

Research Article

Structural and Phase States and Properties of Plasma Coating of High-Speed Molybdenum Steel After Tempering

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Abstract

This article presents a comprehensive analysis of the structural and phase states, as well as the properties of plasma coatings on high-speed molybdenum steel after tempering. Advanced techniques, including scanning and transmission electron microscopy, X-ray diffractometry, and microcomposition analysis, were employed to investigate the impact of heat treatment on the microstructure and phase composition of the coating. Using methods of modern physical materials science, the structure, mechanical and tribological properties of the surface of a plasma deposited layer in a nitrogen medium with high-speed molybdenum steel on a substrate made of CSN 14331 medium carbon steel subjected to two times tempering at a temperature of 560-580 °C for 1 hour have been studied. It was found that tempering of the deposited layer does not lead to a change in the morphology of the polycrystalline structure formed by eutectic grains and grains of a solid solution based on α -iron (BCC crystal lattice). The main phases are α -Fe (85% wt.) and carbides of complex composition Me_{23}C_6 (9% wt.) and Me_6C (6% wt.), forming eutectic grains. The formation of nanoscale particles of iron and chromium carbides along the boundaries of martensite crystals formed during the transformation of residual austenite during tempering has been revealed. The hardness of the deposited layer is 4.3 times higher than the hardness of the substrate, the wear parameter is $1.5 \cdot 10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$, and the coefficient of friction is 0.66.

Keywords

High-Speed Molybdenum Steel, Surfacing, Plasma Method, Heat Treatment, Elemental and Phase Composition, Defective Substructure, Hardness, Wear Resistance

1. Introduction

Over the past century, since the creation of the first high-speed steel P18, researchers have been actively devel-

oping new steels with wide limits of carbon content and alloying elements. The optimal composition of the created

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steels changes due to changes in the properties of the processed materials, technologies and designs of the production of products, the cost of alloying elements and many other factors. The subsequent tempering of high-speed steels of optimal composition is designed to enhance functional properties and provide high heat resistance due to the release of carbides Me_2C and MC . Typically, in such steels (such as P6M5), the content of tungsten and molybdenum should be the same at a vanadium concentration of about 2%. Tungsten, molybdenum, and vanadium are distributed approximately equally in soluble and insoluble carbides. The first of them provide high hardness and heat resistance, while the second (insoluble) ones provide strength properties and toughness.

The main trends in the development of modern machine-building, metallurgical, and mining industries are characterized by the intensification of the use of materials with a unique combination of operational properties in structures and equipment parts, such as high abrasive, impact-abrasive, and waterjet wear resistance, and corrosion resistance [1, 2]. The premature failure of many parts is mainly due to processes occurring on the surface in the friction zone, as a result of which developments and research in the field of increasing the wear resistance of surface layers are relevant for advanced industries. One of the ways to increase the wear resistance of the surface of machine parts and mechanisms is to apply plasma coatings using modern surfacing materials for various operating conditions [3-5].

One of the fundamental tasks of modern physical materials science, which is of great practical importance, is to obtain coatings with high-speed steels with high performance properties that protect products from various types of wear, corrosion, dynamic loads and other external influences. The use of nitrogen as an alloying element in the formation of surfacing coatings, which leads to an increase in the microhardness of the structural components, significantly increases the operational properties [6-9]. In recent years, scientific research and practical developments have been actively conducted in the field of energy- and resource-saving plasma surfacing technology with high-speed steels, which has significant advantages over other coating methods [10-12].

Coatings with high-speed steels most fully meet modern industrial requirements in terms of both the level of achieved properties and economic efficiency.

Recent years have been marked by the increased use of high-speed steels with a molybdenum content of 8-10%. The replacement of W by Mo is due to a number of reasons. Previously, tungsten, which is an expensive and scarce strategic element, was widely used in the production of armor-piercing shells. Mo and W, located in the same group and neighboring periods of the Periodic Table of Elements, have a similar effect on the formation of the structural and phase state and properties of high-speed steels [13, 14]. However, despite this, the nature of transformations occurring in high-speed molybdenum steels and their properties may differ significantly from tungsten and tungsten-molybdenum ones [15].

Molybdenum steels have higher functional properties than tungsten or tungsten-molybdenum high-speed steels with a lower content of alloying elements, which is due to a number of reasons. Thus, the solubility of molybdenum in austenite of these steels is higher compared to tungsten and tungsten-molybdenum steels, which provides higher hardness values. During annealing and hot plastic deformation, smaller carbides are formed, which ensures the formation of a fine-grained structure and increased strength [13-15].

