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# Electrospark Doping of Steel with Tungsten

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**Abstract**. The paper is devoted to the numerical modeling of thermal processes and the analysis of the structure and properties of the surface layer of carbon steel subjected to electrospark doping with tungsten. The problem of finding the temperature field in the system film (tungsten) / substrate (iron) is reduced to the solution of the heat conductivity equation. A one-dimensional case of heating and cooling of a plate with the thickness *d* has been considered. Calculations of temperature fields formed in the system film / substrate synthesized using methods of electrospark doping have been carried out as a part of one-dimensional approximation. Calculations have been performed to select the mode of the subsequent treatment of the system film / substrate with a high-intensity pulsed electron beam. Authors revealed the conditions of irradiation allowing implementing processes of steel doping with tungsten. A thermodynamic analysis of phase transformations taking place during doping of iron with tungsten in equilibrium conditions has been performed. The studies have been carried out on the surface layer of the substrate modified using the method of electrospark doping. The results showed the formation in the surface layer of a structure with a highly developed relief and increased strength properties.

## INTRODUCTION

The method of electrospark doping (ESD) differs from other surface treatment methods in its simplicity, reliability, and cost-effectiveness [1]. Depending on the anode material, an extended surface layer with high strength, tribological, and other properties is formed on the work piece. The disadvantages of ESD are as follows: high surface roughness of the treated surface of a work piece, the presence of cracks, discontinuities, and micropores. To reduce the roughness introduced by the electrospark doping, the methods based on the mechanical impact on the modified surface are used (surface-plastic strain, running the ball, nonabrasive ultrasonic treatment, etc.). [2, 3], as well as treatment with concentrated energy flows (plasma flow, electron and ion beams, laser beams) [4, 5].

The paper is devoted to the numerical modeling of temperature fields and the analysis of the structure and properties of the surface layer of carbon steel subjected to electrospark doping with tungsten.

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## MATERIALS AND METHODS

The material of the study was carbon steel 65G ((0.62-0.7)C; (0.17-0.37)Si; (0.9-1.2)Mn; ≤0.25Ni; ≤0.035S; ≤0.035P; ≤0.25Cr; the rest is Fe, weight %). Steel 65G is used in the industry for manufacture of springs, shock absorbers, bearing discs, brake bands, friction plates, gears, flanges, bearing housings, clamping, feed collets, and other parts that must possess such properties as increased durability and operation without shock loads [6]. Samples of the cylindrical shape with a thickness of 5 mm and a diameter of 50 mm were hardened from 820 °C in oil and tempered at 350 °C. The electrospark treatment was carried out in air on the installation “Elitron 22A” at the discharge current of 2 A and the voltage on the doping electrode of 33 V. Technically pure tungsten was used as an electrode. The studies of the structure of the modified layer were carried out using methods of optical (NEOFOT-32) and scanning electron (SEM-515 Philips) microscopy.

## EXPERIMENTAL RESULTS AND THEIR DISCUSSION

Doping of steel with tungsten allows significant improvement of its durability. This is due to the fact that doping of W increases the volume share of tungsten carbides during quenching at normal temperature. It is important to note that an increase in the volume fraction of tungsten carbides leads to formation of a finer grain and, therefore, to the improvement of mechanical properties, in particular to higher viscosity [7, 8].

In the system Fe-W-C atoms of Fe and W belong to transition metals of the group VIA, and carbon is a nonmetal [9]. In the system W-C formation of three compounds has been established: $W_2C(\beta)$ ($P6_3/mmc$, prototype $Fe_2N$), $\gamma WC_{1-X}$ ($Fm\bar{3}m$, prototype NaCl) and WC(δ) (*P*6*m*2, prototype WC). In the system Fe-C the following has been revealed: formation of a stable compound $Fe_3C$ ($Fe_3C$, prototype *Pnma*) and solid solutions (α-Fe) and (γ-Fe), and at increased pressures the stabilization of the compound $Fe_7C_3$ (*Pnma*, prototype $Cr_7C_3$) takes place. Carbon is a nonmetal and belongs to the group IVB of the periodic table. Carbon atoms have four electrons on the outer shells *s*- and *p*- ($2s^2 2p^2$). As compared to the main alloy-forming metals, carbon atoms are much smaller and when alloyed with metals they form interstitial phases ($R_C$=0.0916 nm, $\delta_R=(R_W-R_C)/R_W=0.38$ and $\delta_R=(R_W-R_C)/R_{Fe}=0.28$).

