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# Nanohardness of Wear-Resistant Surfaces after Electron-Beam Treatment

**V. E. Kormyshev[a], *, Yu. F. Ivanov[b, c], **, V. E. Gromov[a], ***, S. V. Konovalov[d], ****, and A. D. Teresov[b, c], *****

[a]*Siberian State Industrial University, Novokuznetsk, Russia*
[b]*Institute of High-Current Electronics, Siberian Branch, Russian Academy of Sciences, Tomsk, Russia*
[c]*Tomsk Polytechnic University, Tomsk, Russia*
[d]*Samara National Research University, Samara, Russia*
**e-mail: 89239230000@mail.ru*
***e-mail: yufi55@mail.ru*
****e-mail: gromov@physics.sibsiu.ru*
*****e-mail: ksv@ssau.ru*
******e-mail: tad514@sibmail.com*

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**Abstract**—The nanohardness, Young's modulus, and defect substructure of the metal layer applied to Hardox 450 low-carbon martensitic steel by high-carbon powder wire (diameter 1.6 mm) of different chemical composition (containing elements such as vanadium, chromium, niobium, tungsten, manganese, silicon, nickel, and boron) and then twice irradiated by a pulsed electron beam are studied, so as to determine the correct choice of wear-resistant coatings for specific operating conditions and subsequent electron-beam treatment. The metal layer is applied to the steel surface in protective gas containing 98% Ar and 2% $CO_2$, with a welding current of 250–300 A and an arc voltage of 30–35 V. The applied metal is modified by the application of an intense electron beam, which induces melting and rapid solidification. The load on the indenter is 50 mN. The nanohardness and Young's modulus are determined at 30 arbitrarily selected points of the modified surface. The defect structure of the applied metal surface after electron-beam treatment is studied by means of a scanning electron microscope. The nanohardness and Young's modulus of the applied metal after electron-beam treatment markedly exceed those of the base. The increase is greatest when using powder wire that contains 4.5% B. A system of microcracks is formed at the surface of the layer applied by means of powder wire that contains 4.5% B and then subjected to an intense pulsed electron beam. No microcracks are observed at the surface of layers applied by means of boron-free powder wire after intense pulsed electron-beam treatment. The boron present increases the brittleness. The increase in strength of the applied layer after electron-beam treatment is due to the formation of a structure in which the crystallites (in the size range from tenths of a micron to a few microns) contain inclusions of secondary phases (borides, carbides, carboborides). The considerable spread observed in the nanohardness and Young's modulus is evidently due to the nonuniform distribution of strengthening phases.

*Keywords*: surfacing, powder wire, nanohardness, electron-beam treatment, Young's modulus, low-carbon steel

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In many cases, machine parts operate with intense wear. Their useful life may be extended by applying hard metal layers to the frictional surfaces [1, 2]. By forming structural–phase state over submicro- and nanoregions in the surface layer, we may significantly change the physicomechanical properties not only of a thin surface layer but of the part as a whole [3]. Many promising methods have been developed for modifying the surface of metals, alloys, ceramics, and metal–ceramics by means of concentrated energy fluxes and ensuring elevated physicomechanical characteristics [4–15].

A promising method of modifying the structure in the surface layer of steel parts so as to improve their performance involves two stages: the application of a composite coating strengthened by particles that are hard and very elastic (carbides, borides, etc.); and subsequent electron-beam treatment. Modification of metals and alloys by pulsed electron beams significantly changes the structural–phase state of the surface layers and hence increases the corrosion resistance, wear resistance, microhardness, and fatigue life beyond what is possible by traditional surface treatment [11–16].

As a rule, electron-beam treatment of metals produces the greatest strength within a relatively thin surface layer (a few microns). Indentation is widely used to certify the mechanical properties of such layers. Note, however, that the microhardness increases with decrease in load on the indenter; this is most apparent at small loads [16, 17].

In the present work, we analyze the mechanical properties of the layer formed on Hardox 450 steel by electrocontact surfacing with wire of different composition and subsequent application of an intense pulsed electron beam.

The composition of Hardox 450 steel is as follows: 0.19–0.26 wt % C; 0.70 wt % Si, 1.60 wt % Mn, 0.25 wt % Cr, 0.25 wt % Ni, 0.25 wt % Mo, 0.004 wt % B, 0.025 wt % P, and 0.010 wt % S. The remainder is iron.

