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Efficiency of comprehensive chemico-thermal treatment for hardening high-speed steel R6M5

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This study investigates the effectiveness of combined chemical-thermal treatment for enhancing the surface properties of R6M5 high-speed steel. The treatment resulted in the formation of a diffusion boride layer with a thickness of 25–37 μm and an acicular structure, significantly improving wear resistance and surface hardness. The dominant phases identified on the treated surface include FeB, Fe_2B, CrB, and WB. A gradual transition zone with decreasing concentrations of boron and chromium was observed between the boride layer and the steel substrate, contributing to structural integrity. Microhardness testing revealed an increase from 630 HV in the base material to 2650 HV at the surface, with a gradual decrease to 895 HV at a depth of 75 μm. The high content of alloying elements in R6M5 steel limited boron diffusion into the core, maintaining a high surface concentration while preserving the bulk microstructure. The results confirm that chromoboration is an effective method for surface hardening of R6M5 steel, providing enhanced operational performance.

Keywords: chemical-thermal treatment, high-speed steel, R6M5, chromoboration, microhardness.

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Introduction

The development of modern cutting tools is closely linked to the implementation of innovations in the field of materials science. The use of advanced materials significantly increases the productivity of machining processes, reduces manufacturing and operating costs, and ensures high quality of the final product.

A leading trend in this field is the creation of high-tech alloys and composites that combine high hardness, strength, and wear resistance. The application of modern chemical-thermal treatment (CTT) methods contributes to the formation of reinforced structures within the material, which effectively resist abrasive and corrosive effects. This significantly extends the service life of cutting tools and ensures the stability of their cutting performance even under challenging operating conditions.

Chemical-thermal treatment plays a crucial role among the technologies used to improve the performance characteristics of tool materials. For cutting tools made from high-speed steel such as R6M5, this method allows for substantial enhancement of the mechanical properties of the surface layer, which is especially important in high-speed machining. One of the main effects of CTT is the increase in hardness to values of 60–65 HRC, which helps maintain the geometry of the cutting edge even under high thermal and mechanical loads.

The effective service life of cutting tools largely depends on their ability to resist abrasive wear, microplastic deformation, and oxidation in the cutting zone. The implementation of CTT leads to surface structure modification, forming a layer enriched with hard phases that considerably reduces the wear rate. This helps maintain the stability of cutting performance over extended periods, which positively affects machining accuracy and the quality of the machined surface.

From an economic perspective, the application of chemical-thermal treatment for high-speed cutting tools offers several important advantages. One of the main benefits is the reduction in tool breakage and failure rates, which minimizes equipment downtime, reduces tool replacement frequency, and lowers maintenance costs. Additionally, extended intervals between repairs and increased overall tool durability enable more efficient production planning, contributing to the reduction of unit production costs.

The use of chemical-thermal treatment also helps to achieve better surface quality of machined parts, which is particularly important in high-precision operations, such as in instrument making, aviation, and the medical industry. Due to reduced surface roughness and defects, tools treated by this method ensure high operational reliability of the produced parts and, in some cases, eliminate the need for additional finishing operations.

This study focuses on analyzing the potential for improving the wear resistance of R6M5 high-speed steel through modern chemical-thermal treatment methods. The influence of these processes on the microstructure and functional properties of the tool has been investigated, and the potential technological and economic benefits of their application under conditions of serial production have been assessed.

I. Materials and Methods

The object of this study is the R6M5 high-speed tool steel, analyzed both before and after modification by the chromoboration method.

For the experiment, rectangular specimens measuring 10×10×50 mm were prepared from rolled stock of this steel grade. Prior to the experimental procedures, the samples were subjected to mechanical processing to ensure surface quality in accordance with standard requirements, particularly in terms of surface roughness and geometric accuracy.

The chemical composition of R6M5 high-speed steel (in weight percent) is presented in Table 1.

Table 1.

Chemical composition of R6M5 high-speed steel

Chemical Element	Content, wt.%
Carbon (C)	0.82–0.90
Silicon (Si)	0.20–0.50
Manganese (Mn)	0.20–0.50
Chromium (Cr)	3.8–4.4
Tungsten (W)	5.5–6.5
Molybdenum (Mo)	4.8–5.3
Vanadium (V)	1.7–2.1
Cobalt (Co)	up to 0.5
Phosphorus (P)	≤ 0.03
Sulfur (S)	≤ 0.025
Nickel (Ni)	≤ 0.6
Copper (Cu)	≤ 0.25
Iron (Fe)	Balance

The chemical-thermal treatment of the samples was carried out using a saturating paste that served as a source of boron and chromium to ensure effective diffusion saturation of the metal surface layer. The composition of the paste was prepared by thoroughly mixing the components in the following weight ratios: boron carbide (B_4C) – 65%, activated boron – 8%, powdered chromium – 12%, and a silicone-organic binder – 10%.

