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Research Article

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OBTAINING MULTICOMPONENT CHROMIUM COATINGS USING FUNCTIONALLY ACTIVE MIXTURES

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Abstract. *The purpose of our research is to obtain wear-resistant chrome coatings on carbon steels under non-stationary temperature conditions using functionally active powder mixtures, which allows reducing the chemical-thermal treatment time from 6-8 hours to 1 hour. The scientific novelty of the work lies in the original use of thermodynamic analysis to determine the composition of the gas phase formed during chemical-thermal treatment with functionally active charges, which made it possible to optimize the concentration of ammonium compounds for boron-alloyed chrome surface and predict its physical and mechanical characteristics. The practical significance of the developed technology is to increase the wear resistance of chrome coatings on steels with a ferrite-pearlite structure, which ensures their effective use under dynamic and impact loads. The proposed method opens up new opportunities for the creation of highly effective protective coatings for industrial applications. Optical microscopy (Neophot-32) and scanning electron microscopy (REM-106i) were used to study the microstructure and phase composition of the coatings. Tribotechnical tests were carried out on friction installations SMT-1 and MT-5. The composition of the gas medium formed during the chemical heat treatment was determined by thermodynamic modeling, and the optimization of the component composition of the charge materials was carried out using the methods of mathematical planning of experiments with the optimization criterion in the form of wear resistance of the boron-alloyed chrome surface. As a result, it was found that the addition of boron-containing components and ammonium gas transport reagents to the powder charge composition contributes to the generation of gaseous compounds and condensed phases. The proposed functionally active mixtures ensure the formation of protective chromium layers up to 150 μm thick within 15-60 minutes.*

Keywords: carbon steel, chromium plating, alloying, boron, protective coating, charge, thermodynamics, wear resistance.

1. Introduction

Modern materials science focuses on improving the performance of steels by applying chrome coatings, including boron-alloyed ones. One of the most promising methods is laser alloying of steel surfaces with chromium and boron, which produces coatings with high microhardness and corrosion resistance. Studies have shown that the use of a mixture of chromium and boron in different proportions during laser treatment contributes to the formation of coatings with a microhardness of 900 HV0.05 to 1300 HV0.005, depending on the laser treatment parameters [1]

Another approach involves the use of diffusion saturation of steel with boron and chromium. In particular, the study of the effect of chromium as a diffusion additive during boronizing of AISI 4140 steel showed that the formation of mixed boride phases, such as FeCrB, contributes to a significant increase in the corrosion resistance of the coating. Evaluation by electrochemical impedance spectroscopy confirmed the improvement of the corrosion characteristics of boron-chromated samples compared to boron-only samples [2,3]. Boron is one of the most effective elements for increasing the hardness and wear resistance of steels. It forms solid boride phases (e.g., Fe_2B) that have high microhardness (up to 2000 HV) and excellent resistance to abrasive wear. Boron alloying is usually carried out using thermodiffusion methods such as boronizing in powder media or electrolytic boronizing. The resulting boride layers are characterized by considerable thickness (up to 150-200 microns) and high adhesion to the base metal [4,5].

Chrome plating is a classic method of applying protective coatings that provide high wear and corrosion resistance. Chrome coatings can be produced by electroplating or chemical deposition methods. The main advantages of chrome layers are high hardness (up to 1000-1200 HV), excellent corrosion resistance due to the formation of passive oxide films Cr_2O_3, and the ability to self-heal in case of surface damage [6,7].

The combination of boron and chrome plating is a promising area for creating multilayer coatings that combine the high wear resistance of boride layers with the corrosion resistance of chrome plated coatings. Such coatings are often called “hybrid” or “multifunctional”. Galvanic chrome plating is carried out in baths with chromic acid electrolytes, where the cathodic process is controlled by the deposition of metallic chromium. Process parameters such as temperature, electrolyte concentration and current density have a significant impact on the quality of the coating [8].

Researches [9] have shown that the application of a chromium layer on a boron surface significantly reduces the porosity of boride layers, which increases their corrosion resistance. The authors also noted that the optimal thickness of the chromium coating is 20-30 microns, which ensures maximum adhesion to the boride layer and a minimum number of defects. Hybrid coatings demonstrate high resistance to adhesive wear and contact fatigue. Research [10] found that the combination of boron and chromium plating provides a synergistic effect that significantly improves the wear and corrosion resistance of steels. The authors emphasized the importance of controlling process parameters to reduce internal stresses in coatings.

