Surface structure and properties of high-chromium steel irradiated with a submillisecond pulsed electron beam

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Abstract. In this paper we analyze the surface structure and properties of high-chromium steel (steel 420) irradiated with a submillisecond (0.45 ms) intense pulsed electron beam on the COMPLEX vacuum setup at an Ar pressure of 3·10⁻² Pa. The analysis suggests that electron beam treatment with surface melting dissolves the initial carbide phase in the steel, saturates its surface layer with Cr and C atoms, and form dendrites and martensite structure. The microhardness and the wear resistance of the irradiated steel are respectively 1.5 and 50 times higher compared to the initial material, and their maximum values are attained at a beam energy density of 53 J/cm².

1. Introduction
Now, for providing new properties of materials, it is beneficial to develop efficient and ecologically clean technologies based on concentrated energy flows (pulsed and continuous electron beams, intense ion beams, plasma fluxes, laser beams, etc.) [1-4]. For example, high alloys exposed to intense electron beam irradiation with surface melting and rapid crystallization are highly saturated with alloying elements, and their grain structure and second phase inclusions are dispersed to nanosizes [5-7]. Thus, one can impart a complex of properties to a material which are unattainable by conventional treatments.

Here we analyze the surface structure and mechanical and tribological properties of steel 420 irradiated with a submillisecond (0.45 ms) intense pulsed electron beam.

2. Material and research technique
The test material was steel 420 (its Russian analogue is 20Cr13 steel) shaped into specimens of dimensions 15x15x5 mm and exposed to electron beam irradiation on the COMPLEX setup [8] at an Ar pressure in its vacuum chamber of 3·10⁻² Pa. The steel specimens in the vacuum chamber were located on a holder at ≈500 mm from the grid of an electron gun and were irradiated with three pulses at a pulse energy density of 20-53 J/cm², electron energy of 14 keV, pulse duration of 450 µm, and pulse repetition frequency of 0.3 Hz. Figure 1 shows a typical waveform of the beam current. The surface morphology and the elemental composition of the irradiated material were studied by scanning electron microscopy and energy dispersive X-ray analysis (Philips SEM515 microscope and EDAX ECON IV microanalyzer). The phase composition was examined by X-ray diffraction analysis (XRD 6000 diffractometer). The properties of the surface alloy were judged from its hardness (PMT-3 device, indenter load 200 mN) and from its wear resistance (TRIBOtechnic device, J19965 steel ball, ball diameter 6 mm, track radius 2 mm, varied indenter load and track length).
Figure 1. Typical waveform of electron beam current. Pulse energy density 53 J/cm\(^2\), electron energy 14 keV, pulse duration 450 μs.

3. Results and discussion

Steel 420 is a doped alloy whose main elements are chromium and carbon. Under equilibrium conditions, the Cr-Fe system features a series of continuous liquid and solid solutions. In the solid state, it contains an intermediate σ-(FeCr) phase, a continuous region of solid solutions between α-Fe and Cr, and a small amount of solid solution based on γ-Fe [9]. The Cr-C system reveals three stable carbides Cr\(_2\)C\(_6\), Cr\(_7\)C\(_3\), and Cr\(_3\)C\(_2\) [10]. In the Fe-C system, the formation of Fe\(_3\)C is detected. Some studies report on FeC and on a hexagonally structured metastable ε-carbide (Hagg carbide) whose composition approximates Fe\(_2\)C [11-14]. Figure 2 shows the isothermal cross-section of Cr-Fe-C [9]. It is seen that the regions of M\(_2\)C\(_2\), M\(_7\)C\(_3\), and M\(_3\)C\(_3\) (M stands for Cr and Fe atoms) have narrow extended homogeneous zones. The main element of these carbides is Cr, and the maximum solubility of Fe atoms in them at 700°C reaches 24, 43, and 6 at\%, respectively. Thus, it can be stated that Fe-Cr alloys doped with carbon greatly change their structural phase state. Under equilibrium conditions, not only solid solutions based on α-Fe (bcc) and γ-Fe (fcc) can be formed in these material but also carbides of complex composition (M\(_2\)C\(_6\), M\(_7\)C\(_3\), M\(_3\)C\(_2\), M\(_3\)C).