To achieve the required plasticity and ease of application, the paste was brought to a homogeneous suspension state by gradually adding water. The volume of water was selected experimentally, taking into account the desired viscosity and technological properties of the resulting mass. After mixing, all components were stirred thoroughly until a uniform, lump-free consistency was obtained.

The prepared coating was evenly applied to the pre-cleaned surface of the samples as a continuous layer.

Thermal treatment during the study was performed using a laboratory muffle furnace equipped with a digital control system, which ensured high accuracy in regulating the temperature at all stages of the process. The programmable temperature control capability allowed for stable thermal conditions throughout the entire cycle.

Prior to the application of the saturating composition, the samples underwent preliminary thermal preparation in the form of tempering.

After the boron- and chromium-containing paste was applied, the samples were dried at 100°C. Drying continued until all excess moisture had evaporated and a dense, homogeneous coating layer had formed, suitable for further thermal exposure.

The main thermal treatment was conducted in several sequential stages. The initial heating was performed up to 400°C at a rate that ensured uniform heating of the entire sample volume, preventing the formation of thermal gradients and associated stresses. The samples were held at this temperature for one hour to eliminate residual moisture and organic components.

Subsequently, the temperature was increased to 1130°C, followed by an isothermal hold for 4 hours.

After completing the isothermal stage, the samples were cooled in the furnace to 200°C at a reduced thermal gradient. This cooling phase lasted approximately 1.5 hours.

Tempering was carried out at 550°C for one hour, after which the samples were cooled in air to room temperature.

The temperature-time profile of the thermal treatment process is illustrated in Figure 1. It shows the sequence of key stages, including preheating, isothermal soaking, controlled cooling, and final tempering, which provide the necessary conditions for alloying element diffusion and stabilization of the surface microstructure.

After cooling, the samples were cleaned of the protective coating and residual products of thermal processing, then rinsed in distilled water and dried to prepare the surface for further analysis.

Samples for metallographic studies were prepared by cutting with a precision cut-off machine (ATM Brillant 200), followed by hot mounting in phenolic resin using a QATM QPress 50 mounting press.

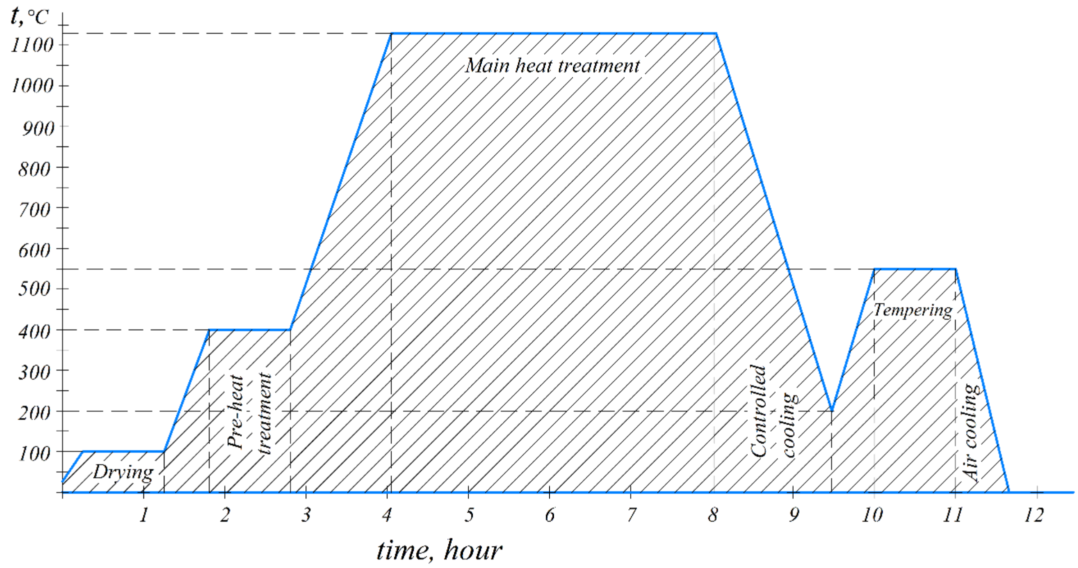

Fig. 1. Temperature-time profile of the thermal treatment process.

Mechanical grinding was performed on a Struers Tegramin automated polishing unit. After grinding, the samples underwent electrolytic polishing and etching to reveal the microstructure. Structural analysis was carried out using a Carl Zeiss AxioObserver Z1m optical microscope, with image capture by an AxioCAM mRC5 camera.

The microhardness of both untreated and treated samples was measured using a QNESS 60 M EVO microhardness tester.

Borides and chromides formed in the coating were identified using a Shimadzu XRD 6000 X-ray diffractometer with Cu Kα radiation.

Hardness was measured on the Rockwell scale (HRC) using a diamond cone indenter with a 150 kgf load, in accordance with the ISO 6508 international standard.