An additional improvement in the properties of surface layers formed by plasma surfacing with high-speed steels is achieved through the use of external energy effects by plasma, laser irradiation, and ion beams modifying the surface [16-21].

There practically have not been published any studies, either in Russia or abroad, based on highly informative methods of modern physical material science (and, first of all, electron microscopy) and devoted to the identification of the physical nature of structural and phase transformations of coatings of molybdenum high-speed steels during manufacture and subsequent heat treatment, which significantly reduces the prospects for practical elaboration.

In connection with the above, the purpose of the work was to study the fine structure and properties of the surface layer formed by plasma deposition of high-speed molybdenum steel on a medium-carbon steel substrate after high-temperature tempering.

2. Materials and Methods

Table 1. Modes of formation of the deposited layer of steel M9.

Welding current (A)	Arc voltage (V)	Welding speed (m/h)	Wire feed speed (m/h)	Arc length (mm)
145-150	50-55	18	60	20

A 4mm-diameter MoCrCoC system powder wire was used to form the deposited layer. Samples for research were obtained by plasma surfacing in nitrogen medium on CSN

14331 steel. The mode of formation of the deposited layer is shown in the Table 1. The surfacing was carried out in four layers with a total thickness of ~ 9-10 mm.

Chemical composition of CSN 14331 steel (weight. %): C - 0.3; Cr - 0.9; Mn - 0.8; Si - 0.9, the rest is Fe. The chemical composition of the deposited layer corresponds to steel M9 according to SAE-AISI M9 (T11309) Molybdenum High-Speed Steel (weight. %): Mo-8.85; Cr-3.57; Co-2.12; V-0.05; Si-1.12; Mn-0.56; Al-1.05, the rest - Fe. Superior grade argon (GOST 10157-79) with a flow rate of 6-8 liters/min was used as a plasma-forming gas; technically pure nitrogen (GOST 9293-74) with a flow rate of 20-22 liters/min was used as a protective gas. The plasma surfacing modes on the UD-417 installation did not differ from those described in the work.

The heat treatment of the deposited layer was carried out at a temperature of 560-580 °C for 1 hour.

The phase composition of the deposited layer was studied by X-ray diffraction analysis. We used a DRON-8H X-ray diffractometer equipped with a parabolic mirror on the primary beam and a position-sensitive Mythen 2R 1D detector (640 channels, the size of one strip is 50 μ). The accelerating voltage applied to the X-ray tube was 40 kV, and the current was 20 mA. The shooting was carried out without rotating the sample. The shooting was carried out in the angular range of 20-35-95°. In all cases, the scan step was 0.1° and the exposure time was 15 seconds. Identification of the phase composition, qualitative and quantitative phase analysis, as well as refinement of the structure parameters were performed using the "CDA Crystallography and Diffraction Analysis" software package with a built-in powder standards file (JSC IC Burevestnik, version 2023-01-24-144022.8dec10c0f).

The structure and elemental composition of the deposited layer were studied by scanning electron microscopy (KYKY-EM6900 device with a thermionic tungsten cathode and an attachment for micro-X-ray spectral analysis of the elemental composition).

The defective substructure, elemental and phase composition of the deposited layer were studied by transmission electron diffraction microscopy of thin foils in the lumen mode and in the scanning mode (JEOL JEM-2100 device, Japan) [22-24]. The method of microdiffraction analysis using the dark-field technique was used to analyze the phase composition of the material. Foils (objects studied by transmission electron diffraction microscopy) were produced by ion thinning (Ion Slicer EM-091001S installation, thinning is carried out by argon ions) of plates cut from massive samples on an Isomet Low Speed Saw installation parallel to the longitudinal axis of the sample, which made it possible to trace the change in the defective substructure of the material as it moved away from the fracture surface. Some of the foils were made by electrolytic polishing in a solution of chromium anhydride in orthophosphoric acid.

The hardness and Young's modulus of the deposited layer were determined by Scanning Nano-Hardness Testers Nano Scan at an indenter load of 0.1 N. Studies of the tribological properties of the deposited layer according to the "pin-on-disc" scheme when sliding around a circle were performed on an Oscillating TRIBO tester (ASTM G99). Test conditions: a

VK8 hard alloy ball with a diameter of 6 mm, a friction track radius of 2 mm, a counterbody distance of 100 m, a sample rotation speed of 25 mm/s, an indenter load of 5 N. Tribological tests were performed under dry friction conditions at room temperature. Tribotrek profiles were recorded on a contact profilometer (an Oscillating TRIBO tester attachment to the tribometer).

