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MODIFICATION OF TRANSITION ZONE STRUCTURE OF HIGH-SPEED STEEL SURFACING – SUBSTRATE BY ELECTRON-BEAM TREATMENT

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Abstract. The structural-phase states and defect substructure of transition zone of plasma surfacing with non-current flux-cored wire in the nitrogen medium of R2M9 high-speed steel on the substrate of medium-carbon steel 30HGSA in the initial state, after high-temperature tempering and electron beam treatment were analyzed using scanning and transmission electron microscopy. The formed deposited layer with a thickness of ~5 mm has a frame-type carbide structure, which is not fractured during subsequent tempering and pulsed electron beams irradiation. Regardless of the state of the studied material, a martensitic structure with retained austenite, located along the boundaries of martensite plates and in the form of individual grains of submicron sizes, is formed in the “deposited layer – substrate” transition zone. Nanosized particles of the carbide phase of various morphologies (plates, globules, spheres), located along the grain boundaries of martensite crystals and austenite layers, were identified in the transition zone. Carbides Fe_3C, V_2C, W_2C, CrC, $Cr_{32}C_2$, Cr_7C_3, MoC, Mo_2C, as well as carbides such as Fe_3W_3C and Fe_6W_6C, the elemental composition of which is determined by the complex composition of the surfacing, were identified. Irradiation of the transition zone with a pulsed electron beam leads to high-speed hardening of the material with the formation of martensite structure of predominantly lamellar morphology. In the volume of martensite plates, particles of chromium carbide of composition CrC were detected.

Keywords: deposited layer, electron microscopy, transition zone, tempering, pulsed electron beam, structure, properties

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МОДИФИКАЦИЯ СТРУКТУРЫ ПЕРЕХОДНОЙ ЗОНЫ НАПЛАВКА ИЗ БЫСТРОРЕЖУЩЕЙ СТАЛИ – ПОДЛОЖКА ЭЛЕКТРОННО-ЛУЧЕВОЙ ОБРАБОТКОЙ

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Аннотация. С помощью сканирующей просвечивающей электронной микроскопии проведен анализ структурно-фазовых состояний и дефектной субструктуры переходной зоны плазменной наплавки нетокопроводящей порошковой проволокой в среде азота быстрорежущей стали марки Р2М9 на подложке из среднеуглеродистой стали марки 30ХГСА в исходном состоянии, после высокотемпературного отпуска и электронно-лучевой обработки. Сформированный наплавленный слой толщиной примерно 5 мм имеет каркасную карбидную структуру, которая не разрушается при последующих отпусках и облучении импульсными электронными пучками. Независимо от состояния исследуемого материала в переходной зоне наплавленный слой – подложка формируется мартенситная структура с остаточным аустенитом, расположенным по границам мартенситных пластин в виде отдельных зерен субмикронных размеров. В переходной зоне выявлены наноразмерные частицы карбидной фазы различной морфологии (пластины, глобулы, сферы), расположенные по границам зерен мартенситных кристаллов и аустенитных прослоек. Выявлены карбиды Fe_3C, V_2C, W_2C, CrC, $Cr_{32}C_2$, Cr_7C_3, MoC, Mo_2C, Fe_3W_3C и Fe_6W_6C, элементный состав которых определяется сложным составом наплавки. Облучение переходной зоны импульсным электронным пучком приводит к высокоскоростному упрочнению материала с образованием мартенситной структуры преимущественно пластинчатой морфологии. В объеме мартенситных пластин обнаружены частицы карбида хрома CrC.

Ключевые слова: наплавленный слой, электронная микроскопия, переходная зона, отпуск, импульсный электронный пучок, структура, свойства

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Introduction

Reliability and durability of the working surfaces of equipment and mechanisms are determined mainly by the quality of their protection against wear and corrosion. The most common causes of premature failure of machine and equipment parts are abrasive and impact-abrasive wear, cavitation, corrosion, and fatigue processes. This problem is solved by controlled changes in the properties of working surfaces through surfacing that provides the required set of properties [1 – 4]. Development of coatings with improved performance characteristics under extreme conditions is a fundamental task of great economic importance [5 – 7].

