wear resistance of the composite depends on the test temperature to a lesser extent than the wear resistance of the steels separately. Thus, the composite has more stable properties. To increase the wear resistance of a laminated composite at low temperatures, it is necessary to choose the layers that ensure minimum uneven wear of the composite, as well as a low cold brittleness threshold.

4. Conclusions

The abrasive wear resistance of a laminated composite consisting of low-alloy and maraging steels at room (+25 °C) and cryogenic (−196 °C) temperatures has been studied. The composite was obtained by explosive welding. It has been found that, at a test temperature of +25 °C, the wear resistance of the composite is higher than that of the steels constituting the composite. This is due to the influence of the interlayer boundaries, which complicate the separation of wear products from the specimen surface under wear, as well as the dispersed structure of the low-alloy steel near these boundaries, which promotes local hardening of the material. Heat treatment at 500 °C additionally increases the wear resistance of the composite determined at a test temperature of +25 °C, this being due to the increasing microhardness of the maraging steel layers. At a test temperature of −196 °C, the wear resistance of the composite, on the contrary, is lower than that of the steels constituting the composite. This is caused by the uneven wear of the composite, when the low-carbon steel layers wear out faster than the maraging steel ones and provide conditions for the separation of protruding microvolumes of the maraging steel by abrasive particles under further wear. Heat treatment at 500 °C additionally decreases the wear resistance of the composite determined at a test temperature of −196 °C, this being due to the increased difference in the hardness of the dissimilar layers and the enhanced effect of uneven wear. The results of testing for abrasive wear resistance at different temperatures have also shown that the wear resistance of the laminated composite and its constituents is higher at −196 °C than at +25 °C. This is due to the low-temperature hardening of the steels constituting the composite, causing a change in the wear mechanism. It should also be noted that the wear resistance of the composite is less dependent on the test temperature than the wear resistance

of the steels separately. Thus, the composite has more stable properties. To increase the wear resistance of a laminated composite at low temperatures, it is necessary to choose the layers that ensure minimum uneven wear of the composite, as well as a low cold brittleness threshold.

Acknowledgments

This study was performed within the state assignment for the IES UB RAS, reg. no. AAAA-A18-118020790147-4. Optical microscopy, microhardness measurements, and tribological tests were performed in the Plastometriya shared access center of the Institute of Engineering Science, UB RAS. Sheets with a thickness of 1 mm made of maraging steel with an ultrafine-grained structure were obtained by multi-stage processing in the Institute for Metals Superplasticity Problems of RAS (Ufa). The seven-layer low-alloy-steel–maraging-steel composite was made by explosive welding under the supervision of V. I. Mali in the Lavrentyev Institute of Hydrodynamics, SB RAS (Novosibirsk). We are also grateful to S. N. Sergeev and S. V. Kuteneva for their assistance in studying the structure of the laminated composite and to I. Yu. Malygina and S. A. Rogovaya for their assistance in processing the results of tribological tests.

References

1. Jia X., Ling X. Influence of Al_2O_3 reinforcement on the abrasive wear characteristic of Al_2O_3/PA1010 composite coatings. *Wear*, 2005, vol. 258, iss. 9, P. 1342–1347. DOI: 10.1016%2Fj.wear.2004.10.003.
2. Hu J., Li D.Y., Llewellyn R. Computational investigation of microstructural effects on abrasive wear of composite materials. *Wear*, 2005, vol. 259, iss. 1–6, P. 6–17. DOI: 10.1016/j.wear.2005.02.017.
3. Kцk M. Abrasive wear of Al_2O_3 particle reinforced 2024 aluminium alloy composites fabricated by vortex method. *Composites Part A*, 2006, vol. 37, iss. 3, P. 457–464. DOI: 10.1016/j.compositesa.2005.05.038.
4. Weber S. Theisen W. Sintering of high wear resistant metal matrix composites. *Adv. Eng. Mater.*, 2007, vol. 9, iss. 3, P. 165–170. – DOI: 10.1002/adem.200600257.
5. Sivaprasad K., Kumaresh Babu S.P., Natarajan S., Narayanasamy R., Anil Kumar B., Dinesh G. Study on abrasive and erosive wear behaviour of Al 6063/TiB_2 in situ composites. *Mater. Sci. Eng. A*, 2008, vol. 498, iss. 1–2, P. 495–500. DOI: 10.1016/j.msea.2008.09.003.
6. Kumar S., Balasubramanian V. Effect of reinforcement size and volume fraction on the abrasive wear behaviour of AA7075 Al/SiC_p P/M composites–A statistical analysis. *Tribol. Int.*, 2010, vol. 43, iss. 1–2, P. 414–422. DOI: 10.1016/j.triboint.2009.07.003.
7. Canakci A. Microstructure and abrasive wear behaviour of B_4C particle reinforced 2014 Al matrix composites. *J. Mater. Sci.*, 2011, vol. 46, P. 2805–2813. DOI: 10.1007/s10853-010-5156-2.
8. Leech P.W., Li X.S., Alam N. Comparison of abrasive wear of a complex high alloy hardfacing deposit and WC–Ni based metal matrix composite. *Wear*, 2012, vol. 294–295, P. 380–386. DOI: 10.1016/j.wear.2012.07.015.
9. Guignier C., Bueno M.-A., Camillieri B., Tourlonias M., Durand B. Tribological behaviour and wear of carbon nanotubes grafted on carbon fibres. *Composites Part A*, 2015, vol. 71, P. 168–175. DOI: 10.1016/j.compositesa.2015.01.013.
10. Sardar S., Karmakar S.K., Das D. High stress abrasive wear characteristics of Al 7075 alloy and 7075/Al_2O_3 composite. *Measurement*, 2018, vol. 127, P. 42–62. DOI: 10.1016/j.measurement.2018.05.090.
11. Guo R.-F., Shen P., Guo N., Yang L.-K., Jiang Q.-C. Al–7Si–5Cu/Al_2O_3–ZrO_2 laminated composites with excellent and anisotropic wear resistance. *Adv. Eng. Mater.*, 2018, vol. 20, iss. 11, p. 1800540. DOI: 10.1002/adem.201800540.