3. Results and Discussion

The profile of hardness and Young's modulus of the deposited layer subjected to additional tempering is shown in Figure 1. It is clearly seen that the hardness of the deposited material varies non-monotonously, reaching the highest value (16.1 GPa) in the surface layer; the average hardness of the deposited layer is 13.8 GPa. It should be noted that the hardness of the deposited layer before tempering reached a maximum value (14.1 GPa) also in the surface layer; the average hardness value for the thickness of the coating was 12.4 GPa. Thus, tempering of the deposited layer leads to an increase in the average hardness of the coating by 1.13 times. The average hardness of the substrate is 3.2 GPa and is significantly (4.3 times) lower than the average hardness of the deposited metal after tempering.

The Young's modulus is also maximal (269 GPa) in the surface layer of the surfacing and decreases slightly as it moves away from the surface of the deposited layer. The average value of the Young's modulus of the deposited layer after tempering is 262 GPa; before tempering, it is 234.9 GPa. Thus, tempering of the deposited layer leads to an increase in the average Young's modulus of deposition by 1.13 times.

Tribological tests have shown that the wear parameter of the deposited layer $k = 1.5 \cdot 10^{-6} \text{ mm}^3 / \text{N} \cdot \text{m}$; the coefficient of friction of the material is $\mu = 0.66$.

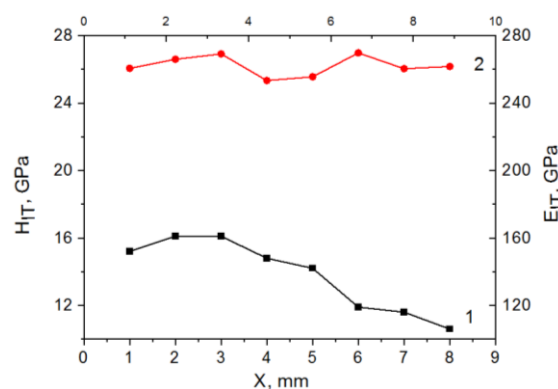


Figure 1. Hardness profile HIT (curve 1) and Young's modulus EIT (curve 2) of the deposited layer after tempering.

Tempering of the deposited layer does not lead to a change in the morphology of the surfacing structure at the macro level: a polycrystalline structure with eutectic layers along grain boundaries is revealed, which is traditional for high-speed

steels [7, 11, 13]. With large increases in the volume of grains, the etching structure is revealed, which obviously indicates the decomposition of the supersaturated solid solution of grains and the formation of nanoscale particles of the carbide phase.

The elemental composition of the deposited layer, studied by micro-X-ray spectral analysis, showed that in addition to the chemical elements of the wire used in the formation of the weld, oxygen atoms are present in the deposited layer, which indicates the oxidation of the material's surface layer.

The mapping method visualized the distribution of the chemical elements of the deposited layer. The research results indicate an inhomogeneous distribution of molybdenum, chromium, aluminum, oxygen, and silicon in the deposited layer. Comparing the mutual distribution of aluminum, silicon, and oxygen atoms, we can assume the formation of aluminum and silicon oxides, as well as aluminosilicates, in the surface layer.

The "point-by-point" method was used to quantify the elemental composition of the characteristic morphological components of the deposited layer structure (rounded inclusions (indicated as "1" in Figure 2), interlayers along grain boundaries (indicated as "2" in Figure 2) and grain volume (indicated as "3" in Figure 2). Presented in Table 2 The results show that rounded inclusions are enriched with aluminum and oxygen atoms, which clearly indicates the formation of aluminum oxides in the deposited layer. The layers along the grain boundaries are mainly enriched with carbon, silicon,

sulfur, vanadium, chromium, and molybdenum atoms, which may indicate a complex phase composition of these structural formations of the weld. The main chemical elements of the grain volume are carbon, chromium, iron and molybdenum.