The wear resistance of R6M5 steel samples was evaluated using the pin-on-disk method on an MTU-01 tribometer under dry friction conditions.

Performance testing was carried out through turning of AISI 304 austenitic stainless steel rod stock on a 16K20 lathe. The cutting parameters were: feed – 0.25 mm/rev, depth of cut – 1 mm, cutting speed – 45 m/min, without coolant. Tool wear was monitored after each 150 mm pass, with testing continued until the limiting flank wear (VB = 0.3 mm) was reached, according to ISO 3685.

II. Results and Discussion

The microstructure of R6M5 high-speed tool steel after chemical-thermal treatment, observed at different magnifications (Figure 2), reveals the formation of a well-defined diffusion layer on the sample surface. This layer gradually transitions into the base microstructure of the steel, indicating a gradient nature of changes caused by diffusion processes during the treatment.

As a result of chromoboration, a diffusion layer with a thickness of 25–37 μm is formed on the surface of R6M5 high-speed steel. The structure of this layer is characteristic of boride coatings and consists of needle-like crystallites of boride phases, oriented predominantly perpendicular to the surface. However, unlike the classical structure of boride layers with sharply defined needle morphology, the crystallites formed in this study exhibit blunted tips and a more compact shape. This contributes to the formation of a nearly continuous, dense protective layer without pronounced microcracks or pores, which are commonly observed in conventional boriding.

This microstructural feature is attributed to the high content of alloying elements in R6M5 steel, particularly carbon, tungsten, and molybdenum. These elements actively interact with boron, forming stable carbide and boride phases that, on one hand, slow down the further diffusion of boron into the metal substrate, and on the other hand, promote its localization in the near-surface region.

A transition zone approximately 6–10 μm thick forms between the boride layer and the base metal, characterized by a gradient distribution of elements: the concentration of boron and chromium gradually decreases toward the substrate. The inner regions of the steel, unaffected by diffusion processes, retain the original microstructure typical of high-speed steel, indicating the localized nature of chromoboration's effect.

Thus, chromoboration provides effective modification of only the surface layers without altering the properties of the bulk material, allowing a combination of high surface wear resistance with the strength and durability of the steel's core structure.

Phase-structural analysis of the hardened layer (Figure 3) confirms the formation of boride compounds, among which iron borides (FeB and Fe_2B), chromium boride (CrB), tungsten boride (WB), and molybdenum boride (MoB) were identified. The formation of these phases is the result of active interaction between boron atoms and the main alloying elements present in the R6M5 steel composition.

The presence of FeB and Fe_2B phases contributes significantly to the increase in surface layer hardness due to their ability to resist plastic deformation and the propagation of microcracks under operational loads.

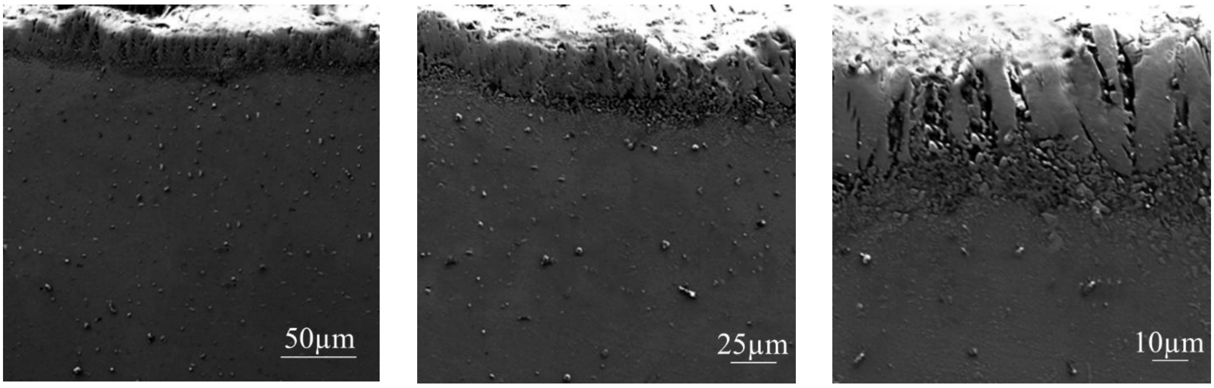

Fig. 2. Microstructure of R6M5 steel after chromoboration.