12. Chandra B.T., Sanjeevamurthy, Shiva Shankar H.S. Effect of heat treatment on dry sand abrasive wear behavior of Al7075-Albite particulate composites. *Mater. Today. Proc.*, 2018, vol. 5, iss. 2, P. 5968–5975. DOI: 10.1016/j.matpr.2017.12.198.
13. Jiang J., Li S., Yu W., Zhou Y. Microstructural characterization and abrasive wear resistance of a high chromium white iron composite reinforced with in situ formed TiC_x. *Mater. Chem. Phys.*, 2019, vol. 224, P. 169–174. DOI: 10.1016/j.matchemphys.2018.12.019.
14. Grejtak T., Jia X., FeP.on F., Joynson S.G., Cunniffe A.R., Shi Y., Kauffman D.P., Vermaak N., Krick B.A. Topology optimization of composite materials for wear: a route to multifunctional materials for sliding interfaces. *Adv. Eng. Mater.*, 2019, vol. 21, iss. 8, art. 1900366. DOI: 10.1002/adem.201900366.
15. Qiu B., Xing S., Dong Q., Liu H. Comparison of properties and impact abrasive wear performance of ZrO_2-Al_2O_3/Fe composite prepared by pressure casting and infiltration casting process. *Tribol. Int.*, 2020, vol. 142, art. 105979. DOI: 10.1016/j.triboint.2019.105979.
16. Savaє Ц. Application of Taguchi's method to evaluate abrasive wear behavior of functionally graded aluminum based composite. *Mater. Today. Commun.*, 2020, vol. 23, art. 100920. DOI: 10.1016/j.mtcomm.2020.100920.
17. Chawla K.K. *Composite Materials: Science and Engineering*, 3rd Edition, Springer–Verlag, New York, 2012. DOI: 10.1007/978-0-387-74365-3.
18. Wadsworth J., Lesuer D.R. Ancient and modern laminated composites – from the Great Pyramid of Gizeh to Y2K. *Mater. Charact.*, 2000, vol. 45, iss. 4–5, P. 289–313. DOI: 10.1016/S1044-5803(00)00077-2.
19. Gladkovsky S.V., Kuteneva S.V., Kamantsev I.S., Galeev R.M., Dvoynikov D.A. Formation of the mechanical properties and fracture resistance characteristics of sandwich composites based on the 09G2S steel and the EP678 high-strength steel of various dispersion. *Diagnostics, Resource and Mechanics of materials and structures*, 2017, iss. 6, P. 71–90. DOI: 10.17804/2410-9908.2017.6.071-090. Available at: https://dream-journal.org/DREAM_Issue_6_2017_Gladkovsky_S.V._et_al._071_090.pdf
20. Sniezek L., Szachogluchowicz I., Wachowski M., Torzewski J., Mierzynski J. High cycle fatigue properties of explosively welded laminate AA2519/AA1050/Ti6Al4V. *Procedia Structural Integrity*, 2017, vol. 5, P. 422–429. DOI: 10.1016/j.prostr.2017.07.191.
21. Yu W.X., Liu B.X., Cui X.P., Dong Y.C., Zhang X., He J.N., Chen C.X., Yin F.X. Revealing extraordinary strength and toughness of multilayer TWIP/Maraging steels. *Mater. Sci. Eng. A*, 2018, vol. 727, P. 70–77. DOI: 10.1016/j.msea.2018.04.097.
22. Gladkovsky S.V., Kuteneva S.V., Sergeev S.N. Microstructure and mechanical properties of sandwich coP.er/steel composites produced by explosive welding. *Mater. Charact.*, 2019, vol. 154, P. 294–303. DOI: 10.1016/j.matchar.2019.06.008.
23. Veretennikova I.A., Konovalov D.A., Smirnov S.V., Zadvorkin S.M., Putilova E.A., Kamantsev I.S. Effect of steplike plastic deformation on the mechanical properties and the fracture of the bimetal produced by exposition welding. *Russ. Metall.*, 2019, vol. 2019, iss. 5, P. 556–564. DOI: 10.1134/S0036029519050124.
24. Zhang L., Wang W., Babar Shahzad M., Shan Y., Yang K. A novel laminated metal composite with superior interfacial bonding composed of ultrahigh‐strength maraging steel and 316L stainless steel. *J. Iron. Steel. Res. Int.*, 2020, vol. 27, iss. 4, P. 433–439. DOI: 10.1007/s42243-020-00382-4.
25. Blazynski T.Z. *Explosive welding, forming and compaction*, Springer Netherlands, 1983. DOI: 10.1007/978-94-011-9751-9.
26. Al-Sahib N. *Designs and practice of explosive metal working: Theory and application of explosive welding plate,* Scholars' Press, 2016.
27. Greenberg B.A., Ivanov M.A., Kuzmin S.V., Lysak V.I. *Explosive welding: Processes and structures*, 1st Edition, CRC Press, 2019.