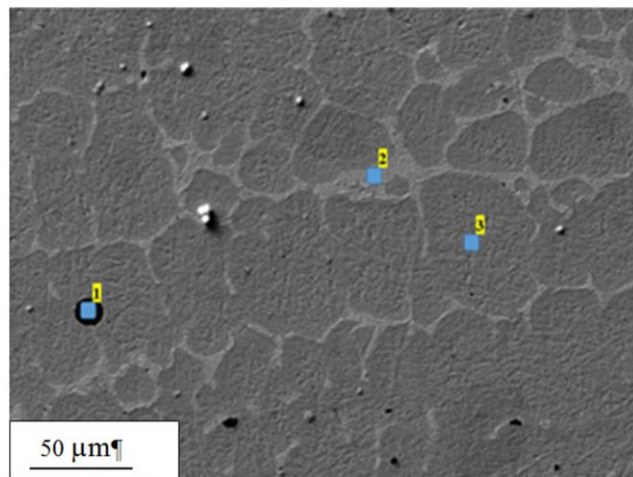


Figure 2. The structure of the etched section of the surface of the deposited layer after tempering. The numbers indicate the surfaced elemental composition determination areas. Scanning electron microscopy.

Table 2. Results of X-ray spectral microanalysis of the surface layer, the image of the structure is shown in Figure 2.

Element	Point 1		Point 2		Point 3		From the area of Figure 2	
	wt. %	at. %	wt. %	at. %	wt. %	at. %	wt. %	at. %
C	0,0	0,0	7,08	26,74	7,64	26,9	0,0	0,0
O	41,35	55,69	2,01	5,69	1,91	5,05	2,16	7,27
Al	52,5	41,93	0,0	0,0	0,07	0,52	0,52	1,05
Si	0,0	0,0	1,38	2,23	1,09	1,63	1,15	2,21
S	0,0	0,0	1,21	1,72	0,0	0,0	0,0	0,0
V	0,0	0,0	0,31	0,27	0,0	0,0	0,07	0,08
Cr	0,33	0,14	5,18	4,52	3,14	2,55	3,64	3,78
Mn	0,0	0,0	0,0	0,0	0,0	0,0	0,58	0,57
Fe	5,82	2,24	57,97	47,08	80,51	60,96	80,54	77,87
Co	0,0	0,0	0,0	0,0	0,0	0,0	2,23	2,05
Mo	0,0	0,0	24,85	11,75	5,39	2,37	9,1	5,12

The phase composition of the deposited layer was studied by X-ray diffraction analysis. The results of the X-ray analysis presented in Table 3 indicate a significant transformation of the phase composition of the deposited layer after tem-

pering. Firstly, residual austenite and Fe_2C iron carbide are not detected. Secondly, the parameter of the α -phase crystal lattice decreases, which indicates the process of decomposition of a solid solution based on α -Fe. Thirdly, the size of the

coherent scattering regions of the α -phase and Me_6C carbide is significantly reduced, which may indicate the transfor-

mation of the defective substructure of the α -phase and the release of nanoscale particles of Me_6C carbide.

Table 3. Calculated data obtained from radiographs of the deposited layer.

Phase	Phase fraction (wt. %)	Lattice parameters (Å)	OCD dimensions (nm)
Pre-tempering state			
α -Fe	65	$a = 2.887$	52
γ -Fe	12	$a = 3.598$	34
M_{23}C_6	11	$a = 10.466$	23
Me_6C	7	$a = 11.002$	28
Fe_2C	5	$a = 2.701$ $c = 4.449$	13
Post-tempering state			
α -Fe	85	$a = 2.873$	26
M_{23}C_6	9	$a = 10.420$	23
Me_6C	6	$a = 11.002$	13

Studies of the elemental and phase composition, morphology of phases, and defective substructure of the deposited layer subjected to heat treatment performed by transmission electron microscopy showed that the grains have a lamellar structure characteristic of lamellar martensite of hardened steel (Figure 3). Along the grain boundaries, extended interlayers are observed with a structure characteristic of eutectic transformation, i.e. the eutectic of the lamellar type is located along the grain boundaries (Figure 3a). A dislocation substructure of the mesh type is observed in the volume of the plates. The scalar dislocation density, measured by the secant method [25], $\langle \rho \rangle = 6.5 \cdot 10^{10} \text{ cm}^{-2}$.

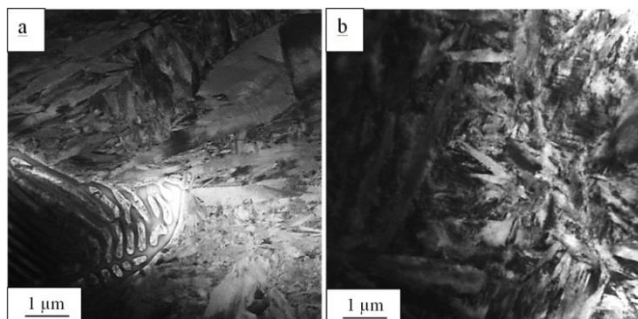


Figure 3. Electron microscopic image of the deposited layer structure: a - the image was obtained by STEM analysis methods; b - by TEM analysis methods.

along the grain boundaries are mainly enriched with molybdenum, chromium, carbon, and iron atoms. Eutectic grains are formed by alternating plates enriched mainly with iron and molybdenum atoms.