The use of electron beam surfacing of boron on chromium-nickel steels can increase their resistance to water-jet wear. The formation of a coating with densely arranged borides, mainly Fe_2B, increases the water-abrasive strength of steel by 1.5-2 times [11]. It is also worth noting that laser remelting of diffusion boron-chromium layers on 145Cr6 tool steel leads to the formation of zones with eutectic structures of boron and chromium, which improves the microhardness and wear resistance of surface layers [12].

Despite their numerous advantages, combined coatings have a number of problems that require further research. One of the key tasks is to control the porosity of boride layers before applying chromium, as excessive porosity can adversely affect the performance of the coating. In addition, an important aspect is to ensure the adhesion of the chrome coating to the boride layer, as strong adhesion between the layers is the key to the durability and reliability of the combined coating. Another issue that requires attention is the optimization of process parameters to reduce internal stresses in the coatings, which can lead to deformation or material failure during operation. Thus, overcoming these difficulties is an important step towards creating effective and reliable combined coatings.

The application of chrome coatings on boron-alloyed steels is a promising area for improving the service characteristics of steels. Hybrid coatings combine high wear resistance, corrosion resistance and mechanical strength, making them suitable for use in high-stress and aggressive environments. Further technology improvements and optimization of process parameters will expand the scope of such coatings. Increasing the durability and performance of steel materials is possible through the application of hard coatings that serve as protective layers. Such coatings modify the surface characteristics of the base material, giving it increased chemical resistance, increased hardness and reduced wear rates. Traditional methods of surface hardening are often characterized by significant energy consumption and process duration, which limits their practical application. In this context, the development of innovative chemical-thermal treatment technologies that allow controlling the composition and structure of protective coatings, providing the required performance parameters while minimizing the formation time, is a relevant area for Ukraine [13,14]. Particular attention is drawn to coatings formed under non-stationary thermal conditions, which exhibit high functionality due to the complex interaction of gas-phase deposition mechanisms and intense diffusion mass transfer. The formation of such coatings is based on the synergistic combination of two key processes: the formation of a film structure induced by gas-phase reactions and the formation of wide transient diffusion zones characteristic of diffusion saturation methods. This approach makes it possible to obtain materials with improved physical and chemical characteristics that exceed those of traditional coatings, which makes them promising for use under high mechanical loads [15].

2. Materials and methods of research

For the formation of protective coatings on samples from 45 and 40X steels we using functionally active (FA) powder mixtures included such components as chromium component (CC), boron, aluminum oxide, aluminum, ammonium fluoride, and ammonium iodine. The choice of the optimal powder fraction was based on preliminary experimental studies, which showed that particle sizes in the range of 100–120 μm are most effective for obtaining wear-resistant coatings and ensuring maximum completeness of chemical reactions. This range provides an optimal balance between the activity of the reagents and their processability for diffusion processes.

The process of forming protective coatings using functionally active charges was carried out on a specially designed experimental and industrial installation. The design of this unit was developed to meet modern requirements for process accuracy and safety. The unit integrates reaction equipment, a system for monitoring and controlling key process parameters (temperature, pressure and time), as well as a comprehensive gas cleaning system that ensures process safety and environmental friendliness. This approach made it possible to obtain coatings with high performance characteristics while minimizing the negative impact on the environment [16].

The evaluation of structural and phase changes in titanium-doped chrome coatings was carried out using optical and electron microscopy methods. A Neophot-32 optical microscope and a REM-106i scanning electron microscope were used to visualize the microstructure. To contrast the microstructure of the coatings obtained on the basis of steels, a 3% ethanol solution of picric acid in ethyl alcohol was used [17]. This method provided a clear visualization of the morphological features of the coatings, which made it possible to conduct a detailed analysis of their structure and identify characteristic defects.

X-ray structural analysis was used to analyze the phase composition of the diffusion zone on samples measuring 25×10×5 mm. To study the phase composition of the coatings, a DRO-3M X-ray machine was used in conjunction with a computer complex running the ARFA program. The tube emitted radiation with copper and cobalt anodes. The detector rotation speed was 1 deg/min in the angle range 2θ = 15-163°.

Wear resistance testing on the SMT-1 friction machine under conditions of limiting sliding friction with lubrication using automotive tractor oil according to the roller-block scheme, at a counterbody (roller) rotation speed of 500 rpm. The counter body was made of U8A steel with subsequent hardening and low tempering to a hardness of 61...63 HRC. The load on the sample was: P = 500 H.