Figure 2. Isothermal cross-section of Cr-Fe-C at 700°C [9].
According to electron diffraction microscopy, the test steel in the initial state (before electron beam irradiation) represented a polycrystalline aggregate with an average grain size of 19 µm. Inside and at the boundaries of grains, globular M23C6 particles ((Fe, Cr)23C6) with a size of 0.15-0.35 µm were located. The carbide particles were single crystals almost free of dislocation substructure. The microhardness of the steel was 4400 MPa (indenter load 0.2 N), and its specific wear rate was $1.6 \times 10^{-4}$ mm³/N·m.

During pulsed electron beam irradiation, the surface microhardness of the steel changes nonmonotonically. Its minimum values in the material are found after irradiation at a beam energy density of 40 J/cm², and its maximum values after irradiation at 53 J/cm² (figure 3, curve 1). The specific wear rate of the modified steel behaves in the same way. Its minimum values (maximum wear resistance) in the material are found after irradiation at 53 J/cm² (figure 3, curve 2).

![Figure 3. Microhardness HV (1) and specific wear rate k (2) vs electron beam energy density Es.](image-url)

Figure 3. Microhardness HV (1) and specific wear rate k (2) vs electron beam energy density $E_s$.

Obviously, the steel during irradiation changes its surface strength and tribological properties due to changes in its elemental composition, phase state, and defect substructure. Our structural analysis of the irradiated steel shows that at a beam energy density of 20 J/cm², the structural phase state of its surface layer is modified in the presence of $\alpha$-phase. Any polymorphic $\alpha \rightarrow \gamma \rightarrow \alpha$ transition of Fe escapes detection, as evidenced by the absence of reliefs typical of martensite transformation (figure 4a, b). At 30-46 J/cm², melting of a thin surface layer occurs, which is evident from a cellular crystallization structure revealed by scanning electron microscopy. The relief characteristic of martensite transformation is not found (figure 4c-f).

Increasing the beam energy density up to $E_s=53$ J/cm² causes surface melting with the formation of a cellular crystallization structure. When quenched, the material is involved in martensite transformation (figure 4g, h).

Figure 5 presents X-ray spectral data on the elemental composition of the steel surface after electron beam irradiation.

The Cr concentration in the steel surface layer at different beam energy density is presented in Table 1. It is clearly seen that as the steel experiences surface melting at 30-46 J/cm², the Cr concentration in its surface layer grows. Chromium stabilizes the bcc $\delta$-Fe and $\alpha$-Fe phases, forming continuous solid solutions with them [9]. The region of Cr solid solutions in the fcc $\gamma$-Fe phase is rather narrow, ranging to 13.3 at%. From comparison of these data with the data of X-ray spectral analysis (Table 1) it can be concluded that the absence of $\gamma \rightarrow \alpha$ martensite transformation in the steel irradiated at $E_s=30-46$ J/cm² owes to the high Cr concentration in its surface layer. The decrease in the Cr concentration to 13.2 at% during irradiation at $E_s=53$ J/cm² allows high-rate quenching of the steel with the formation of martensite structure, which increases the surface microhardness of the steel 1.6 times and its wear resistance more than 50 times.
Figure 4. Electron micrograph of steel 420 surface after electron beam irradiation at different beam energy densities, J/cm²: 20 (a, b); 30 (c, d); 40 (e, f); 53 (g, h).
Figure 5. Electron micrograph of steel 420 surface after irradiation at $E_s=30$ J/cm$^2$ (a), corresponding energy spectrum (b), and percentage of elements (inset).

Table 1. Concentration of Cr atoms in steel 420 surface layer after electron beam irradiation.

| Beam energy density, J/cm$^2$ | Cr concentration, at% |
|------------------------------|------------------------|
| 20                           | 13.5                   |
| 30                           | 16.1                   |
| 40                           | 15.4                   |
| 46                           | 15.2                   |
| 53                           | 13.2                   |

4. Conclusion

Thus, our study shows that electron beam irradiation with surface melting at any electron beam energy (30–53 J/cm$^2$) dissolves the initial carbide phase $M_23C_6$ ((Cr, Fe)$_{23}C_6$) in steel 420, saturates its surface layer with Cr and C atoms, and forms dendrites, nanosized Cr carbide precipitates, and martensite structure. All these factors in total increase the surface hardness and wear resistance of the steel. The microhardness and the wear resistance of the irradiated steel are respectively 1.5 and 50 times higher compared to the initial material, and their maximum values are attained after irradiation at a beam energy density of 53 J/cm$^2$.

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