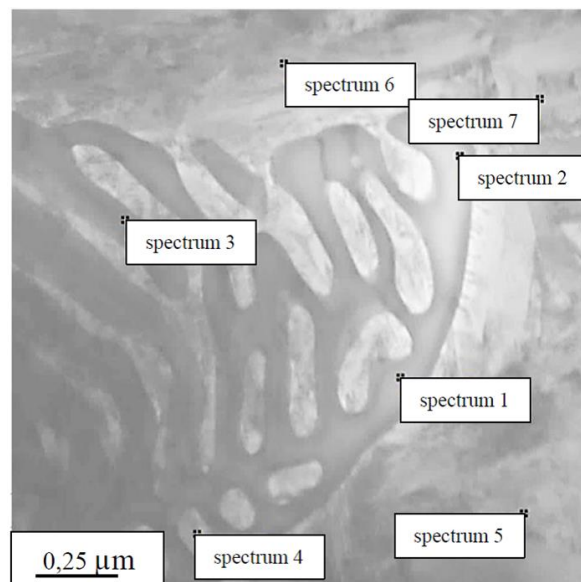


Figure 4. Results of a X-ray microanalysis of the deposited layer by the "point-by-point" method. The sites for determining the elemental composition are indicated.

Mapping methods have shown that the interlayers located

By the method of "point by point" micro-X-ray spectral analysis, some clarifying quantitative studies of the eutectic

and α -phase grains elemental composition were performed, see Figure 4 for electron microscopic image. It is clearly seen that the layered structure of the eutectic grain has a different elemental composition. The darker layers (spectra 1-3) are enriched with molybdenum and carbon atoms and do not contain aluminum atoms (Table 4). The light contrast layer

(Spectrum 4) and the martensitic structure of the grain located next to the eutectic are enriched mainly with iron atoms. This suggests that the interlayers located along the grain boundaries are formed by alternating layers of carbides such as Me_{23}C_6 and Me_6C and layers based on a solid iron solution.

Table 4. The results of the elemental analysis of the foil section shown in Figure 4.

Spectrum	Chemical element (at. %)							
	C	Al	Si	V	Cr	Mn	Fe	Mo
1	46.58	-0.01	2.43	0.17	2.57	0.39	19.79	28.08
2	53.43	0.03	2.32	0.08	2.22	0.09	15.91	25.92
3	30.28	0.03	2.19	0.41	3.46	0.18	23.22	40.23
4	25.56	0.13	1.44	-0.01	3.16	0.46	66.55	2.72
5	27.32	0.15	2.22	0.04	2.77	0.39	59.63	7.47
6	32.40	0.31	1.65	-0.03	3.02	0.29	57.27	5.09
7	32.74	0.59	2.49	-0.02	2.91	0.44	56.38	4.47