The content of alloying elements in Hardox 450 steel is low. Consequently, it is easy to weld and machine. By special quenching—essentially, fast cooling of the rolled sheet without subsequent tempering—a small-grain structure is formed in the steel, which is consequently very hard. As a result, the steel effectively resists most forms of wear.

The applied metal layer is formed by means of powder wire (diameter 1.6 mm), with the following composition (the remainder is iron):

| Wire | C | V | Cr | Nb | W | Mn | Si | Ni | B |
|---|---|---|---|---|---|---|---|---|---|
| PP-1 | 0.7 | – | – | – | – | 2.0 | 1.0 | 2.0 | 4.5 |
| PP-2 | 1.4 | 1.0 | 7.0 | 8.0 | 1.2 | – | – | – | – |
| PP-3 | 1.3 | – | 7.0 | 8.5 | 1.4 | 0.9 | 1.1 | – | – |

The applied layer is formed on the steel surface in protective gas containing 98% Ar and 2% $CO_2$, with a welding current of 250–300 A and an arc voltage of 30–35 V. The applied metal is modified by the application of an intense electron beam, which induces melting and rapid solidification [14]. The treatment conditions are as follows: the energy density of the electron-beam pulse is 30 J/cm$^2$; in the first stage, the pulse length is 200 μs and the number of pulses is 20; in the second stage, the pulse length is 50 μs; and the number of pulses is 1. The treatment conditions are selected on the basis of calculation of the temperature field in the surface layer on application of a single pulse.

In mechanical tests, the nanohardness and Young's modulus of the modified surface are determined at 30 arbitrarily selected points of the modified surface. We use a Shimadzu DUH-211S instrument and a diamond indenter in the form of a Berkovich pyramid. The minimum load corresponding to the scale dependence of the measured hardness (the small-load effect) will be significantly reduced if the load in nanoindentation is no less than 50 mN, as shown in [16–18]. In the present work, the load on the indenter is 50 mN. The nanohardness and Young's modulus are determined by the Oliver–Pharr method [19]. The defect structure of the applied metal surface after electron-beam treatment is studied by means of a Philips SEM-515 scanning electron microscope.

On the basis of the 30 measurements, the mean/mean square deviation of the nanohardness $\langle H \rangle$ and Young's modulus $\langle E \rangle$ of the applied metal after electron-beam treatment are as follows:

| Wire | $\langle H \rangle$, GPa | $\langle E \rangle$, GPa |
|---|---|---|
| PP-1 | 20.83/2.53 | 347.7/26.6 |
| PP-2 | 6.17/1.48 | 221.3/29.0 |
| PP-3 | 13.0/2.2 | 260.3/33.1 |

Analysis of the results shows that the hardness is greatest for the layer applied by means of PP-1 wire, which contains boron, unlike PP-2 and PP-3 wire. We know that borided layers on steel surfaces are characterized by exceptionally high hardness and high resistance to abrasive wear, on account of the formation of the very hard iron borides FeB and $Fe_2B$ on the surface [20–22]. The embrittlement of the steel should be less for single-phase boride layers than for two-phase layers. The microhardness of iron borides FeB and $Fe_2B$ in a two-phase layer on Armco iron is 19200–20600 and 13500–14200 MPa, respectively, with an indenter load of 0.98 N. The microhardness of the boride $Fe_2B$ in a single-phase boride layer is somewhat higher than in a two-phase layer: 13700–16200 MPa. Increasing the carbon content in the steel reduces the hardness of boride FeB and has practically no influence on the hardness of $Fe_2B$. Molybdenum, tungsten, and chromium increase the hardness of FeB in a two-phase boride layer, while nickel, aluminum, and copper reduce the hardness of FeB [20–22].

Note that borided layers are very brittle [20–22]. In fact, our experiments on the layer applied by means of PP-1 wire, which contains 4.5 wt % boron, reveal the presence of microcracks on the irradiated surface after electron-beam treatment (Fig. 1a). When using boron-free PP-2 wire, by contrast, no surface cracks are seen (Fig. 1b). We see that the electron-beam treatment is not responsible for the microcrack formation.

In many cases, the mean values of the nanohardness and Young's modulus do not satisfactorily reflect the properties of the material, especially for a multiphase and multilayer material such as the applied metal layers obtained after electron-beam treatment. In Fig. 2, we show the distributions of the nanohardness and Young's modulus for such surfaces. Regardless of the composition of the powder wire, considerable spread is observed in the nanohardness (Figs. 2a–2c) and Young's modulus (Figs. 2d–2f) of the applied layer. The spread is greatest for the layer applied by means of PP-2 wire and least for the layer applied by means of PP-1 wire, which contains boron.