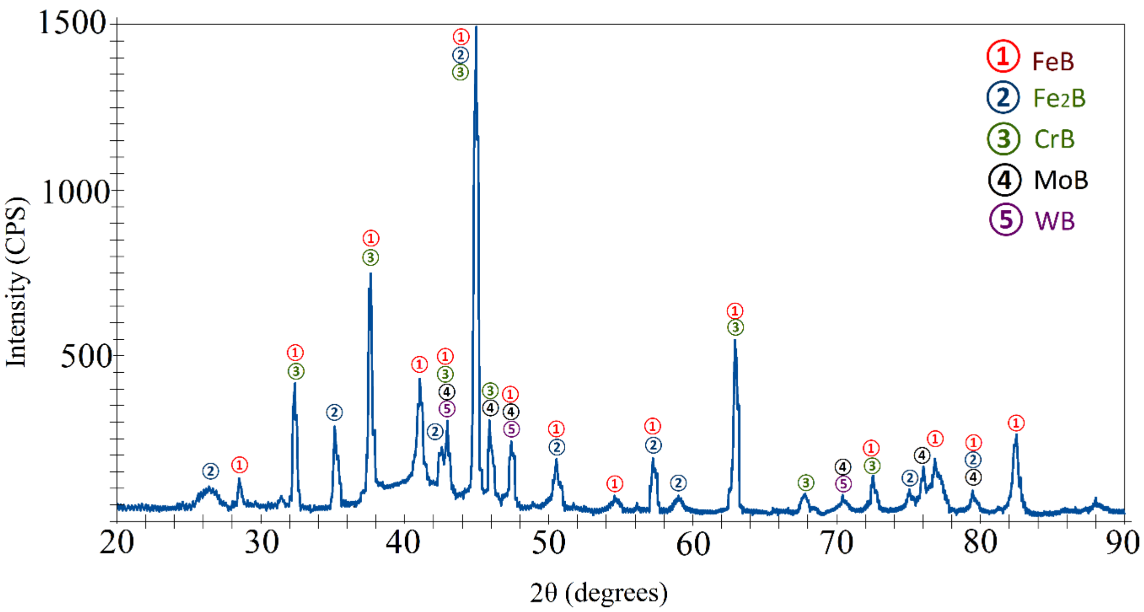

Fig. 3. X-ray diffraction pattern of R6M5 steel after chromoboration.

Chromium borides (CrB), in turn, further strengthen the layer's structure by enhancing its thermal stability and corrosion resistance at elevated temperatures. In addition to iron and chromium, molybdenum borides–particularly MoB–were also identified in the hardened layer. These compounds are known for their high hardness and wear resistance, which further improve the functional properties of the surface.

The combined presence of iron, chromium, and molybdenum borides ensures a uniform stress distribution in the hardened zone and contributes to maintaining high mechanical performance under intense mechanical and thermal loading conditions.

A study was conducted on the distribution of chemical elements across the cross-section of the chromoborated sample to evaluate the diffusion processes and the formation of the modified layer (Table 2).

Table 2 presents the results of measurements of concentration changes of the main chemical elements (Fe, B, W, Mo, Cr, C, V) across the cross-section of the sample depending on the depth from the surface to 40 μm. The analysis of the obtained data reveals a clearly defined zonal distribution of chemical composition: in the near-surface region, elevated concentrations of boron and chromium are observed, while their content gradually decreases toward the base metal. At the same time, the iron concentration increases with depth, which is a characteristic feature of diffusion saturation processes. A graphical representation of the distribution of chemical elements by depth in the treated layer after chromoboration is shown in Figure 4, further illustrating the compositional changes within the diffusion layer.

At the surface of the treated material layer (depth 0 μm), elevated contents of boron (12.44 %) and chromium (14.12 %) were recorded, along with significant amounts of tungsten, molybdenum, and vanadium. As depth increases, the boron concentration decreases sharply: at a depth of 20 μm it is 3.45 %, and at 40 μm it drops to just 0.40 %. This trend is typical of boriding processes, in which boron actively diffuses only into the near-surface zones of the material. A similar distribution pattern is observed for chromium: its content decreases from 14.12 % at the surface to 4.28 % at a depth of 40 μm, indicating surface alloying with limited penetration depth.

Tungsten (W) shows an increase in concentration within the near-surface zone, rising to 6.87 % within the first 10 μm, and then stabilizing between 5.4–6.3 % at greater depths up to 40 μm. This distribution indicates stable formation of tungsten-containing phases in the hardened layer. Molybdenum (Mo) exhibits similar behavior, with concentrations ranging from 4.1 to 5.1 %, showing a slight upward trend beyond 30 μm.

Table 2.

Distribution of chemical elements by depth in the sample

Depth, µm	Fe	B	W	Mo	Cr	C	V
0	61.29	12.44	4.18	4.36	14.12	0.83	1.88
5	60.74	11.85	6.85	4.16	12.80	0.85	1.95
10	62.99	9.56	6.87	4.68	11.76	0.89	2.05
15	70.30	5.85	5.18	5.14	9.87	0.92	2.04
20	78.40	3.45	5.44	4.23	4.52	0.91	2.06
25	78.61	2.88	6.03	4.14	4.44	0.92	2.08
30	79.47	1.55	5.88	4.48	4.33	0.95	2.14
35	79.85	0.98	6.05	4.39	4.32	0.92	2.09
40	79.90	0.40	6.25	4.81	4.28	0.94	2.12