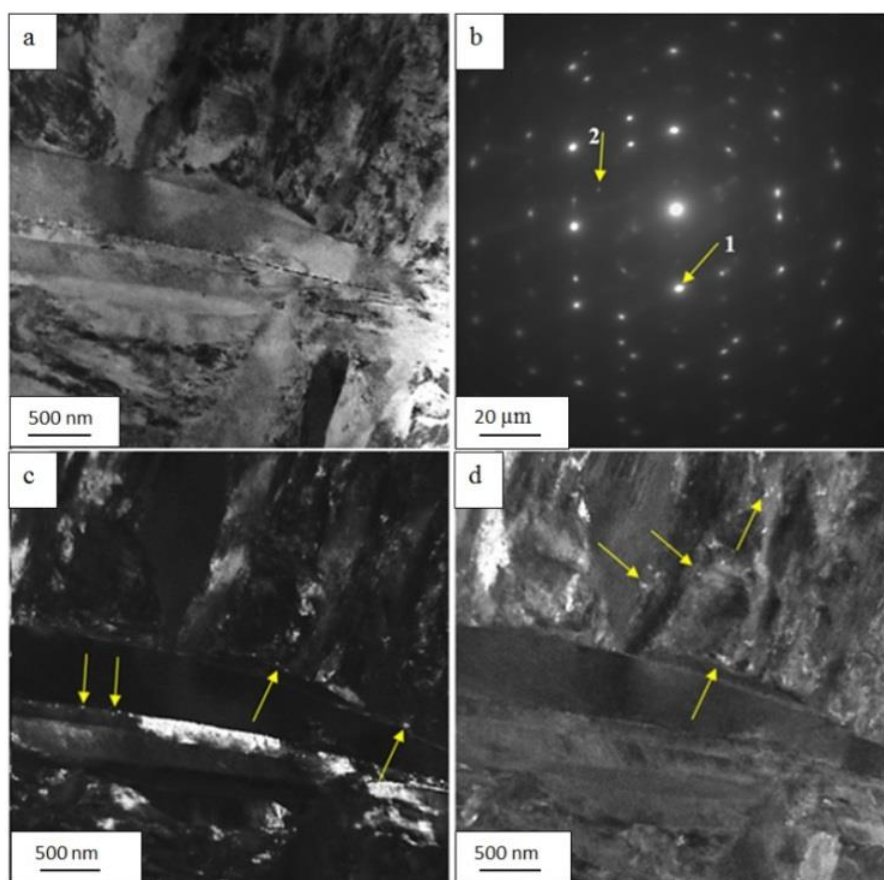


Figure 5. TEM image of the deposited layer structure: a - light field; b - microelectronogram; c, d - dark fields obtained in reflexes $[112]\alpha\text{-Fe} + [322]\text{Fe}_3\text{C}$ (c) and $[112]\alpha\text{-Fe} + [631]\text{Cr}_3\text{C}_2$ (d); on (b) the arrows indicate the reflexes in which dark fields are obtained: 1 - for (c); 2 - for (d). On (c, d), the arrows indicate the particles of the carbide phase.

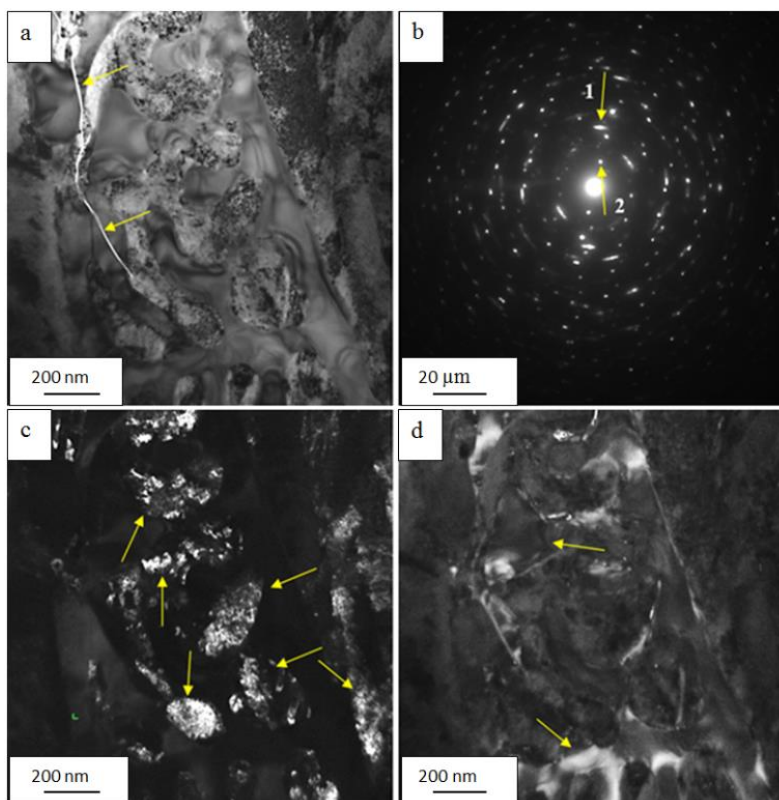


Figure 6. TEM image of the structure of carbides and α -phase with microcracks: a - light field; b - microelectronogram; c, d - dark fields obtained in reflexes $[002]\alpha\text{-Fe}$ (c); $[113]M_6C$ (d); On (a) the arrows indicate a microcrack located along the interfaces of eutectic grains; on (b) the arrows indicate reflexes in which dark fields are obtained: 1 - for (c); 2 - (d); on (c), the arrows indicate the $\alpha\text{-Fe}$ sections, on (d), the arrows indicate the Me_6C type carbide plates.

