Non-vacuum electron-beam surfacing of coatings with the ultrafine structure

I M Poletika and M V Perovskaya

1 Institute of Strength Physics and Materials Science of SB RAS, Tomsk, Russia
E-mail: mv_perovskaya@inbox.ru

Abstract. The paper employs an ELV-6 accelerator to surface low-carbon steel with a tungsten carbide powder thus obtaining steel coatings with high hardness but low wear resistance. The abrasive wear resistance is considerably increased by changing the composition of the surfacing mixture due to the introduction of nickel as an austenite stabilizer and titanium carbide as a modifier. Besides, the paper deals with surfacing with a powder mixture of chromium carbide, chromium, and titanium carbide to produce bifunctional coatings with both high wear and corrosion resistance, which is explained by the presence of chromium in the layer. The methods of physical metallurgy are used to study mechanisms responsible for property changes. A substantial increase in wear resistance is shown to be related to the ductile austenitic structure formed in the deposited layer matrix when nickel is introduced and to rapid structure refinement in the presence of multiple centers of crystallization represented by dispersed precipitates of TiC.

1. Introduction
Abrasive wear of the surfaces of machine parts and mechanisms considerably reduces their service life. A widely-used method for restoration and hardening of parts is electric arc surfacing. It is analogous to electron-beam surfacing performed with the electron accelerator, which was developed by BINP SB RAS in collaboration with ISPMS SB RAS [1, 2]. The accelerator is characterized by a high quality of formed coatings and ease of injection of alloying elements. Electric arc surfacing with tungsten carbide gives high hardness and satisfactory resistance to abrasive wear. This carbide can also be used for electron beam surfacing. To improve the wear resistance of coatings, tungsten carbide can be mixed with nickel allowing for structure austenization and titanium carbide as a modifier forming a homogeneous dispersed structure. A common and relatively inexpensive system for electric arc surfacing that ensures high resistance to abrasive wear is Cr-C. Hardening is achieved by precipitation of chromium carbides in the deposited layer. Chromium injected into surfacing mixtures during processing can improve corrosion resistance of coatings. Formed coatings will protect products against both wear and corrosion. An additional increase in wear resistance can be achieved by the structure refinement of deposited metal due to the introduction of modifiers.

The aim of the work is to determine the mechanical properties of the composites obtained by the method of non-vacuum electron-beam cladding of the powder mixture (Cr₃C₂ + TiC) on low-carbon steel. In this study, the ultimate strength and deflection of composite with coating were determined depending on the deposition modes.
2. Experimental
Surfacing is performed with an ELV-6 electron accelerator at the radiation energy of 1.4 MeV. Low-carbon steel is initially surfaced with a mixture of WC, Ni and TiC powders in the ratio of 6:3:1. The substrate were 5x10 mm plates cut from sheets (14 mm) of S235 low-carbon steel. The beam current I equaled 40 mA and the deposition velocity V was varied from 1.45 to 2.0 cm/s. A 1-mm powder layer was applied to the specimen surface before processing. The packed density was 0.45 g/cm². The surfacing mixtures was injected with flux MgF₂ to protect against environmental influences. To increase the processed surface area the beam was scanning with the magnetic sweep width l = 5 cm. The second series of experiments presented surfacing with a powder mixture of chromium carbide Cr₃C₂, chromium, and titanium carbide TiC in the ratio of 6:3:1. At the beam current 40 mA the translational velocity of a specimen under the beam, V, varied in the range of 0.5–1.2 cm/s. In both cases the radiation energy density W at the specimen surface ranged from 5.6 to 7.72 kJ/cm². The deposited metal structure is investigated by the Neophot metallographic microscope. The X-ray phase analysis was performed with a DRON-2M diffractometer. The PMT-3 device was employed to measure the microhardness distribution in the deposited layers. The average microhardness Hμave in the layer was measured by 100–150 measurements. The abrasive-wear tests were conducted at loosely fixed abrasive particles fed into the friction zone and pressed against the specimen by a rotating rubber roller (GOST 23.208-79). The corrosion resistance was determined in nitric-acid tests by measuring the mass wear of the specimen.

3. Results and Discussion
When surfacing with a mixture of tungsten carbide, titanium carbide and nickel powders, the deposited layer thickness L varied from 1.5 to 3 mm (Fig. 1a).

Coating microhardness (Fig. 1b) and coefficient of wear resistance (Fig. 1c) had high average values and however they decrease with increasing radiation energy density W. At W = 5.6–6.8 kJ/cm², the deposited layer contained a significant amount of γ-iron, a small amount of α-iron, tungsten carbide Fe₃W₃C, and titanium carbide TiC.

Moreover, the intensity of γ-ion lines was much higher than that of α-iron lines, which is indicative of the formation of the austenitic-martensitic structure with a large volume fraction of the austenitic phase and a small volume fraction of the martensitic phase. A solid solution becomes enriched with nickel.