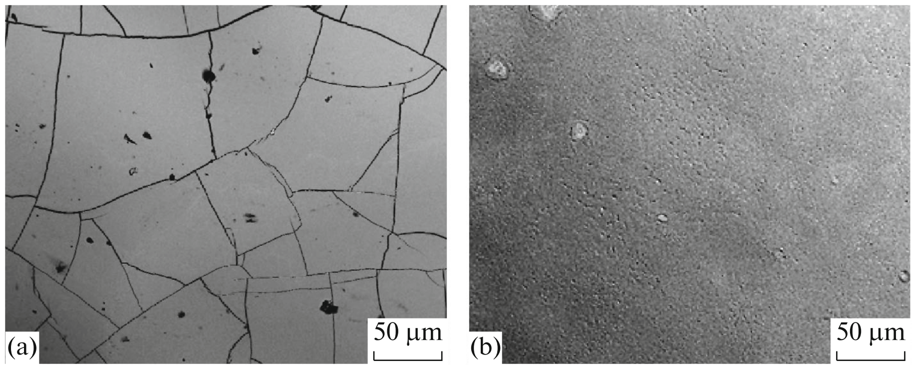


**Fig. 1.** Surface structure of the layers applied to Hardox 450 steel by means of PP-1 (a) and PP-2 (b) wire, after electron-beam treatment. Images from a scanning electron microscope.

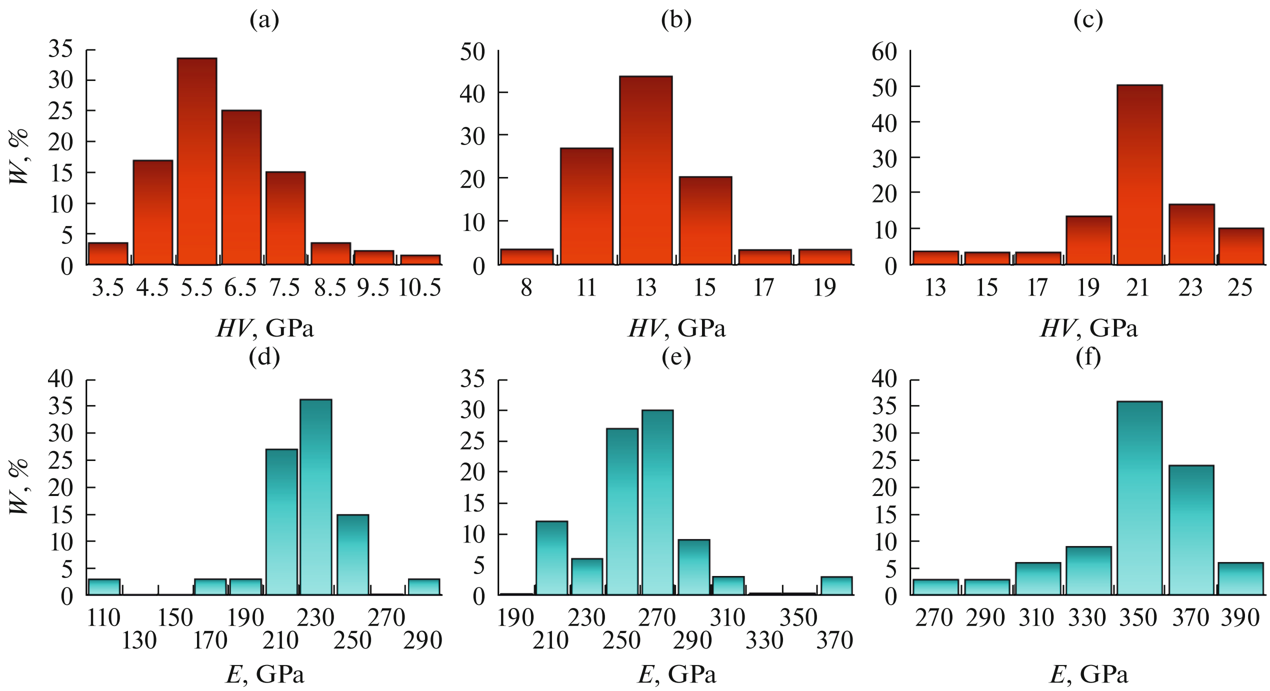


**Fig. 2.** Distribution of nanohardness (a–c) and Young's modulus (d–f) of the layers applied to Hardox 450 steel by means of PP-2 (a, d), PP-3 (b, e), and PP-1 (c, f) wire, after electron-beam treatment: $W = N_i/N$ is the relative frequency, where $N_i$ is the number of measurements of size class $i$ and $N$ is the total number of measurements.