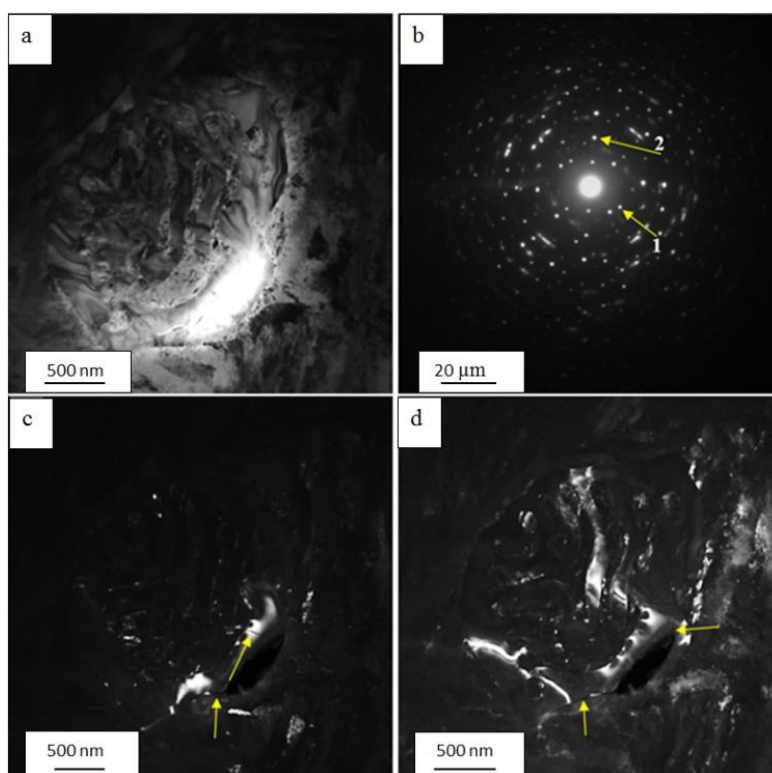


Figure 7. Electron microscopic image of the coating structure in the tempered state; a - bright field; b - microelectron diffraction pattern; c, d - dark fields obtained in reflections $[244]M_{23}C_6$ (c); $[133]M_{23}C_6$ (d); In (b), arrows indicate reflections in which dark fields were obtained: 1 - for (c); 2 - (d); in (c, d), arrows indicate microcracks located in the volume of carbide phase plates.

Studies of the phase composition of the deposited layer performed by transmission electron diffraction microscopy using microelectronogram analysis and dark-field analysis [22-24] showed that the tempering of the deposited metal is accompanied by a partial transformation of residual austenite with the formation of iron carbide and chromium carbide particles along the boundaries of the martensite plates (Figure 5). No particles of the carbide phase were found in the volume of the martensite plates. No particles of the carbide phase were found in the volume of the martensite plates.

Above, it was shown that the surfacing under study is formed by grains of a solid solution based on α -Fe and grains of eutectic. Analysis of microelectronograms obtained from eutectic grains suggests that they are multiphase formations and are formed by layers of carbides of complex composition such as $M_{23}C_6$ or Me_6C (Figure 6d) and alpha-phase layers (Figure 6c). Along the interface (Figure 6a) and in the volume. Microcracks are detected in the plates of the carbide phase (Figure 7). This indicates that the eutectic grains are in an elastically stressed state and can be sources of macro cracks that can lead to the destruction of the deposited material.

4. Conclusions

The technology of plasma surfacing in a nitrogen medium of 4mm-diameter MoCrCoC system powder wire on steel CSN 14331 formed a surfaced layer with a thickness of ~ 10 mm. Argon of the highest grade was used as a plasma-forming gas. The deposited layer was tempered twice at a temperature of 560-580 °C for 1 hour. Mechanical and tribological tests were performed and it was found that the hardness of the deposited layer is significantly (4.3 times) higher than the hardness of CSN 14331 steel, the wear parameter of the deposited layer $k = 1.5 \cdot 10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$; the coefficient of friction of the material $\mu = 0.66$. It is shown that tempering of the deposited layer does not lead to a change in the morphology of the surfacing structure at the macro level: a polycrystalline structure formed by eutectic grains and grains of a solid solution based on α -iron (BCC crystal lattice) is revealed. The formation of a multiphase structure in the deposited layer was revealed, represented by an α -phase (solid solution based on the BCC crystal lattice Fe), a γ -phase (solid solution based on the FCC crystal lattice Fe), carbides of complex composition $Me_{23}C_6$ and Me_6C , iron carbides of composition Fe_3C and chromium of composition Cr_3C_2 . The main phases are a solid solution based on α -Fe (85 wt. %) and carbides of complex composition $Me_{23}C_6$ (9 wt. %) and Me_6C (6 wt. %), forming eutectic grains. It has been established that the tempering of the deposited layer is accompanied by the pre-transformation of residual austenite with the formation of nanoscale particles of iron and chromium carbides along the boundaries of martensite crystals. It can be assumed that the increase in hardness and wear resistance of the deposited metal as a result of heat treatment is due to the decomposition of a solid solution based on γ -iron with the formation of nanoscale