High performance properties of deposited high-speed steels (HSS) are achieved by special alloying and complex heat treatment, which ensures a certain phase composition [8 – 12]. High hardness and wear resistance of high-speed steels are due to their alloying with carbide-forming elements: tungsten, vanadium, molybdenum and chromium. These elements, under certain temperature and time conditions, form particles of the carbide phase in steel, which are the strengthening phase of the material [13].

Recent research and development in the field of plasma surface technology with high-speed steels indicate that its application most fully meets the requirements of industry both in terms of the level of properties achieved and in terms of economic efficiency [1; 2]. Plasma surfacing is used not only for the repair and restoration of worn-out equipment, but also for imparting special properties to the surfaces of new products before they are put into operation. The properties of the selected surfacing material will be the main factor providing the required parameters of the hardened surface.

The use of a shielding and alloying medium of nitrogen during plasma surface treatment, which has significant advantages over other methods, substantially improves abrasive wear resistance, corrosion and impact resistance, and strength due to the formation of carbonitrides with increased microhardness [14; 15]. Plasma surfacing in the nitrogen medium with a non-current-carrying flux-cored wire leads to the production of deposited high-speed steels alloyed with nitrogen and aluminum, which increases their hardness and wear resistance and reduces the cost of surfacing [1; 14; 15]. Improvement of tribological and mechanical properties and the quality of the deposited surface layer can be achieved by electron beam treatment [16 – 20]. It provides good damping properties under mechanical and thermal loads and prevents the premature initiation of brittle microcracks.

The analysis of related literature published in Russia and abroad shows that there are very few studies devoted to the physical nature and formation mechanisms of transition zone structure of HSSs surfacing-substrate using transmission electron microscopy [1; 20].

The purpose of this work is to analyze the results obtained from studying the transition zone structure of the layer deposited on 30HGSA steel with PP-R2M9 flux-cored wire and subjected to high-temperature tempering and electron beam treatment.

Materials and methods

The deposited material was investigated in three states: firstly, after the formation of the deposited layer (hereinafter referred to as the initial state), secondly, after three temperings of samples in the initial state, and thirdly, after three temperings and additional irradiation with a pulsed electron beam.

The samples for research were produced by plasma surfacing using R2M9Yu non-current-carrying flux-cored wire on 30HGSA steel in the nitrogen medium. Chemical composition of 30HGSA steel, % (by weight): 0.3 C; 0.9 Cr; 0.8 Mn; 0.9 Si. Chemical composition of R2M9Yu alloy, % (by weight): 0.86 C; 4.80 Cr; 2.50 W, 9.4 Mo; 0.50 V; 0.85 Al; 0.08 N; the rest is iron. Plasma surfacing modes did not differ from those described in [1; 2; 15]. Some samples of 30HGSA steel with a deposited layer of R2M9 alloy were subjected to high-temperature tempering at a heating temperature of 580 °C, holding time – 1 hour, number of temperings – 3. After tempering, part of the samples was subjected to additional irradiation with a pulsed electron beam. Pulsed electron beam treatment was carried out on the SOLO installation (IHCE SB RAS) [19; 20] with the following parameters: energy of accelerated electrons – 18 keV; electron beam energy density – 30 J/cm^2, exposure pulse duration – 50 μs, pulse repetition frequency – 0.3 s^{-1}, number of pulses – 5; irradiation was carried out at a residual gas pressure (argon) in the working chamber of the installation – 0.02 Pa.

Studies of the transition zone structure of the deposited layer were performed using scanning (KYKY-EM6900 device equipped with an AZtec Live Lite Xplore 30 EDS energy-dispersive microanalysis system) and transmission diffraction (JEM2100 device) electron microscopy [21 – 23]. The phase composition and state of the crystal lattice of the phases were studied by X-ray diffraction analysis (DRON-8N X-ray diffraction meter).

Results and discussion

Plasma surfacing in the nitrogen medium with R2M9Yu non-current-carrying flux-cored wire on 30HGSA steel led to the formation of a layer with a thickness of 5 mm. The deposited layer has a frame-type carbide structure formed by grains of two dimensional levels. The grains of the first level have sizes varying within the range of 15 – 35 μm. The grain sizes of the second level vary within the range of 3.5 – 11.0 μm.

It was found that the transition zone has a martensitic structure (Fig. 1, *a*). Along the boundaries of the martensite plates there are extended layers of retained austenite (Fig. 1, *c*).