According to the X-ray diffraction patterns, with increasing energy density W, the intensities of lines of γ-iron, tungsten carbide, and titanium reduce, while those of α-iron lines (martensite) increase. This bars evidence of a decreasing volume fraction of the wear-resistant austenitic phase. The observed changes are related to an increasing thickness of the deposited layer (Fig. 1a) and decreasing average concentration of alloying elements in it, including nickel that stabilizes the austenite.
Coatings formed are peculiar in high structure refinement. The micrographs of the deposited layers exhibit a significant reduction in grain size (up to 1–5 μm, Figs. 2a and 2b).

![Figure 2](image)

**Figure 2.** Structure of the layer surfaced with the mixture WC+Ni+TiC: W = 5.60 (a); 6.79 (b), and 7.72 kJ/cm² (c).

This is due to the large number of dispersed particles TiC precipitated in the molten layer (T<sub>melt</sub> = 3180 °C). They are the first to precipitate from the melt presenting multiple centers of crystallization and hindering the austenite grain growth. Besides, high quenching rates applied to the solid phase induce the formation of the ultrafine-grained lath martensite. With increasing radiation energy austenitic-martensitic grains and martensite packets grow in size (Fig. 2c) and consequently hardness and wear resistance drop (Figs. 1b and 1c).

At the next experimental stage S235 steel was surfaced with a mixture of Cr<sub>3</sub>C<sub>2</sub>, Cr and TiC powders. The layers formed varied in thickness from 1 to 3 mm (Fig. 3a).

![Figure 3](image)

**Figure 3.** Thickness L (a), average microhardness H<sub>μ</sub> (b), and coefficient of wear resistance Ki of the deposited layer (c) versus specific surface energy W for the surfacing mixture Cr<sub>3</sub>C<sub>2</sub>+Cr+TiC.

The coating hardness was 4.5 GPa at the specific surface energy W = 5.6 kJ/cm² (Fig. 3b). Coatings surfaced with this mixture had the abrasive wear resistance of 31.4 (Fig. 3c). With increasing depth of the remelted layer the structure changes as follows. At low specific surface energy the ultrafine hypoeutectic dendritic structure with the grain size 2–6 μm is formed (Figs. 4a and 4b). High wear resistance is associated with considerable structure refinement in the presence of dispersed titanium carbides as well as with precipitation of chromium carbides and wear-resistant austenitic phase in the coating. Moreover, TiC added to the surfacing mixture makes the structure more equiaxial so that wear is not accompanied by brittle fracture of long dendrite branches.

According to the X-ray phase analysis, for a thin deposited layer the radiographs show intense lines of chromium carbide Cr<sub>C</sub> which compounds enter the austenitic-martensitic matrix with the predominant austenitic phase. The X-ray phase analysis reveals no compounds of titanium carbide, apparently, due to their high dispersability. With increasing thickness of the layer the intensity of
chromium carbide lines reduces so that at the layer thickness 5–6 mm these lines are almost indistinguishable against the background. The intensity of austenitic phase lines also decreases. The α-iron (martensite) prevails in the structure.

![Figure 4](image1.png)

**Figure 4.** Structure of the layer surfaced with the mixture Cr$_3$C$_2$+Cr+TiC: W = 5.60 (a), 6.79 (b), and 7.72 kJ/cm$^2$ (c).

Figure 5 demonstrates measurement results for the corrosion resistance of the deposited coatings at dissolution in concentrated nitric acid and comparison of St3 and 12Kh18N10T steel specimens. In all tests the corrosion resistance of coatings is shown to achieve high values and approach the corrosion resistance of stainless steel 12Kh18N10T.

![Figure 5](image2.png)

**Figure 5.** Relative mass wear of steel specimens and coatings surfaced with the mixture Cr$_3$C$_2$+Cr+TiC versus time in nitric acid: W =5.60 (1), 6.22 (2), 6.79 (3), 7.23 (4), 7.72 kJ/cm$^2$ (5).

The specific position of the curves in Fig. 5 is obviously dependent on the chromium content in a solid solution, from which it passes to the metal surface and forms a protective oxide film. With multiple chromium carbides precipitated in the layer corrosion losses increase slightly, which is related to the decreasing chromium content in a solid solution and propagation of interphase corrosion.

4. **Conclusion**

Deposition of tungsten carbide mixed with nickel and titanium carbide on low-carbon steel yields coatings with high hardness and wear resistance. The found effect is related to the nickel possibility to stabilize the wear-resistant phase, i.e. austenite, and to the precipitation of multiple dispersed particles TiC causing the formation of the homogeneous highly dispersed structure. Non-vacuum electron-beam surfacing of a mixture of chromium carbide, chromium and titanium carbide powders on low-carbon steel St3 provides bifunctional coatings with high wear resistance and corrosion resistance approaching that of stainless steel.
Acknowledgments

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References

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