inclusions of the carbide phase. Microcracks have been identified along the interfacial interfaces and in the volume of the plates of the carbide phase of eutectic grains, which can initiate the destruction of the deposited layer material under mechanical stress.

Abbreviations

TEM	Transmission Electron Microscopy
BCC	The Body-Centered Cubic
SEM	Scanning Electron Microscopy

Author Contributions

Irina Viktorovna Baklushina: Project administration, Validation, Writing – review & editing

Yuriy Fedorovich Ivanov: Investigation, Methodology, Writing – original draft

Victor Evgenievich Gromov: Conceptualization, Supervision

Igor Yurievich Litovchenko: Visualization

Yuriy Sergeevich Serenkov: Writing - original draft

Alexander Sergeevich Chapaikin: Formal analysis

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Conflicts of Interest

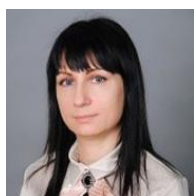
The authors declare no conflicts of interest.

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Biography



Irina Viktorovna Baklushina is a researcher at Siberian State Industrial University, Novokuznetsk, Russia. She specializes in physical materials science, focusing on structural and phase states and the properties of plasma coatings and high-speed steels. Baklushina is an active author in the field of materials engineering with expertise in transmission electron microscopy and surface coating technologies. She has contributed to studies on plasma deposited layers and tempering effects on steels.



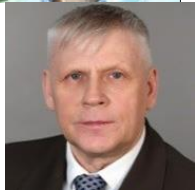
Yuriy Fedorovich Ivanov is a leading scientist at Siberian State Industrial University, Russia. He holds a doctorate in physics or materials science and focuses on microstructural analysis, phase transformations, and mechanical properties of steel alloys. Ivanov's research involves heat treatment and plasma surfacing of high-speed steels. He has extensive experience in electron microscopy techniques and has published numerous papers on structural materials.



Victor Evgenievich Gromov works at Siberian State Industrial University, Novokuznetsk. His research areas include metallurgical engineering, physical materials science, and phase transformations in high-speed steels. Gromov holds an advanced degree in materials science and collaborates closely with colleagues on the investigation of plasma coatings and structural analysis of alloys.



Igor Yurievich Litovchenko is affiliated with the Institute of Strength Physics and Materials Science, SB RAS, Tomsk, Russia. He is a specialist in electron microscopic visualization and materials characterization. His work involves detailed electron diffraction microscopy studies to analyze defective substructures and phase compositions of steel coatings. Litovchenko's expertise supports structural metallurgy research on high-speed steels.



Yuriy Sergeevich Serenkov is a research scientist at Siberian State Industrial University. His specialization includes surface engineering, plasma metallurgy, and materials characterization of steel coatings. Serenkov contributes to the development and analysis of plasma surfacing technologies and mechanical properties improvement.



Alexander Sergeevich Chapaikin is a materials science researcher based at Siberian State Industrial University. His research focuses on high-speed molybdenum steels, plasma coating technologies, and mechanical property enhancement through heat treatment processes. Chapaikin holds a relevant advanced degree and participates in studies on microstructural and phase transformation effects in steel.

Research Field

Irina Viktorovna Baklushina: Plasma coatings, High-speed steels, Materials characterization, Electron microscopy, Phase transformations

Yuriy Fedorovich Ivanov: Structural analysis of steels, Phase transformations, Electron microscopy, Plasma surface engineering, Tribological properties

Victor Evgenievich Gromov: Plasma surfacing, Microstructure of steels, Mechanical properties, Alloy phase composition, Materials science

Igor Yurievich Litovchenko: Transmission electron microscopy, Phase analysis, Coating microstructure, Materials visualization, Nanostructured materials

Yuriy Sergeevich Serenkov: Steel coatings, Surface modification, Microstructural characterization, Plasma engineering, Materials properties

Alexander Sergeevich Chapaikin: High-speed steel alloys, Plasma deposited layers, Mechanical testing, Carbide phases, Steel surface engineering