28. Bataev I.A., Tanaka S., Zhou Q., Lazurenko D.V., Jorge Junior A.M., Bataev A.A., Hokamoto K., Mori A., Chen P. Towards better understanding of explosive welding by combination of numerical simulation and experimental study. *Mater. Des.*, 2019, vol. 169, art. 107649. DOI: 10.1016/j.matdes.2019.107649.
29. Makarov A.V., Pozdeeva N.A., Savrai R.A., Yurovskikh A.S., Malygina I.Y. Improvement of wear resistance of hardened structural steel by nanostructuring frictional treatment. *J. Frict. Wear*, 2012, vol. 33, iss. 6, P. 433–442. DOI: 10.3103/S1068366612060050.
30. Kragelsky I.V., Dobychin M.N., Kombalov V.S. *Friction and wear: Calculation methods*, Elsevier, 2013. DOI: 10.1016/C2013-0-03333-6.
31. Trueb L.F. Microstructural effects of heat treatment on the bond interface of explosively welded metals. *Metall. Trans.*, 1971, vol. 2, iss. 1, P. 145–153. DOI: 10.1007/BF02662650.
32. Ghaderi S.H., Mori A., Hokamoto K. Analysis of explosively welded aluminum–AZ31 magnesium alloy joints. *Mater. Trans.*, 2008, vol. 49, iss. 5, P. 1142–1147. DOI: 10.2320/matertrans.MC200796.
33. Tarasenko L.V., Titov V.I., Elyutina L.A. Control of variation of properties of maraging chromium-nickel steels in long-term heating. *Met. Sci. Heat Treat.*, 2010, Vol. 52, iss. 5–6, P. 251–254. DOI: 10.1007/s11041-010-9259-9.
34. Gladkovsky S.V., Potapov A.I., Lepikhin S.V. Studying the deformation resistance of EP679 maraging steel. *Diagnostics, Resource and Mechanics of materials and structures*, 2015, iss. 4, P. 18–28. DOI: 10.17804/2410-9908.2015.4.018-028. Available at: http://dream-journal.org/netcat/full.php?inside_admin=&sub=473&cc=685&message=32
35. Potak Y.M. *High-strength steels* [Vysokoprochnye stali]. Metallurgiya Publ., Moscow, 1970. (In Russian).
36. Terentiev V.V., Bunin I.Z., Zagreev P.V. Effect of the aging temperature on the complex of mechanical properties of maraging steel. *Materialovedenie*, 1998, no. 1, P. 40–49. (In Russian).
37. Buckley D.H. *Surface effects in adhesion, friction, wear, and lubrication*, Elsevier, 1981.
38. Khrushchev M.M., Babichev M.A. *Abrazivnoe iznashyvanie* [Abrasive wear]. Nauka Publ., Moscow, 1970. (In Russian).
39. Chintha A.R., Valtonen K., Kuokkala V.-T., Kundu S., Peet M.J., Bhadeshia H.K.D.H. Role of fracture toughness in impact-abrasion wear. *Wear*, 2019, vol. 428–429, P. 430–437. DOI: 10.1016/j.wear.2019.03.028.