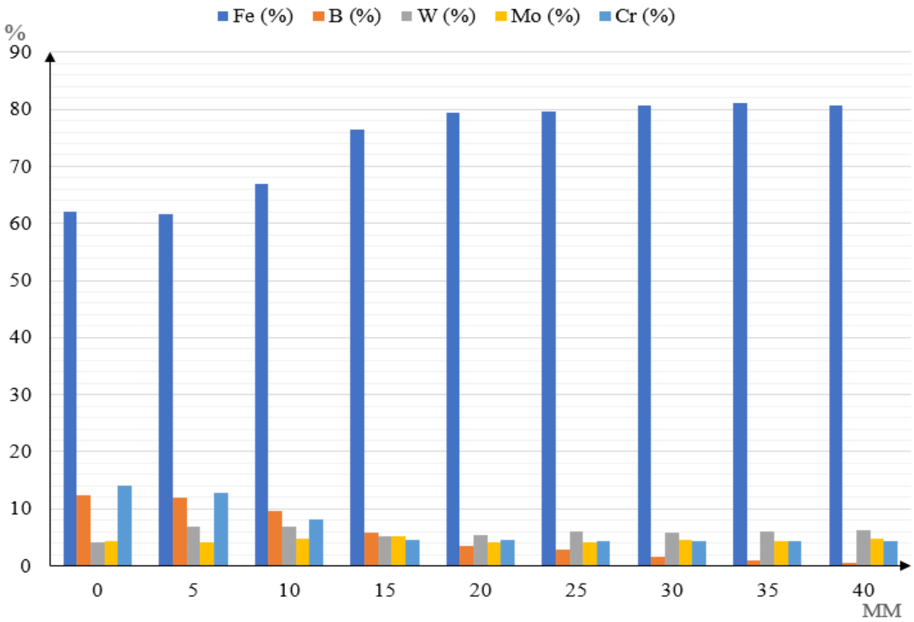

Fig. 4. Distribution of chemical element concentrations by depth in the treated layer after chromoboration.

Vanadium (V) shows a gradual increase in concentration from 1.88 % at the surface to 2.12 % at a depth of 40 µm, which may be associated with partial redistribution during diffusion or dissolution into the base metal phases during treatment.

Iron (Fe), on the contrary, has its minimum concentration at the surface (61.29 %) and gradually increases with depth, reaching 79.90 % at 40 µm, indicating a transition to the bulk metal structure not affected by diffusion saturation.

Carbon (C) demonstrates a relatively stable distribution throughout the diffusion layer: its concentration changes only slightly – from 0.83 % at the surface to 0.94 % at a depth of 40 µm – indicating no significant effect of thermal treatment on the distribution of this element.

Figure 5 presents a detailed profile of microhardness distribution across the cross-section of R6M5 high-speed steel samples. The graph illustrates the variation in microhardness from the surface to the core of the material, allowing for the analysis of the effects of thermal or chemical-thermal treatment on the structure and mechanical properties of the steel.

The figure presents a graphical representation of microhardness distribution across the cross-section of R6M5 high-speed steel samples in the initial state and after chemical-thermal treatment (CTT). The X-axis shows the depth from the surface in micrometers (µm), while the Y-axis displays microhardness values in Vickers units (HV), allowing for an assessment of how the material properties change with distance from the treated surface.

In the untreated samples, the steel exhibits a stable and uniform microhardness distribution of approximately 550–600 HV throughout the investigated depth range of 0 to 50 µm. This uniformity indicates a homogeneous structure with no localized diffusion hardening or gradient in hardness, which is typical for steel after conventional heat treatment.

After chemical-thermal treatment, a significant increase in microhardness is observed in the near-surface zone. The maximum microhardness reaches approximately 2650 HV directly at the surface (0 µm), which is nearly 4–5 times higher than that of the untreated steel. As depth increases, the microhardness gradually decreases: at 20 µm it drops to around 1500 HV, and at 35 µm it reaches 1000 HV. Beyond 40 µm, the values stabilize at 900–950 HV, indicating a transition to the base steel structure.

This microhardness profile confirms the formation of a well-defined hardened diffusion layer with a high property gradient typical of surface saturation processes during chemical-thermal treatment. The gradual decrease