The transition zone structure contains particles of the second phase. Particles of the second phase are characterized by a variety of shapes (plates, globules, spheres), sizes (from 2 to 60 nm), location (dislocations, grain boundaries, martensite crystals and layers of retained austenite).

Dark-field analysis with subsequent indexing of microelectron diffraction patterns showed that nano-sized particles formed on dislocations are vanadium carbide (Fig. 2, *c*, particles are indicated by doted arrows); the particles located at the boundaries of the martensite plates are molybdenum and tungsten carbides (Fig. 2, *d*, particles are indicated by arrows). It should be noted that there are grains of retained austenite in the structure of the transition zone (Fig. 2, *a*, *c*; grains of retained austenite are indicated by arrows). A twin structure is almost always observed in the bulk of austenite grains, which indicates a low value of the γ-phase stacking fault energy.

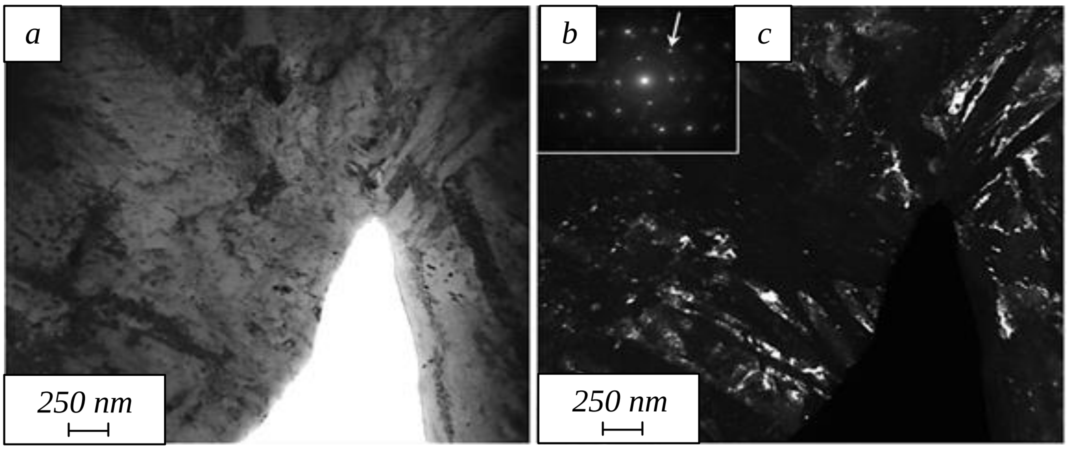

Fig. 1. EM image of the transition zone structure in the state after surfacing (initial state):
a – bright field; *b* – microelectron diffraction pattern; *c* – dark field obtained in the reflection [022] γ-Fe (the reflection is indicated by the arrow in *b*)

Рис. 1. ЭМ-изображение структуры переходной зоны в состоянии после наплавки (исходное состояние):
a – светлое поле; *b* – микроэлектронная дифракционная картина; *c* – темное поле, полученное в рефлексе [022] γ-Fe (рефлекс указан стрелкой на поз. *b*)