In the system Fe-W the following has been discovered: three intermediate phases $\lambda(Fe_2W)$ ($P6_3/mmc$, prototype $MgZn_2$) ), $\mu(Fe_7W_6)$ ($R\bar{3}m$, prototype $Fe_7W_6$), γ(FeW) ($P2_12_12_1$ prototype MoNi), and solid solutions (W), (α-Fe) and (γ-Fe). In this system alloy-forming elements have a size factor $\delta_R$=0.139 ($R_W$=0.148 nm, $R_{Fe}$=0.1274 nm), which is significantly less than 0.2; however, metals Fe and W during alloying form solid solutions with a very limited solubility. The solubility in W (α-Fe) with a decrease in the temperature decreases from 14.3% (at.) at 1548 °C up to 4.6% (at.) at 1190 °C [10]. The solubility of Fe in (W) <2.6% (atm.) is at a temperature of 1677 °C [10]. In the ternary system Fe−W−C a whole range of intermediate stable and metastable compounds with complex crystalline structures that exist in different temperature and concentration ranges have been discovered (Fig. 1).

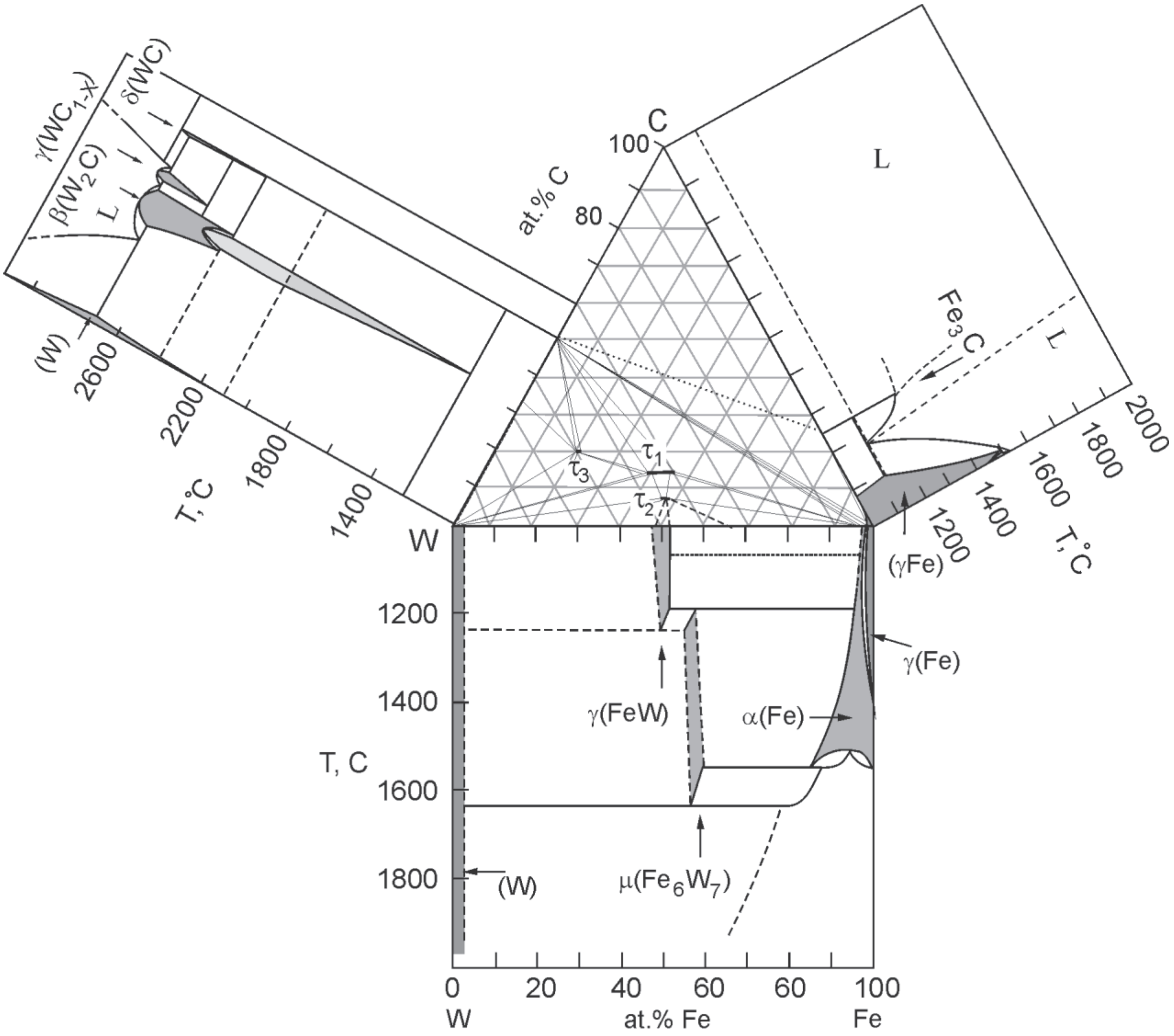


**FIGURE 1**. Binary diagrams of systems Fe-W, Fe-C, WC [10] and the isothermal section of the ternary system Fe-W-C at 1000°C [11]

Analyzing the equilibrium diagram of the system Fe-W a significant difference in melting points of iron and tungsten can be noted. Consequently, it is possible to expect great complications both at the electrospark doping of iron with tungsten and at the additional heat treatment of the system film (tungsten) / substrate (steel) formed during the electroerosion doping.

Indeed, the carried out studies of the structure of the surface layer of steel subjected to electrospark doping with tungsten have revealed formation of a surface layer with a high level of roughness, having micropores and microcracks. The typical image of the surface structure of steel subjected to electroerosion doping is shown in Fig. 2.