We conclude that the strength of the steel is determined by the defect substructure of the material. In Fig. 3, we show typical electron microphotographs of the surface applied to Hardox 450 steel by means of powder wire PP-2 and then subjected to pulsed electron-beam pulses.

In the surface layer of the applied layer, we note the formation of a structure containing crystallites in the range from tenths of a micron to a few microns. If greater resolution were available, we would expect to see nanoparticles of carbide phase, on account of the superfast surface cooling of the material subjected to an intense pulsed electron beam for 50 μs.

## CONCLUSIONS

Experiments on the nanohardness, Young's modulus, and defect substructure of the metal layer applied to low-carbon steel by high-carbon powder wire of different chemical composition and then irradiated by a pulsed electron beam show that the nanohardness and Young's modulus of the applied metal after electron-beam treatment markedly exceed those of the base (Hardox 450 steel).

The increase in strength of the applied layer after electron-beam treatment is due to the formation of a submicrostructure in which strengthening is due to

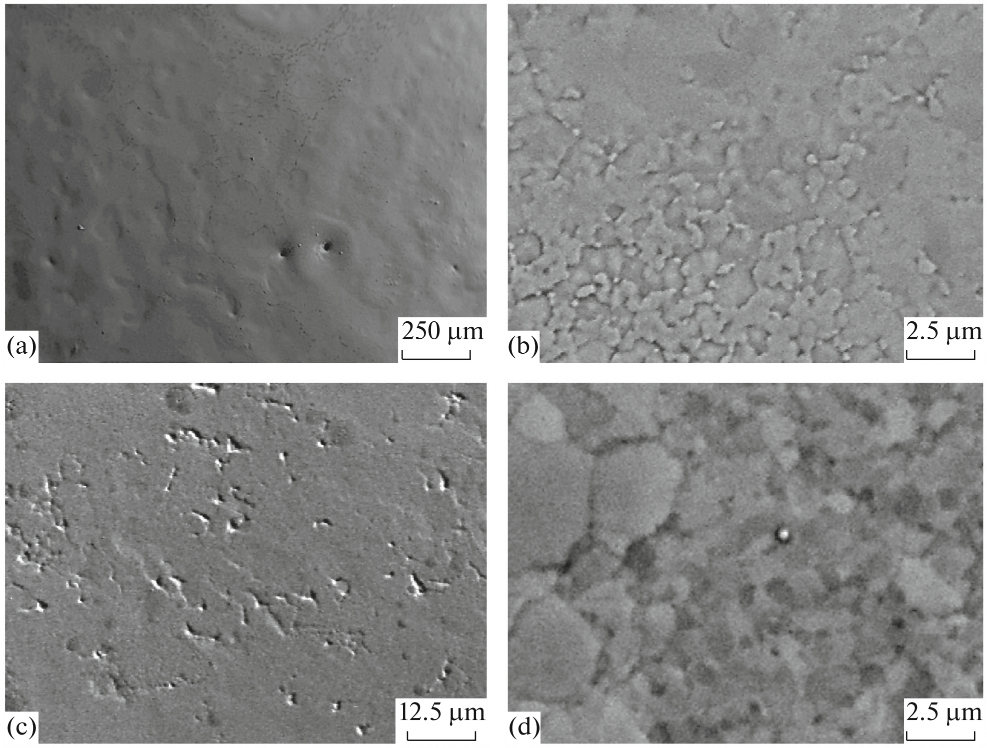


**Fig. 3.** Surface structure of the layers applied to Hardox 450 steel by means of PP-2 wire, after electron-beam treatment. Images from a scanning electron microscope.

quenching and the presence of secondary phases (borides, carbides, carboborides). The strengthening of the applied layer is greatest when boron is introduced. Note, however, that borided layers tend to be very brittle.

The considerable spread observed in the nanohardness and Young's modulus is evidently due to the nonuniform distribution of strengthening phases.

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