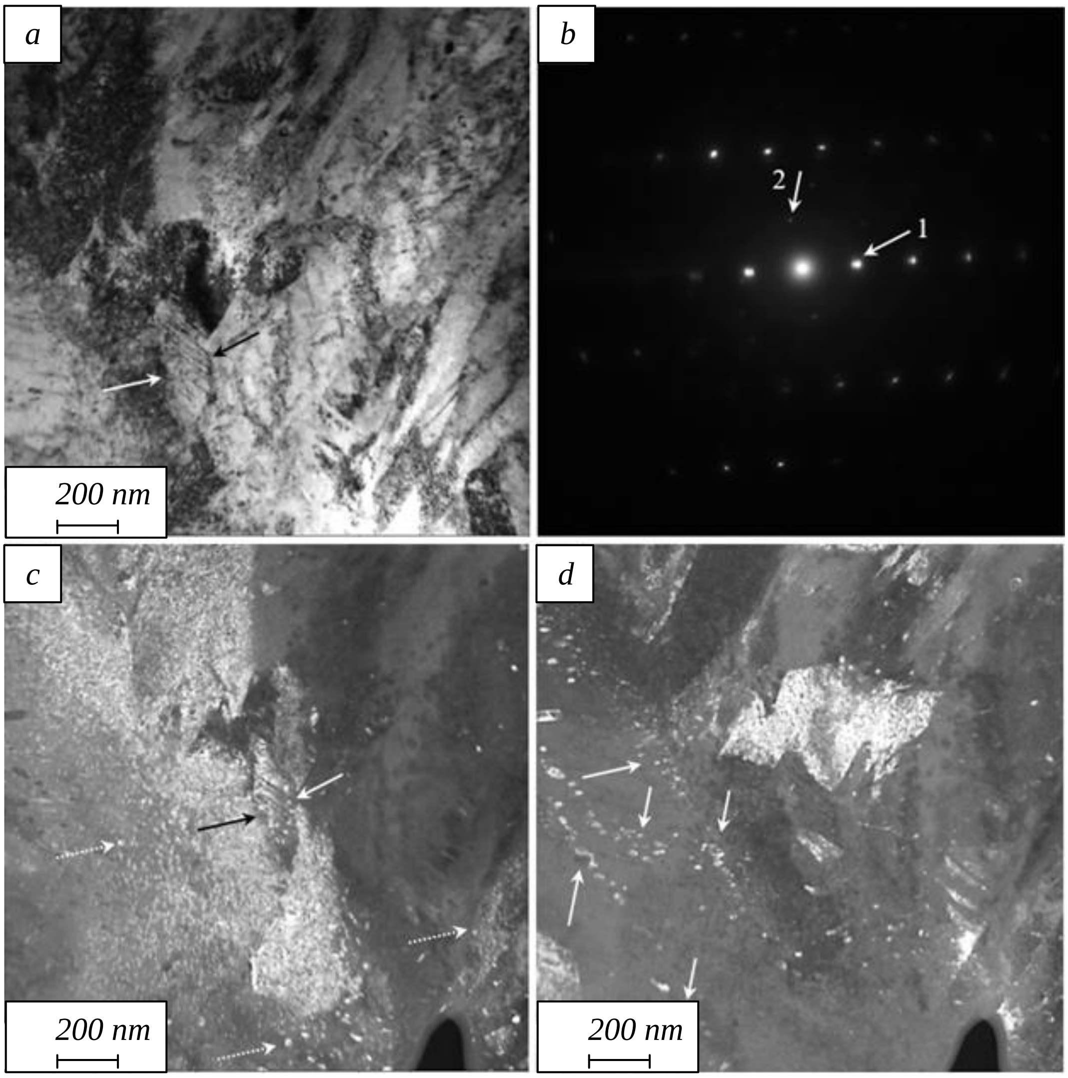

Fig. 2. EM image of the transition zone structure in the state after surfacing (initial state):
a – bright field; *b* – microelectron diffraction pattern; *c* and *d* – dark fields obtained in the reflections [110] α-Fe + [002] γ-Fe + [012] V_2C and [110] α-Fe + [103] MoC + [101] W_2C, in (*b*) the arrows indicate the reflections in which dark fields were obtained for *c* (*1*), for *g* (*2*)
Рис. 2. ЭМ-изображение структуры переходной зоны в состоянии после наплавки (исходное состояние):
a – светлое поле; *b* – микроэлектронная дифракционная картина; *c* и *d* – темные поля, полученные в рефлексах [110] α-Fe + [002] γ-Fe + [012] V_2C и [110] α-Fe + [103] MoC + [101] W_2C (на поз. *b* стрелками указаны рефлексы, в которых получены темные поля для поз. *c* (*1*), для поз. *g* (*2*))

Three high-temperature temperings of steel samples with a deposited layer did not lead to a significant change in the morphology of particles of the carbide phase in the transition zone. As in the initial state, particles of spherical, globular and lamellar shapes are observed in the structure of the transition zone after tempering. The sizes of globular particles vary within a range of up to 100 nm; spherical particles – within a few nanometers.

Analysis of the microelectron diffraction patterns and corresponding dark-field images shows that the particles are chromium-based carbides of the composition Cr_3C_2 and Cr_7C_3, molybdenum (MoC and Mo_2C), iron (Fe_3C) and multi-element carbides of the type M_6C $(Fe, W)_6C$.