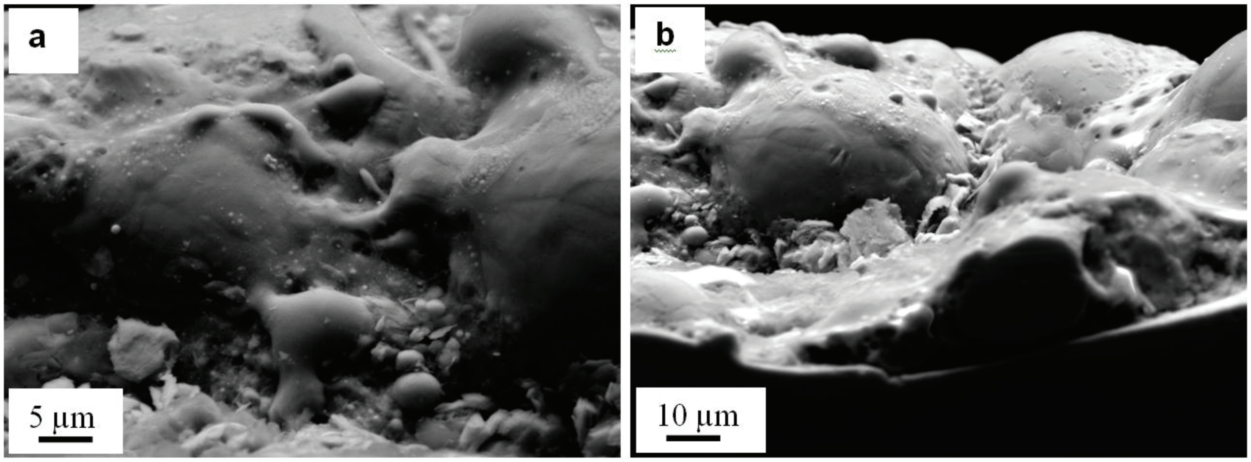
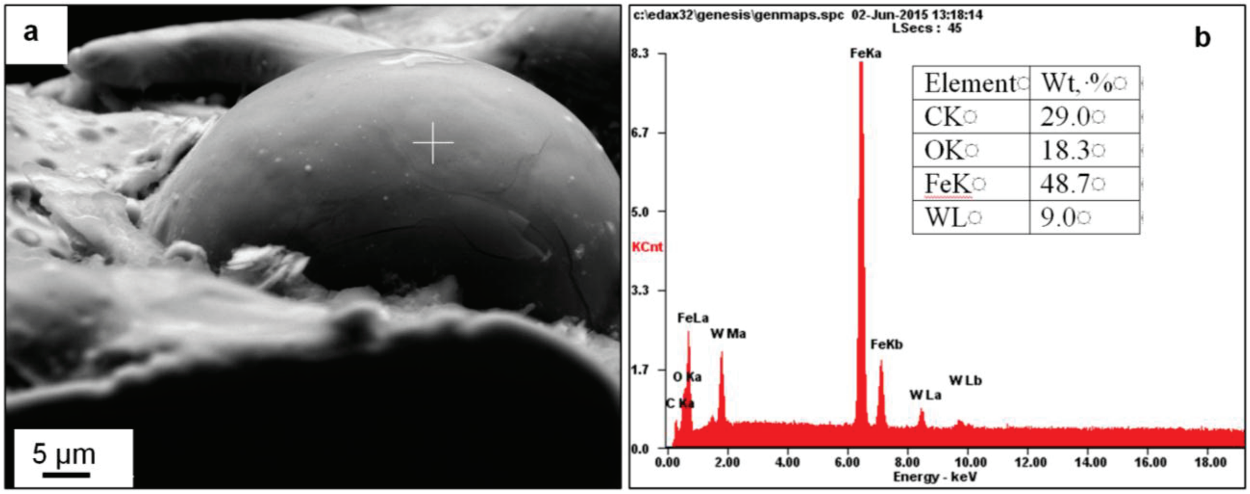


**FIGURE 2**. The surface structure of steel 65G subjected to electroerosion doping with tungsten

The large amount of microdroplets on the doping surface may indicate the liquid-phase mixing of iron and tungsten during the doping process. Indeed, an electron microprobe analysis of the surface doped layer has revealed the presence of iron and tungsten atoms. The results of the electron microprobe analysis of the electroerosion doping of steel 65G with tungsten is shown in Fig. 3.



| Element | Wt.% |
|---|---|
| CK | 29.0 |
| OK | 18.3 |
| FeK | 48.7 |
| WL | 9.0 |

**FIGURE 3**. An electron microscope image of the surface structure of the electroerosion doping of steel with tungsten (a); (b) are energy spectra obtained from the area of the surface marked on (a) with a cross

Analyzing the results of the electron microprobe analysis it is possible to note the presence of iron, tungsten, carbon, and oxygen atoms in the surface layer. The presence of carbon and oxygen atoms indicates a possible formation in the doped layer of particles of oxides and carbides of iron and tungsten, which will be an additional strengthening phase of the surface layer.

The analysis of the surface of steel subjected to electroerosion doping, as mentioned above, has revealed a high level of roughness of the modified layer. The next step of our developed technology, the ultimate goal of which is to create a highly-alloyed surface layer with low roughness, is the additional exposure of the doped layer to a high-intensity pulsed electron beam on the installation SOLO (Institute of High Current Electronics (IHCE), Siberian Branch, Russian Academy of Sciences) [5, 12].

In order to further optimize the process of an additional heat treatment of the system film (tungsten) / substrate (steel) a numerical modeling of thermal processes occurring during the irradiation of the material with a high-intensity pulsed electron beam has been carried out. The problem of finding the temperature field in a certain range of the energy density of electrons is reduced to the solution of the heat equation. A one-dimensional case of heating and cooling of a plate with the thickness d is considered. This object of physical impact is a system of a bulk sample (substrate) with a thin coating (film) on it [13-15]. Pure iron was used as the substrate, tungsten as the film. The thickness of the tungsten film was 0.5 microns. Thermal and physical properties of iron and tungsten, taken at a temperature of 1000 K, are presented in Table. 1. Analyzing the results presented in Table. 1 it can be noted that iron and tungsten have substantially different thermal properties and, therefore, will react differently to the impact of a high energy pulsed electron beam.