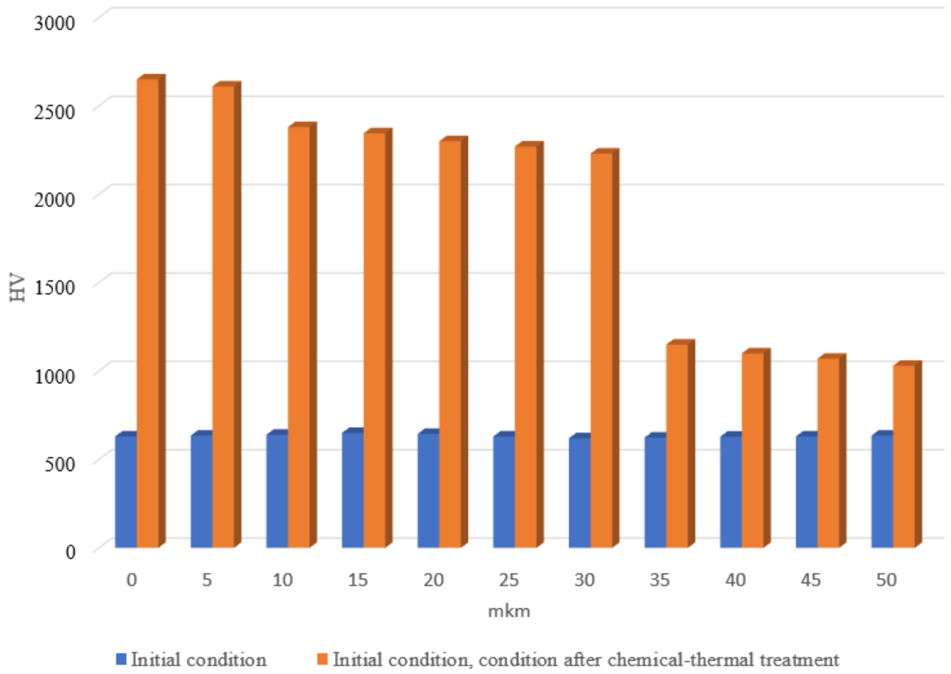

Fig. 5. Microhardness distribution profile across the cross-section of R6M5 steel samples.

in microhardness with depth suggests a smooth transition without abrupt changes in mechanical properties, positively affecting the coating's operational reliability by reducing the risk of delamination or cracking.

The depth of effective chemical-thermal treatment, determined by the microhardness profile, is estimated at 35–40 µm from the surface.

Within the framework of the study, the hardness of R6M5 high-speed steel was measured before and after chromoboration to assess the effectiveness of the treatment. Hardness testing was performed on the Rockwell scale (HRC) using a diamond cone indenter under a 150 kgf load, in accordance with the ISO 6508 standard.

In the initial state, the steel exhibited a hardness of 63–66 HRC, typical for high-speed tool steels with elevated thermal and heat resistance. This level of hardness ensures efficient tool performance under high thermal and mechanical loads common in metal cutting operations.

After chromoboration, a significant increase in surface hardness was recorded. The hardness in the near-surface zone rose to 75–78 HRC, indicating a considerable improvement in surface mechanical properties. This increase is a direct result of the formation of a diffusion-hardened layer that effectively resists plastic deformation during operation. Overall, the hardness increased by 15–20% compared to the untreated condition.

To assess the wear resistance of R6M5 steel samples in both untreated and chromoborated states, experimental sliding wear tests were conducted using the "pin-on-disk" scheme. The tests were performed on the MTU-01 universal tribometer, which simulates dry friction contact conditions under controlled load, speed, and temperature.

Samples measuring 10×10×50 mm were used, made from R6M5 steel before and after chemical-thermal treatment. The counterbody was a disk made of 45-grade structural steel, hardened to 45 HRC and polished to a surface roughness of Ra ≈ 0.4 µm.

The tests were carried out under dry friction conditions at a load of 20 N, sliding speed of 0.3 m/s, contact radius of 30 mm, and a total friction path of 300 m at a temperature of 20 ± 2°C. Each experiment was repeated three times to ensure the reliability of the results. Wear resistance was quantified based on mass loss, determined by weighing the samples on Sartorius electronic analytical balances with a precision of 0.1 mg.

The results showed that the average mass loss of the untreated samples was 3.1 mg, whereas after chromoboration the loss decreased to 1.3 mg. This 2.38-fold reduction in wear indicates the high efficiency of chromoboration as a surface hardening method.

Additional optical analysis of the worn surfaces was performed using an MBS-10 microscope. The untreated samples showed signs of microplastic deformation, local adhesion, and work hardening, indicating a predominantly adhesive-plastic wear mechanism. After chromoboration, the surfaces exhibited uniform fine abrasive scratches with no signs of intense adhesion, indicating friction stabilization and reduced wear intensity.

These results confirm that chromoboration produces a hardened diffusion layer with increased hardness that significantly improves the tribological performance of R6M5 steel. The observed reduction in mass loss proves a real increase in wear resistance, which is crucial for extending the service life of cutting tools and friction elements operating under intense loads.

To confirm the effectiveness of chromoboration in improving the performance properties of R6M5 high-speed steel, operational tests of cutting tools were carried out under real machining conditions. The aim of the study was to evaluate wear resistance, cutting edge retention, and the quality of the machined surface during turning of stainless steel.

The tests were performed on a universal lathe model

Table 3.