It should be noted that nano-sized or submicron carbide particles are formed in the transition zone as a result of high-temperature tempering of regions with a relatively high density. This fact obviously indicates a non-uniform distribution of chemical elements in the deposited layer, which is clearly revealed when the material is tempered as a result of supersaturated solid solution decomposition with the formation of second-phase particles.

Irradiation of the transition zone with a pulsed electron beam leads to high-speed hardening of the material with the formation of martensite structure of predominantly lamellar morphology (Fig. 3). In the volume of martensite plates, particles of chromium carbide of composition CrC were detected (Fig. 3, *b*). Along with chromium carbides, globular carbides of complex elemental composition $M_{12}C$ (Fe_6W_6C) were identified in the studied layer (Fig. 4)

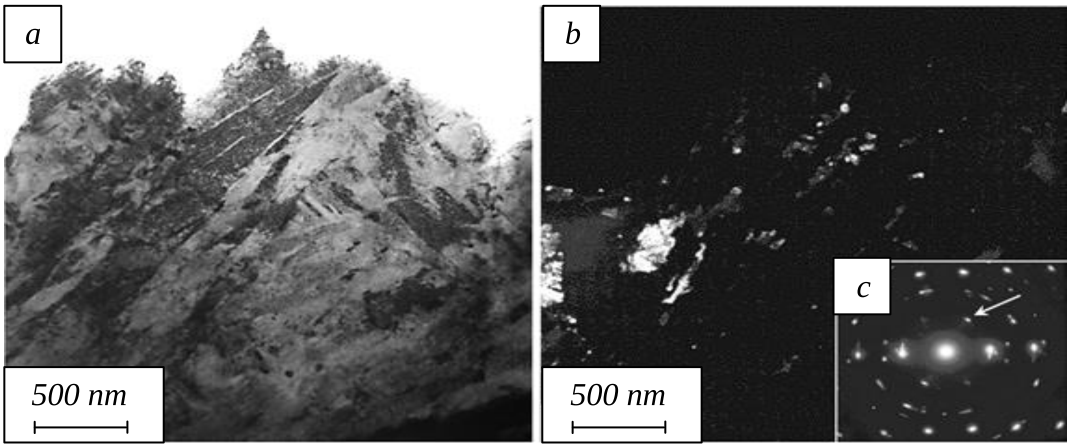

Fig. 3. EM image of the martensitic structure of the transition zone in the state after repeated high-temperature temperings and subsequent irradiation with a pulsed electron beam:
a – bright field; *b* – dark field obtained in reflections [110] α-Fe + [002] CrC; *c* – microelectron diffraction pattern (the arrow indicates the reflection in which the dark field was obtained)

Рис. 3. ЭМ-изображение мартенситной структуры переходной зоны после многократных высокотемпературных отпусков и последующего облучения импульсным электронным пучком:
a – светлое поле; *b* – темное поле, полученное в рефлексах [110] α-Fe + [002] CrC; *c* – микроэлектронограмма (стрелкой показано отражение, в котором получено темное поле)

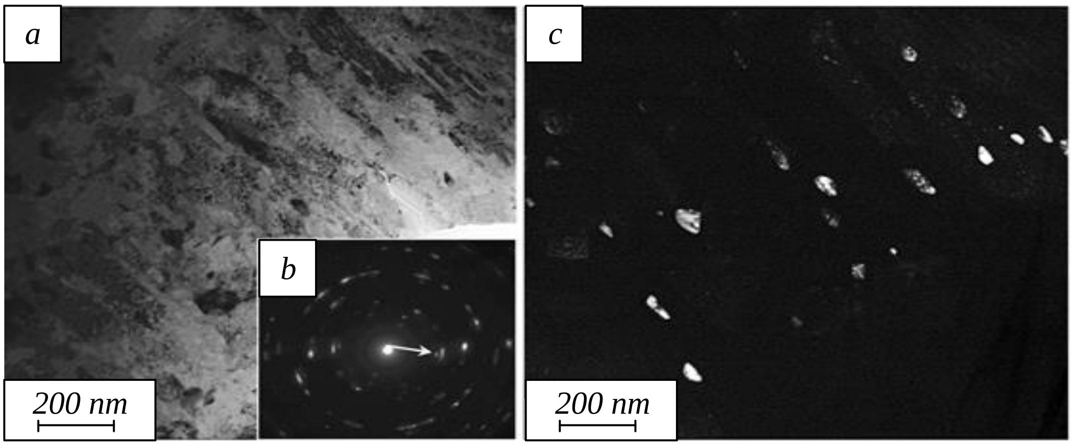

Fig. 4. EM image of the martensitic structure in the transition zone in the state after repeated high-temperature temperings and subsequent pulsed electron beam irradiation:
a – bright field; *b* – microelectron diffraction pattern (the arrow indicates the reflection in which the dark field was obtained); *c* – dark field obtained in the [422] Fe_6W_6C reflection