**TABLE 1.** Thermal and physical properties of iron and tungsten [16]

| **Element** | **λ(l), $10^{-2}$, W/(cm*K)** | **$c_p$, $10^{-3}$, J/(g*K)** | **ρ(r), g/cm$^3$** | **T(mel.), K** | **T(ev.), K** | **$Q_{mel}$, kJ/kg** | **$Q_{ev}$, kJ/kg** |
|---|---|---|---|---|---|---|---|
| **Fe** | | 975 | 7.87 | 1811 | 3145 | 247 | 6266 |
| **W** | 118 | 148 | 19.35 | 3693 | 5953 | 191 | 4187 |

Where: λ(l) is the thermal conductivity coefficient; $c_p$ is the specific heat capacity; ρ(r) is the density; T(mel.) is the melting point; T(ev.) is the evaporating temperature; $q_{mel}$ is the melting heat; $q_{ev}$ is the evaporation heat.

Indeed, the carried out heat calculations show that the surface layer of iron begins to melt at energy density of the electron beam of (10-12) J/cm$^2$ (at pulse length of the electron beam of 50 microseconds), and at 35 J/cm$^2$ the surface layer of the molten iron starts boiling (Fig. 4, curve 3). At the same time, the tungsten film, located on the surface of iron, begins to melt only at the energy density of the electron beam of 36 J/cm$^2$ (Fig. 4, curve 1). The tungsten sample, not reacting with iron, begins to melt only when irradiated with an electron beam with the energy density of the electron beam of 42 J/cm$^2$ (at a pulse length of the electron beam of 50 microseconds) (Fig. 4, curve 2). The lifetime and of the melted layer and its thickness are substantially different for iron and tungsten, calculated in the system film (tungsten) / substrate (iron) (Fig. 5).

Thus, the numerical modeling of thermal processes occurring during the irradiation of the system film (tungsten) / substrate (iron) with a high-intensity pulsed electron beam gives reason to conclude that doping of a steel surface with tungsten is possible only under conditions of dissolution of solid tungsten in liquid iron. Simultaneous melting of iron and tungsten with a high-intensity pulsed electron is beam accompanied by boiling of the molten iron layer, followed by formation of a surface with high roughness.

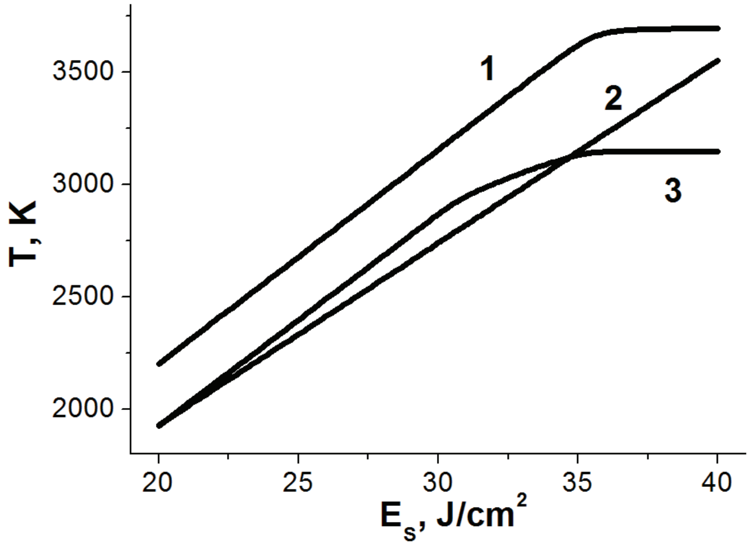


**FIGURE 4.** The dependence of the maximum heating temperature of the tungsten surface (curve 2), the tungsten film located on iron (curve 1), and the iron substrate (curve 3) irradiated with an electron beam on the density of the beam energy (taking into account melting and evaporation of the material) at a pulse duration of 50 microseconds

