Evaluation of wear resistance of boron-containing layers on steel 20 after microarc surface alloying

L V Davidyan*, Yu M Dombrovskii, G V Chumachenko, M V Balinskaya, T B Asten

Don State Technical University, Rostov-on-Don, Russian Federation

*e-mail: davidyan_90@mail.ru

Abstract. The evaluation results of abrasive wear resistance on a friction machine K4-B of boron-containing coatings on steel samples are presented in this paper. It was obtained with the method of microarc chemical heat treatment from coatings. Samples of steel 20 with a diameter 4 mm and a length 30 mm were tested after microarc borating, borovanadium treatment, boromolybdenation and borochromization. It was identified that after borating with microarc heating, the wear rate decreases by 3.04 times in comparison with the wear rate of the reference - steel 20 in the initial structural state. Microarc multicomponent saturation, when borides, carbides, and more complex substances that contain chromium, molybdenum or vanadium were found in the diffusion layer, significantly reduces the wear rate of steel products up to 4.4 times in comparison with the initial state.

1. Introduction

Methods of obtaining coatings with a special complex of mechanical properties are a perspective direction of modern mechanical engineering. One of the methods that allows to get such coatings is borating. During application of this type of chemical heat treatment conditions of boride layers’ formation, their phase composition and properties [1-13] were studied. These researches have shown that borated coatings are highly brittle. This disadvantage was minimized by electric spark, laser and HFC heating [14,15] by forming diffusion layers with a eutectic structure that consists of solid matrix of boron in iron with boride inclusions. Such coatings have greater ductility than those obtained by conventional borating, but still maintain increased wear resistance.

Preliminary researches have shown that layers with a eutectic structure can be obtained by microarc borating from coatings that are based on an electrically conductive gel, and include powders of boron-containing substances and carbide-forming elements. The essence of the method is that in electric heating of a steel sample immersed in coal powder by the occurrence of micro-discharges between powder particles and treated surface. That provide the creation of a "microarc halo" [16-18]. These conditions lead to an effective heating of the surface, transition of the diffuser to the atomic state, its further adsorption and diffusion. We came to conclusion that the "microarc halo" protects the heated surface from oxidation because of the carbon monoxide ignition in the process of coal powder pyrolysis.
2. The aim of the work
The aim of this work is to estimate wear resistance coatings based on pure boron and boron with carbide-forming elements, which are formed on the surface of steel in the process of microarc borating from coatings.

3. Methods and materials
The end part of the cylindrical steel sample 20 with a diameter 4 mm and a length 30 mm was subjected to diffusion saturation. For this purpose, coatings on the basis of an electrically conductive “Unigel” gel were applied to the treated surface in the volume ratio of the following compositions: for borating - 50% “Unigel” and 50% boron carbide powder (B$_2$C). For multicomponent saturation, 25% of powders were added to 50% “Unigel” and 25% of boron carbide powder (B$_2$C) in volume ratio: for borovanadium treatment - ferrovanadium (FeV80), boromolybdenation - ferromolybdenum (FeMo70), borochromization - ferrochrome (FCh010A). After application of the coating, the test samples were lowered into a metal container and filled with coal powder with a dispersion of 0.4-0.6 mm. Then, voltage was supplied from the diode-thyristor rectifier. That led to the appearance of current in the “power supply-container-coal powder-sample” circuit [18]. The treatment was carried out for 3 minutes, with a current density on the surface of the sample of 0.53 A/cm$^2$ and a maximum heating temperature of 1250 °C. [19-21].

Wear resistance was determined according to National Standard 17367-71 by friction against fixed abrasive particles on the machine K4-B [22-24]. Loading of the sample during friction was carried out with a weight 310 g with a total friction path length 30 m. The test duration of each sample was 100 seconds. As an abrasive material, a fabric grinding skin, according to National Standard 5009-82, with abrasive grain from a normal electric corundum of the grade 14A graininess M40 on a mezzanine glue was used. After each sample, the grinding paper was changed to a new one. The weight loss of the samples was determined on laboratory weighing-machine VLT-150-P with a limit of permissible absolute error ± 0.005 g.

During microarc heating, there is simultaneous diffusion of boron and carbide-forming element from the composition of coating, as well as carbon from coal powder. This eliminates the possibility of adequately comparing the wear resistance of samples after microarc saturation with the results of multicomponent doping, since they provide for sequential saturation of alloying elements. In this regard, this value was compared by weight loss of the treated samples with weight loss of the reference, as which steel 20 in the initial structural state was used.