Рис. 4. ЭМ-изображение мартенситной структуры в переходной зоне после многократных высокотемпературных отпусков и последующего облучения импульсным электронным пучком:
a – светлое поле; *b* – микроэлектронная дифракционная картина (стрелкой указано отражение, в котором получено темное поле); *c* – темное поле, полученное в отражении [422] Fe_6W_6C

Conclusion

Plasma surfacing in the nitrogen medium with a non-current-carrying flux-cored wire PP-R2M9Yu on 30HGSA steel formed a layer with a thickness of 4.5 – 5.0 mm having a frame-type carbide structure. It was shown that additional heat treatment (repeated temperings, pulsed electron beam irradiation) does not result in a fracture of this structure.

It is shown that, regardless of the state of the studied material, a lamellar-type martensitic structure is formed in the transition zone. Along with martensite (a solid solution based on the bcc crystal lattice of iron), the transition zone contains residual austenite (a solid solution based on the fcc crystal lattice of iron) located in the form of extended layers along the boundaries of martensite plates and in the form of separately located grains of submicron and micron sizes. It was established that the transition zone is characterized by the presence of a large number of particles of the carbide phase with various morphologies (plates, globules, spheres) and sizes (from units to tens of nanometers). The particles are located along the boundaries of grains, martensite crystals and austenite layers, in the volume of martensite plates on dislocations. The elemental composition of carbide phase particles is diverse: carbides based on iron (Fe_3C), vanadium (V_2C), tungsten (W_2C), chromium (CrC, Cr_3C_2, and Cr_7C_3), molybdenum (MoC and Mo_2C), carbides of multi-element composition type M_6C (Fe_3W_3C) and $M_{12}C$ (Fe_6W_6C) were identified. Obviously, the diverse set of carbide phase is due to the complex elemental composition of the material deposited on the steel.