Results of operational testing of R6M5 steel

Parameter	Tool without CTT	Tool after chromoboration
Average flank wear VB after 10 passes, mm	0.27	0.11
Total cutting length until VB = 0.3 mm, m	27	74
Surface roughness Ra, µm	2.1	1.3
Visual defects on cutting edge	Microchipping, burrs	None, uniform wear

16K20 in longitudinal turning mode using bar stock of AISI 304 austenitic stainless steel. Two types of tools were compared: tools made from untreated R6M5 steel and tools after chromoboration.

The cutting parameters for both groups were identical: feed – 0.25 mm/rev, depth of cut – 1 mm, cutting speed – 45 m/min, and dry cutting without coolant. Tool condition was monitored after each machining cycle of 150 mm length. The tests continued until the limiting flank wear (VB = 0.3 mm) was reached, in accordance with ISO 3685. Additionally, surface roughness and visual condition of the cutting edge were evaluated.

Analysis of the results of operational testing of cutting tools indicates a significant improvement in their performance characteristics after chromoboration. A substantial reduction in wear intensity was observed: the average flank wear of the treated tool after 10 passes was only 0.11 mm, compared to 0.27 mm for the untreated tool. This corresponds to more than a twofold decrease in tool wear rate.

The total cutting length achievable before reaching the critical wear limit (VB = 0.3 mm) also increased significantly: the untreated tool reached 27 meters, whereas the chromoborated tool achieved 74 meters. Thus, the tool life increased nearly threefold, indicating a considerable enhancement in operational durability.

Improvements were also observed in the quality of the machined surface. The surface roughness Ra decreased from 2.1 µm when using the untreated tool to 1.3 µm with the chromoborated tool. This reflects enhanced machining precision, improved surface finish, and greater process stability.

Visual inspection of the cutting edge after testing further confirmed the advantages of chromoborated tools. The untreated tools exhibited numerous signs of microchipping, local burr formation, and plastic deformation, which are typical for accelerated wear when machining hard materials. In contrast, the chromoborated tools maintained a sharp edge geometry, uniform cutting zone structure, and showed no visible signs of localized damage–indicating improved resistance to mechanical and thermal loads.

Conclusions

This study has established that chromoboration is an effective method for improving the performance characteristics of R6M5 high-speed tool steel. Structural and phase analysis confirmed the formation of a dense diffusion layer 25–37 µm thick with a gradient distribution of boron, chromium, molybdenum, and tungsten. The hardened layer exhibited high surface microhardness–up to 2650 HV–gradually decreasing toward the base metal.

Following chromoboration, the steel hardness increased from 63–66 HRC to 75–78 HRC, indicating a significant improvement in the mechanical properties of the surface zone. Wear resistance tests using the pin-on-disk method revealed a 2.38-fold reduction in mass loss, confirming a substantial decrease in wear intensity.

Operational testing of cutting tools demonstrated that tool life increased nearly threefold after chromoboration (from 27 to 74 meters of cutting before reaching the critical wear level). A reduction in average flank wear was also observed–from 0.27 mm to 0.11 mm–as well as an improvement in surface finish, with roughness (Ra) decreasing from 2.1 µm to 1.3 µm.

Thus, chromoboration significantly enhances the hardness, wear resistance, and operational lifetime of R6M5 high-speed steel without negatively affecting its core structural characteristics, confirming the feasibility of applying this method for strengthening cutting tools and friction components.

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[1] V.A. Derbaba, V.A. Kozechko, S.T. Patsera, O.L. Voichyshen, V.I. Kozechko, *Performance indicators of cutting tools from extra hard materials*, Collection of Scientific Works of the Na-tional Mining University, 74, 133 (2023); https://doi.org/10.33271/crpnmu/74.133.

[2] I. Savchenko, V. Kozechko, A. Shapoval, *Method for Accelerating Diffusion Pro-cesses When Borating Structural Steels*. In: Radionov, A.A., Gasiyarov, V.R. (eds) Proceed-ings of the 7th International Conference on Industrial Engineering (ICIE 2021). ICIE 2021. Lecture Notes in Mechanical Engineering. Springer, Cham. (2022). https://doi.org/10.1007/978-3-030-85230-6_94.

[3] O. Savchenko, V. Shapoval, O. Kozechko, N. Markov, Hrudkina and V. Voskoboynik, *Optimization of Informative Signals Stability Along the Waveguides*, 2021 IEEE Interna-tional Conference on Modern Electrical and Energy Systems (MEES), Kremenchuk, Ukraine, 1 (2021); https://doi.org/10.1109/MEES52427.2021.9598675.

[4] I. Savchenko, A. Shapoval, V. Kozechko, V. Voskoboynik, O. Khrebtova, & S. Shlyk, *Mechanical loading systems safety processes modeling.* In IOP Conference Se-ries: Materials Science and Engineering, 1164 (1), 012070 (2021); http://dx.doi.org/10.1088/1757-899X/1164/1/012070.

[5] V. Pilipenko, S. Grigorenko, V. Kozechko, O. Bohdanov. *A Deformation mode in a cold roll-ing condition to provide the necessary texture of the ti-3AL-2.5V alloy*, Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, (1): 078 (2021); https://doi.org/10.33271/nvngu/2021-1/078.

