Structure of high-chromium steel treated by a microsecond (50–450 µs) low-energy electron beam

Yu F Ivanov, O V Krysina, Yu H Akhmadeev, I V Lopatin, E A Petrikova and A D Teresov

Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk, 634055, Russia

E-mail: yufi55@mail.ru

Abstract. Here we study the elemental composition, phase state, and defect substructure of high-chromium steel 420 exposed to intense low-energy electron beam irradiation with three pulses of duration 50-200 µs on the SOLO setup and with three pulses of duration 450 µs on the COMPLEX setup at a beam energy density of 40-43 J/cm². The research methods include scanning electron microscopy, transmission electron microscopy, and X-ray diffraction analysis. The study shows that electron beam irradiation with surface melting, irrespective of the pulse duration, dissolves the initial carbide phase M₂₃C₆ ((Cr, Fe)₂₃C₆) in steel 420, saturates its surface layer with Cr atoms, and forms submicron dendrite cells, nanosized Cr₃C₂ and FeCr precipitates, and martensite structure in the steel.

1. Introduction
One of the ways of increasing the service properties of metals, alloys, ceramics, and metal ceramics is to form a submicro and nanosized multiphase structure in them [1-4], which provides plastic strain localization on submicro- and nanoscales, uniform elastic stress distribution, and an increase in the nucleation energy of critical stress concentrators [5]. Among the methods of surface modification is irradiation with micro- and submillisecond intense low-energy (up to 30 keV) pulsed electron beams. In metals, alloys, ceramics, and metal ceramics, such treatment provides surface nanostructuring up to amorphous states [6]. The so substantial change in the structural phase state of a material up to a depth of hundred micrometers improves its physicochemical, electrophysical, and strength properties to levels unattainable by conventional surface treatments [1-8].

Here we analyze the elemental composition, phase state, and defect substructure of high-chromium steel 420 exposed to intense low-energy pulsed electron beam irradiation at widely varied pulse durations.

2. Material and research techniques
The test material was steel 420 (US grade, Russian analogue 20Cr13) exposed to intense low-energy electron beam irradiation with three pulses of duration 50-200 µs on the SOLO setup [7] and with three pulses of duration 450 µs on the COMPLEX setup [9]. In both cases, the beam energy density was 40-43 J/cm². All processes were realized in a vacuum chamber at an Ar pressure of ≈3·10⁻² Pa. The morphology and the elemental composition of steel 420 surface layers were studied by scanning electron microscopy and energy dispersive X-ray analysis (Philips SEM515 microscope and EDAX ECON IV microanalyzer). The phase composition was studied by X-ray diffraction analysis (XRD 6000 diffractometer). The defect substructure of the steel before and after electron beam irradiation was examined by thin foil transmission electron microscopy.
3. Results and discussion
Numerical calculations were performed for the temperature field formed in steel 420 under intense low-energy electron beam irradiation in single-pulse mode. The problem of estimating the temperature field in a certain range of electron energy densities was reduced to solving a heat conduction equation for one-dimensional heating and cooling of a plate of thickness \(d=0.5 \times 10^{-3} \text{ m}\). In the calculations, the electron energy was 17 keV, the beam energy density was 10-50 J/cm\(^2\), the pulse duration was 50, 200, and 450 µs, and the observation time was 600 µs.

Figure 1 shows temperature profiles as functions of the beam energy density and pulse duration. As can be seen, increasing the beam energy density at a constant pulse duration increases the maximum surface temperature. Increasing the pulse duration at a constant beam energy density decreases the maximum surface temperature, the molten layer thickness, and the lifetime of the molten state.

![Figure 1. Maximum surface temperature vs beam energy density at pulse durations of 50 (1), 200 (2) and 450 µs (3).](image)

The curves in figure 1 suggest that with a pulse duration of 50-200 µs, the surface layer of the steel is melted at energy densities of 12-26 J/cm\(^2\), and with 450 µs, it is melted at 46 J/cm\(^2\). We also estimated the thickness and the lifetime of two-phase (solid plus liquid) and single-phase (liquid) layers at different electron beam parameters. The calculation results were used for selection of irradiation modes and for research data interpretation.

According to optical microscopy (etched sections) and thin foil transmission electron microscopy, steel 420 in its initial martensite state (before electron beam irradiation) is a polycrystalline aggregate with an average grain size of 19 µm. Inside the grains and at their boundaries, there are globular M\(_{23}\)C\(_6\) particles ((Fe, Cr)\(_{23}\)C\(_6\)) with a size of 0.15-0.35 µm.

Such carbide particles form segregated dendrite structures which are clearly distinguished on the surface after electron beam etching (figure 3).

Under intense pulsed electron beam irradiation with surface melting at constant energy densities of 40-43 J/cm\(^2\), irrespective of the pulse duration, a cellular crystallization structure arises in the steel due to very fast quenching (figure 4). The cell size increases with decreasing the pulse duration from 330 nm at \(\tau=450\) µs to 500-600 nm at \(\tau=200\) µs.

Electron beam irradiation at \(\tau=450\) µs involves substantial dispersion of the grain structure of steel 420 such that a polycrystalline structure with a grain size of 3.2-5.7 µm is formed in its surface layer (figure 4). At \(\tau=50\) µs, its surface layer assumes a polycrystalline structure with a grain size of 3-22 µm and average size of 10.5 µm.
After irradiation of steel 420 at $\tau=450$ µs (43 J/cm$^2$), not all second phase inclusions are dissolved in its surface layer (figure 5, arrows). At the stage of fast quenching, such inclusions represent crystallization centers. In the steel surface layer, islands of dendrite crystallization appear (figure 5, insert, arrows). At 50-200 µs (40 J/cm$^2$), no second phase inclusions are detected in the surface layer, and the layer assumes a homogeneous structure of cellular crystallization.

Figure 2. Structure of steel 420 in its initial state with a M$_{23}$C$_6$ particle (arrow). Electron diffraction microscopy.

Figure 3. Surface structure of steel 420 with segregated dendrites (arrows) after electron beam irradiation with three pulses at 23 J/cm$^2$, 450 µs.

Figure 4. Surface structure of steel 420 irradiated with three pulses at 43 J/cm$^2$, 450 µs.

Figure 5. Surface structure of steel 420 with second phase inclusions (arrows) after irradiation with three pulses at 43 J/cm$^2$, 450 µs.
According to X-ray spectral analysis, the second phase particles are enriched in Al and Ti atoms and are likely Ti aluminides (figure 6).

![Figure 6. Surface structure of steel 420 with a second phase particle (+) after irradiation with three pulses at 43 J/cm², 450 µs (a) and its energy spectrum (b)](image)

4. Conclusion

Thus, our study of high-chromium steel 420 after intense electron beam irradiation with three pulses of duration 50–450 µs at a beam energy density of 40–43 J/cm² shows the following. Irradiation with surface melting dissolves the initial M23C6 carbide phase ((Cr, Fe)23C6) in steel 420, saturates its surface layer with Cr atoms, and forms submicron dendrite cells, nanosized Cr2C2 and FeCr particles, and martensite structure. Increasing the pulse duration to 450 µs at constant beam energy densities of 40–43 J/cm² provides a more than six-fold decrease in the grain size, compared to the initial state, and a structure composed of crystallization cells and dendrite islands in the steel surface layer.

Acknowledgments

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