СПИСОК ЛИТЕРАТУРЫ

1. Громов В.Е., Чапайкин А.С., Невский С.А. *Структура, свойства и модели быстрорежущей стали после отпуска и электронно-лучевой обработки*. Новокузнецк: Полиграфист, 2024:171.
2. Иванов Ю.Ф., Громов В.Е., Потекаев А.И., Гусева Т.П., Чапайкин А.С., Ващук Е.С. Структура и свойства наплавки Р18У на быстрорежущую сталь после ее высокого отпуска. *Физический журнал*. 2023 66:731–739. *https://doi.org/10.1007/s11182-023-02999-w*
3. Нефедьев С.П., Емелюшин А.Н. *Плазменная закалка поверхности*. Старый Оскол: Издательский дом «ТНТ», 2021:156.
4. Мозговой И.В., Шнейдер Е.А. *Наплавка быстрорежущей стали*. Омск: Изд-во «ОмГТУ», 2016:200.
5. Chaus A.S., Pokorný P., Čaplovič Ľ., Sitkevich M.V., Peterka J. Complex fine-scale diffusion coating formed at low temperature on high-speed steel substrate. *Appl Surf Sci*. 2018;437:257–270. *https://doi.org/10.1016/j.apsusc.2017.12.173*
6. Krukovich M.G., Prusakov B.A., Sizov I.G. Plasticity of boronized layers. Cham: Springer, 2016:364.
7. Edenhofer B., Joritz D., Rink M., Voges K. Carburizing of steels. In: *Thermochemical Surface Engineering of Steels*. Woodhead Publishing, 2015:485–553.
8. Wu W., Chen W., Yang S., Lin Y., Zhang S., Cho T.-Y., Lee G.H., Kwon S.-Ch. *Design of AlCrSiN multilayers and nanocomposite coating for HSS cutting tools*. *Appl Surf Sci*. 2015;351:803–810.
9. Cho I.S., Amanov A., Kim J.D. The effects of AlCrN coating, surface modification and their combination on the tribological properties of high speed steel under dry conditions. *Tribol Int*. 2015;81:61–72. *https://doi.org/10.1016/j.triboint.2014.08.003*
10. Kottfer D, Ferdinandy M, Kaczmarek L, Maňková I, Beňo J. *Investigation of Ti and Cr based PVD coatings deposited onto HSS Co 5 twist drills*. *Appl Surf Sci*. 2013;282:770–776.
11. Gerth J, Wiklund U. The influence of metallic interlayers on the adhesion of PVD TiN coatings on high-speed steel. *Wear*. 2008;264:885–892.
12. Chaus A.S., Rudnitskii F.I. Structure and Properties of Cast Rapidly Cooled High-Speed Steel R6M5. *Metals Science and Thermal Treatment*. 2003;45:157–162.
13. Геллер Ю.А. *Инструментальные стали*. Москва: Металлургия, 1983:527.
14. Нефедьев С.П., Емелюшин А.Н. Влияние азота на формирование структуры и свойств плазменных покрытий типа 10Р6М5. *Вестник Югорского государственного университета*. 2021;3(62):33–45.
15. Почетуха В.В., Бащенко Л.П., Гостевская А.Н., Будовских Е.А., Громов В.Е., Чапайкин А.С. Структура и свойства плазменных покрытий из быстрорежущей стали после высокотемпературного отпуска. *Вестник Сибирского государственного индустриального университета*. 2023;3(45):30–38. *https://doi.org/10.57070/2304-4497-2023-3(45)-30-38*
16. Громов В.Е., Кобзарева Т.Ю., Иванов Ю.Ф., Будовских Е.А., Бащенко Л.П. Модификация поверхности сплава Ti методом электровзрывного легирования и электронно-лучевой обработки. В кн.: *Труды конференции AIP*. 2016;1698:030006. *https://doi.org/10.1063/1.4937828*
17. Громов В.Е., Иванов Ю.Ф., Глезер А.М., Кормышев В.Е., Коновалов С.В. Электронно-лучевая модификация поверхностного слоя, нанесенного на малоуглеродистую сталь методом дугового напыления. *Известия Российской академии наук: Физика*. 2017;81(1):1353–1359
18. Коваль Н.Н., Иванов Ю.Ф. *Эволюция структуры поверхностного слоя стали, подвергнутой электронно-ионно-плазменной обработке*. Томск: НТЛ, 2016:298.
19. Коваль Н.Н., Иванов Ю.Ф. Наноструктурирование поверхностей металлокерамических и керамических материалов электронными пучками. *Физический журнал*. 2008;51(5):60–70.
20. Иванов Ю.Ф., Чапайкин А.С., Гусева Т.П., Романов Д.А., Громов В.Е. Трансформация структуры и свойств наплавки Р18Ю после высокотемпературного отпуска и электронно-лучевой обработки. *Проблемы черной металлургии и материаловедения.* 2023;3:62–79.
21. Egerton F.R. *Physical Principles of Electron Microscopy*. Basel: Springer International Publishing, 2016:196.
22. Kumar C.S.S.R. *Transmission Electron Microscopy. Characterization of Nanomaterials*. New York: Springer, 2014:717.
23. Carter C.B., Williams D.B. *Transmission Electron Microscopy*. Berlin: Springer International Publishing, 2016:518.