4. Results and discussion
After microarc borating [18,19] a diffusion layer on the surface of steel (Figure 1, a) was identified. It consisted of a triple Fe-B-C eutectic continuous grid with a micro hardness up to 13.5 GPa, and inclusions of Fe$_2$B and FeC (X-ray phase analysis data) [19], along the boundaries of a dispersed ferritocarbide mixture based on. Micro hardness of the ferritocarbide base of the layer reached 3.6-3.7 GPa. Under the layer was a carburized area with a ferrite-cementite eutectic and a micro hardness of up to 3.5 GPa, passing into the initial ferrite-pearlite structure of steel 20.

The structure of steel after microarc borating was formed due to the simultaneous grain-boundary diffusion of boron from the composition of coating and carbon from coal powder. The presence of solid eutectics along the grain boundaries increases micro hardness and wear resistance, but can increase the brittleness of the surface layer under dynamic loads.

Microarc multi-component saturation with boron and carbide-forming elements in the same conditions prevents the formation of a continuous carboroid mesh (Figure 1 b, c, d). According to the results of X-ray phase and microrentgengospectral analyses [20,21], the layers included separate sections of complex refractory eutectics containing Fe, B, C and a carbide-forming element, with inclusions of borides and carbides of these elements and more complex compounds (for example, complex carbide Fe$_2$MoC) [21]. High hardness of these compounds increases the micro hardness of the ferritocarbide base of the layers up to 8.5-9.0 GPa, individual inclusions - 14.5-16.5 GPa.
Figure 1. Diffusion layers, after: a – borating, b – boromolybdenation, c – borovanadium treatment, d – borochromization.

Samples after these types of microarc treatment were tested for abrasive wear resistance. The results are shown in Table 1.

| Diffusion layer                  | Mass wear, g | Wear rate, $\times 10^{-4}$ g/sec |
|----------------------------------|--------------|-----------------------------------|
| Reference (steel 20)             | 0.07         | 7                                 |
| Borating                        | 0.023        | 2.3                               |
| Borochromization                | 0.017        | 1.7                               |
| Boromolybdenation               | 0.015        | 1.5                               |
| Borovanadium treatment          | 0.0175       | 1.75                              |

As it can be seen from Table 1, the wear rate of the borated sample in conditions of dry friction against fixed abrasive particles is reduced up to 3.04 times in comparison with the reference, because of the layer structure that contains a solid carboborid mesh with inclusions of Fe$_2$B boride and cementite.

The two-component saturation with boron and carbide forming elements reduces the wear rate up to 4.4 times in comparison with steel 20 in the initial structural state. This effect is achieved by the presence of solid inclusions in the layers such as borides, carbides of the alloying carbide-forming element, and more complex compounds [20,21].

5. Conclusions.
Thus, in conditions of dry friction against fixed abrasive particles, it has been experimentally established that after microarc borating of steel 20, weight wear decreases from 0.07 g to 0.023 g, and the wear rate
is reduced up to 3.04 times. After microarc multicomponent saturation layers that contain borides, carbides, and more complex compounds of chromium, molybdenum or vanadium, reduce the wear rate of steel samples up to 4.4 times in comparison with steel 20 in the initial state.