[6] R.P. Didyk, & V.A. Kozechko, *Forming of multilayer constructions by explosion welding*, Chernye metally, 7, 66 (2016); http://rudmet.com/journal/1546/article/26547/.

[7] O.V. Beketov, D.V. Laukhin, L.M. Dadiverina, V.I. Kozechko, F.J. Taranenko, *Study of the relationship between thickness and structural condition of rolled metal from low carbon low alloy steel 10G2FB*, Ukrainian Journal of Construction and Architecture, 2(20), 26 (2024); https://doi.org/10.30838/J.BPSACEA.2312.260324.26.1039.

[8] O. Beketov, D. Laukhin, N. Rott, E. Babenko, V. Kozechko, *Use of the Pro-cessing Arrays Theory of Experimental Data for the Analysis of the Technological Scheme in the Rolled Metal Production – Controlled Rolling*. In: Ivanov, V., Trojanowska, J., Pavlenko, I., Rauch, E., Piteľ, J. (eds) Advances in Design, Simulation and Manufacturing VII. DSMIE 2024. Lecture Notes in Mechanical Engineering. Springer, Cham. (2024); https://doi.org/10.1007/978-3-031-61797-3_13.

[9] D. Laukhin, O. Beketov, L.M. Dadiverina, V.I. Kozechko, *Study of the relationship between the temperature of the end of hot deformation and the complex of mechanical properties of low-carbon low-alloy steels based on the analysis of regression models*, Mathematical Mod-eling, 2(49), 182 (2023); https://doi.org/10.31319/2519-8106.2(49)2023.293197.

[10] V.A. Kozechko, V.I. Kozechko, *Characteristics of changes in microstructure and characteris-tics under high energy load*, Collection of Scientific Works of the National Mining Universi-ty, 74, 154 (2023); https://doi.org/10.33271/crpnmu/74.154.

[11] V. A. Kozechko and V. I. Kozechko, *Combined Ultrasonic–Mechanical Treatment*, Metallofiz. Noveishie Tekhnol., 46(9), 851 (2024); https://doi.org/10.15407/mfint.46.09.0851.

[12] A.V. Siasiev, R.O. Bilichenko, *Construction of a non-linear analytical model for the rotation parts building up process using regression analysis*. Researches in Mathematics, 32(1), 16 (2024); https://doi.org/10.15421/242413.

[13] A. Siasiev, *Mathematical modelling of manufacturing processes of parts and structural elements by build-up methods*. European Science, 1(sge12-01), 66 (2022); https://doi.org/10.30890/2709-2313.2022-12-01-002.

[14] A. Siasiev, A. Dreus, S. Horbonos, I. Balanenko, & S. Dziuba, *The stressed¬strained state of a rod at crystallization considering the mutual influence of temperature and mechanical fields*. Eastern-European Journal of Enterprise Technologies, 3(5 (105), 38 (2020); https://doi.org/10.15587/1729-4061.2020.203330.

[15] V. Kozechko, & V. Kozechko, *Challenges and risks of using renewable energy sources*. In Fifth International Conference on Green Energy, Environment, and Sustainable Development (GEESD 2024),13279, 78 (2024); https://doi.org/10.1117/12.3042210.

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Ефективність комплексної хіміко-термічної обробки для зміцнення швидкорізальної сталі Р6М5

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В роботі показано, що після хіміко-термічної обробки на поверхні сталі Р6М5 утворився дифузійний шар боридів товщиною 25-37 мкм з голчастою структурою, що забезпечує високу зносостійкість та твердість матеріалу. Основними фазами, виявленими на поверхні, є FeB, Fe_2B, CrB WB. У перехідній зоні між поверхневим шаром боридів і основним матеріалом спостерігалося зниження концентрації бору та хрому, що забезпечує поступовий перехід до основної структури сталі.

Аналіз мікротвердості показав значне підвищення твердості поверхні після ХТО: з 630 HV до 2650 HV на поверхні, з поступовим зниженням до 895 HV на глибині 75 мкм. Це свідчить про ефективність обробки в покращенні поверхневих властивостей сталі.

Хіміко-термічна обробка швидкорізальної сталі Р6М5 дозволяє значно покращити її зносостійкість та корозійну стійкість завдяки утворенню захисного шару боридів. Високий вміст легуючих елементів обмежує проникнення бору в глибину матеріалу, що дозволяє утримувати його більшу концентрацію на поверхні. Внутрішні шари сталі зберігають свою первісну мікроструктуру, забезпечуючи загальну міцність матеріалу. Отримані результати підтверджують ефективність хромоборування як методу зміцнення поверхні швидкорізальної сталі Р6М5, що значно покращує її експлуатаційні властивості.

Ключові слова: хіміко-термічна обробка, швидкорізальна сталь, Р6М5, комплексна обробка, мікротвердість.