REFERENCES

1. Gromov V.E., Chapaikin A.S., Nevskii S.A. *Structure, properties and models of high-speed steel after tempering and electron beam treatment*. Novokuznetsk: Polygraphist, 2024:171. (In Russ.).
2. Ivanov Yu.F., Gromov V.E., Potekaev A.I., Guseva T.P., Chapaikin A.S., Vashchuk E.S. Structure and properties of R18U surfacing of high-speed steel after its high tempering. *Russian Physics Journal* 2023;66:731–739. (In Russ.). *https://doi.org/10.1007/s11182-023-02999-w*
3. Nefedyev S.P., Emelyushin A.N. *Plasma surface hardening*. Stary Oskol: Publishing house "TNT", 2021:156. (In Russ.).
4. Mozgovoy I.V., Shneider E.A. *Surfacing of high-speed steel*. Omsk: Publishing house "OmSTU", 2016:200. (In Russ.).
5. Chaus A.S., Pokorný P., Čaplovič Ľ., Sitkevich M.V., Peterka J. Complex fine-scale diffusion coating formed at low temperature on high-speed steel substrate. *Appl Surf Sci.* 2018;437:257–270. *https://doi.org/10.1016/j.apsusc.2017.12.173*
6. Krukovich M.G., Prusakov B.A., Sizov I.G. *Plasticity of boronized layers*. Cham: Springer, 2016:364.
7. Edenhofer B., Joritz D., Rink M., Voges K. Carburizing of steels. In: *Thermochemical Surface Engineering of Steels*. Woodhead Publishing, 2015:485–553.
8. Wu W., Chen W., Yang S., Lin Y., Zhang S., Cho T.-Y., Lee G.H., Kwon S.-Ch. Design of AlCrSiN multilayers and nanocomposite coating for HSS cutting tools. *Appl Surf Sci.* 2015;351:803–810.
9. Cho I.S., Amanov A., Kim J.D. The effects of AlCrN coating, surface modification and their combination on the tribological properties of high speed steel under dry conditions. *Tribol Int.* 2015;81:61–72.
10. Kottfer D., Ferdinandy M., Kaczmarek L., Maňková I., Beňo J. Investigation of Ti and Cr based PVD coatings deposited onto HSS Co 5 twist drills. *Appl Surf Sci.* 2013;282:770–776.
11. Gerth J., Wiklund U. The influence of metallic interlayers on the adhesion of PVD TiN coatings on high-speed steel. *Wear* 2008;264:885–892.
12. Chaus A.S., Rudnitskii F.I. Structure and Properties of Cast Rapidly Cooled High-Speed Steel R6M5. *Metals Science and Heat Treatment* 2003;45:157–162.
13. Geller Yu.A. *Tool steels*. Moscow: Metallurgy, 1983:527. (In Russ.).
14. Nefedyev S.P., Emelyushin A.N. The influence of nitrogen on the formation of the structure and properties of plasma coatings of the 10P6M5 type. *Bulletin of the Yugra State University* 2021;3(62):33–45. (In Russ.).
15. Pochetukha V.V., Baschenko L.P., Gostevskaya A.N., Budovskikh E.A., Gromov V.E., Chapaikin A.S. Structure and properties of plasma coatings from high-speed steel after high-temperature tempering. *Bulletin of the Siberian State Industrial University*. 2023;3(45):30–38. (In Russ.). *https://doi.org/10.57070/2304-4497-2023-3(45)-30-38*
16. Gromov V.E., Kobzareva T.Yu., Ivanov Yu.F., Budovskikh E.A., Bashchenko L.P. Surface Modification of Ti Alloy by Electro-explosive Alloying and Electron-Beam Treatment. *AIP Conference Proceedings* 2016;1698:030006. (In Russ.). *https://doi.org/10.1063/1.4937828*
17. Gromov V.E., Ivanov Yu.F., Glezer A.M., Kormyshev V.E., Konovalov SV. Electron-Beam Modification of a Surface Layer Deposited on Low-Carbon Steel by Means of Arc Spraying. *Bulletin of the Russian Academy of Sciences: Physics* 2017; 81(1): 1353-1359. (In Russ.).
18. Koval' N.N., Ivanov Yu.F. *Evolution of the structure of the surface layer of steel subjected to electron-ion-plasma treatment*. Tomsk: NTL, 2016:298. (In Russ.).
19. Koval' N.N., Ivanov Yu.F. Nanostructuring of surfaces of metalloceramic and ceramic materials by electron-beams. *Russian Physics Journal*. 2008;51(5):60–70. (In Russ.).
20. Ivanov Yu.F., Chapaikin A.S., Guseva T.P., Romanov D.A., Gromov V.E. Transformation of the structure and properties of R18Yu surfacing after high-temperature tempering and electron beam treatment. *Problems of ferrous metallurgy and materials science*. 2023;3:62–79. (In Russ.).
21. Egerton F.R. *Physical Principles of Electron Microscopy*. Basel: Springer International Publishing, 2016:196.
22. Kumar C.S.S.R. *Transmission Electron Microscopy. Characterization of Nanomaterials*. New York: Springer, 2014:717.
23. Carter C.B., Williams D.B. *Transmission Electron Microscopy*. Berlin: Springer International Publishing, 2016:518.

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