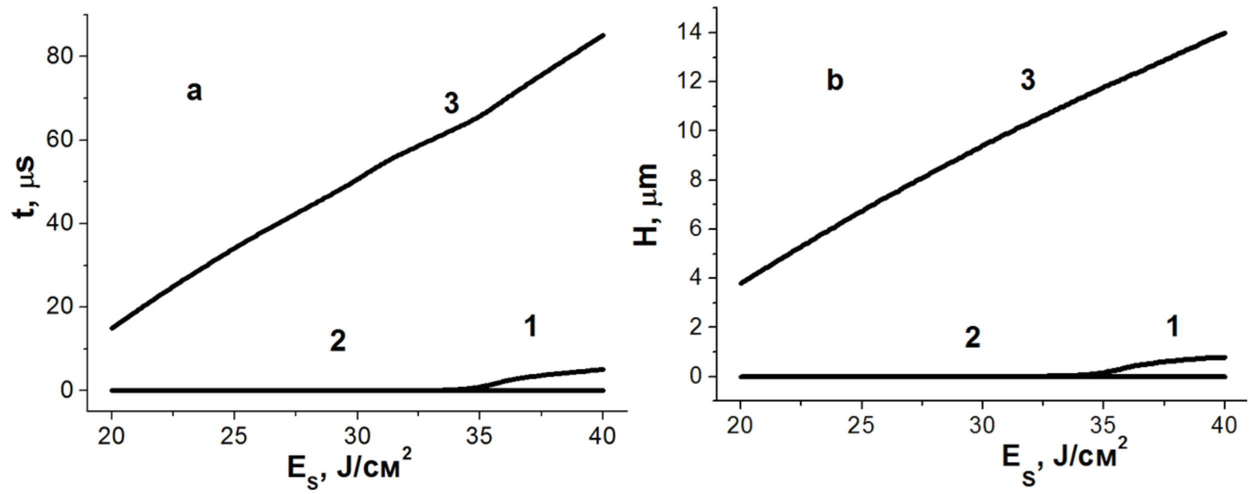


**FIGURE 5**. The dependence of the time interval from the beginning of melting to the completion of crystallization $\boldsymbol{t}$ (a) and the maximum thickness of the two-phase layer (liquid + solid phases) $\boldsymbol{H}$ (b) on the energy density of the electron beam $\boldsymbol{E_S}$ at a pulse duration of 50 microseconds; curve 1 is the tungsten film located on iron; curve 2 is the surface of tungsten not in contact with iron; curve 3 is the substrate (iron)

## CONCLUSION

The analysis has been carried out on the phase formation in the binary (Fe-W) and the ternary (Fe-W-C) systems formed during doping of carbon steel with tungsten. In the binary system Fe-W the following has been revealed: formation of three intermediate phases of the composition λ($Fe_2W$) ($P6_3/mmc$, prototype $MgZn_2$), μ($Fe_7W_6$) ($R\bar{3}m$, prototype $Fe_7W_6$), γ(FeW) ($P2_12_12_1$ prototype MoNi) and solid solutions (W), (α-Fe) and (γ-Fe). In the ternary system Fe-W-C a whole range of intermediate compounds both stable and metastable with complex crystalline structures that exist in different temperature and concentration fields has been discovered.

Investigations have been performed on surface layer of steel with tungsten modified using the method of electrospark doping. Formation of a multi-element surface layer characterized by a highly developed relief has been revealed.

The problem of determining the temperature field in the system film (tungsten) / substrate (iron) subjected to irradiation with a high-intensity pulsed electron beam has been solved. Calculations of temperature fields formed in the system film / substrate synthesized using methods of electrospark doping have been carried out as part of the one-dimensional approximation. It has been shown that doping of the steel surface with tungsten is possible only under conditions of dissolution of solid tungsten in liquid iron. The simultaneous melting of iron and tungsten with a high-intensity pulsed electron beam is accompanied by boiling of the molten layer of iron, followed by formation of a surface with high roughness.

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