References
[1] L.G. Voroshnin, L.S. Lyakhovich. 1978. Boration of steel. Moscow. Metallurgia. 239 p.
[2] A.N. Minkevich. 1965. Chemical-thermal treatment of metals and alloys. Moscow. Mechanical Engineering. 491 p.
[3] L.G. Voroshnin. 1981. Borating of industrial steels and cast iron. (Reference manual). Minsk. Belarus. 205 p.
[4] M. Keddam and M. Kulka. 2020. Materials Performance and Characterization. Modeling of the Kinetics of Boron Diffusion in Dehydrated Paste Pack-Borided AISI M2 Steel Based on Two Mathematical Approaches. Vol. 9. № 3. Pp. 303-314.
[5] M. Keddam, N. Makuch, M. Kulka, A., Miklaszewski. 2020. Indian Journal of Engineering and Materials Sciences. Mechanical properties and kinetics of boride layers on AISI D2 steel produced by plasma paste boriding. Vol. 27(2). Pp. 221-233.
[6] M. Keddam, M. Kulka. 2020. Metal Science and Heat Treatment. Simulation of Boriding Kinetics of AISI D2 Steel using Two Different Approaches. Vol. 61. Pp. 756-763.
[7] N.Makuch, M.Kulka, P.Dziarski, S.Taktak. 2019. Surface and Coatings Technology. The influence of chemical composition of Ni-based alloys on microstructure and mechanical properties of plasma paste borided layers. Vol. 367. Pp. 187-202.
[8] Xuan Zhou, Mingjia Wang, Yifeng Fu, Zixi Wang, Yanmei Li, Shunkai Yang, Hongchang Zhao, Hangbo Li. 2017. Materials Characterization. Effect of borides on hot deformation behavior and microstructure evolution of powder metallurgy high borated stainless steel. Vol. 124. Pp. 182-191.
[9] M. Keddam, R. Chegroune, M. Kulka, N. Makuch, D. Panfil, P. Siwak, S. Taktak. 2018. Transactions of the Indian Institute of Metals. Characterization, Tribological and Mechanical Properties of Plasma Paste Borided AISI 316 Steel. Vol. 71. Pp. 79-90.
[10] B. Boumaali, M. Keddam, S. Taktak. 2018. International Journal of Materials Engineering Innovation (IJMATEI). Growth kinetics of two-phase boride layers formed by boriding in molten salts on Cp-Ti substrate. Vol. 9. № 3. Pp. 240-255.
[11] O. Azouani, M. Keddam, O. Allaoui, A. Sehisseh. 2017. Protection of Metals and Physical Chemistry of Surfaces. Characterization of boride coatings on a ductile cast iron. Vol. 53. Pp. 306-311.
[12] M. Kulka, N. Makuch, A. Piasecki. 2017. Surface and Coatings Technology. Nanomechanical characterization and fracture toughness of FeB and Fe₂B iron borides produced by gas boriding of Armco iron. Vol. 325. Pp. 515-532.
[13] M. Kulka, N. Makuch. 2016. Ceramics International. Fracture toughness of hard ceramic phases produced on Nimonic 80A-alloy by gas boriding. Vol. 42. Iss. 2, Part B. Pp. 3275-3289.
[14] M.G. Krukovich, B.A. Prusakov, I.G. Sizov. 2010. Plasticity of borated layers. Moscow. FIZMATLIT. - 384 p.
[15] V.F. Labunets, L.G. Voroshnin, M.V. Kindarchuk. 1989. Wear-resistant boride coatings. Kiev. Tekhnika, 158 p.
[16] Yu.M. Dombrovskii, M.S. Stepanov. 2015. Bulletin of mechanical engineering. New possibilities of surface alloying of steel in powder media. Vol. № 8. Pp. 79-81.
[17] M.S.Stepanov, Yu.M. Dombrovskii, V.N. Pustovoiit. 2017. Metal science and thermal treatment of metals. Diffusion saturation of carbon steel in the mode of microarc heating. Vol. № 1 (739). Pp. 54-57.
[18] Yu. M. Dombrovskii, M. S. Stepanov. 2015. News of higher educational institutions - Ferrous metallurgy. Formation of a composite boride coating on steel during microarc chemical and thermal treatment. Part 58. Vol. №3. Pp. 214-215.

[19] L.V. Davidyan, M.S. Stepanov, Yu.M. Dombrovskii. 2018. Izvestia of the Volgograd State Technical University. Part "Problems of materials science, welding and strength in mechanical engineering." Structural-phase state and properties of steel 20 after microarc borating. Vol. 3 (213). Pp.131-137.

[20] M.S. Stepanov, Yu.M. Dombrovskii, L.V. Davidyan. 2019. News of higher educational institutions. Ferrous metallurgy. Structure, phase composition, mechanical properties, wear resistance of steel after microarc borovanading. Part 62. Vol. 6. Pp. 446-451.

[21] M.S. Stepanov, L.V. Davidyan, Yu.M. Dombrovskii. 2018. Izvestia of the Volgograd State Technical University. Part "Problems of materials science, welding and strength in mechanical engineering." Structure, phase composition and properties of steel after microarc borochromation and boromolybdenation. Vol. 3 (213). Pp. 124-131.

[22] M. M. Khrushchov, M. A. Babichev. 1970. Abrasive wear resistance. Moscow. Science. 251 p.

[23] M.M. Khrushchov, M.A. Berkovich, S.P. Kozyrev, L.B. Kraposhina, L.Yu. Pruzhansky. 1971. Wear resistance and structure of solid surfaces. Moscow. Mechanical Engineering. 98 p.

[24] M.M. Khrushchov. 1962. On standardization of one of the methods of testing for abrasive wear resistance. Proceedings of the meeting held on December 7-10, 1960. Moscow. Publishing House of the USSR Academy of Sciences. Pp. 40-47.