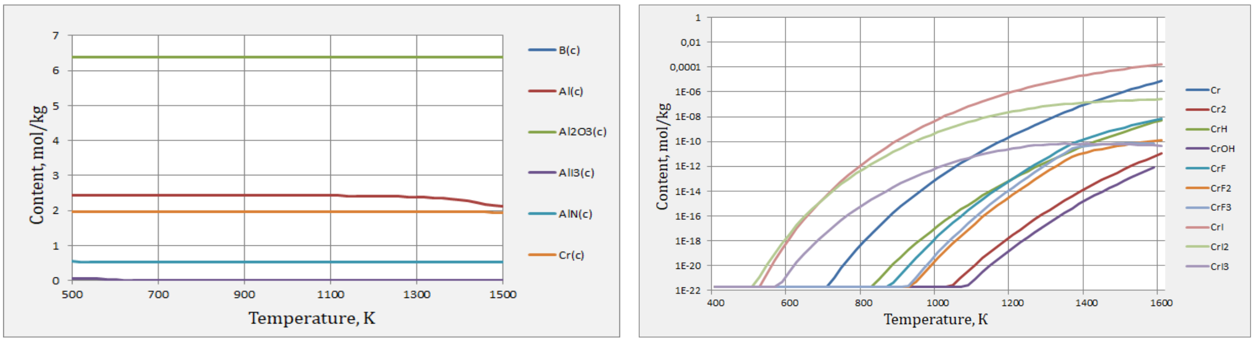
Thermodynamic modeling of chemical transformations in the process of obtaining chrome coatings using functionally active charges included the calculation of the equilibrium composition of reaction products using the TERRA software package. This made it possible to predict possible phase transitions and assess the effect of temperature conditions on the formation of coatings [18,19]. To optimize the composition of powdered functionally active charges that allow obtaining the required coating thickness and high wear resistance, mathematical experiment planning methods were used. The study used a 3-factor, 3-level compositional asymmetric plan of the second order, which allowed us to systematically assess the effect of key parameters such as temperature, process duration, and reagent concentration on the characteristics of the resulting coatings [20]. This comprehensive approach to the study and optimization of coating formation processes not only improved their quality but also significantly reduced the time and cost of their manufacture, which is an important factor for industrial applications. In addition, the analysis of the results confirmed the possibility of obtaining coatings with improved physical and mechanical characteristics, which makes them promising for use under high mechanical and corrosion loads.

3. Results and discussion

Thermodynamic modeling of chemical processes entails a comprehensive assessment of the equilibrium state of a system that is treated as a quasi-isolated material domain. Within this framework, the system’s interaction with the external environment is constrained to energy and heat exchange only. The determination of thermodynamic equilibrium for arbitrary multi-component systems involves calculating the state variables and equilibrium parameters by minimizing the Gibbs free energy (G) under isobaric-isothermal conditions or, alternatively, by maximizing the system's entropy (S). This method takes into account the full set of potentially stable chemical species present in the system, providing a highly accurate prediction of the system’s chemical and phase composition under specific thermodynamic constraints.

In scenarios characterized by non-stationary temperature regimes, the kinetic behavior of chemical transformations is governed by both the thermal gradient and the diffusion mechanisms present within the system. It is generally assumed that during the thermal ramp-up phase, diffusion limitations in the gas phase are negligible, and the temporal rate of temperature change remains lower than that of gas-phase chemical reactions. This condition enables the presumption that a quasi-equilibrium composition is achieved at each discrete temperature interval. By performing calculations of equilibrium product distributions across a spectrum of temperatures, it becomes feasible to monitor the evolving chemical profile of the system, which is particularly advantageous in analyzing complex reaction pathways involving multiple intermediate steps influenced by both thermodynamics and kinetics.

However, the feasibility of utilizing combustion synthesis techniques in practical applications is constrained by the presence of threshold temperatures required for stable propagation of the combustion wave. These boundaries define the minimum thermal conditions necessary for reaction initiation and sustained front advancement. Failure to meet these thresholds can result in partial reaction inhibition or uncontrolled front propagation, thereby compromising process reliability. Consequently, precise identification of critical temperature limits and strategic optimization of operational parameters are essential to ensure both the functional efficiency and the thermal safety of combustion-based synthesis methods.

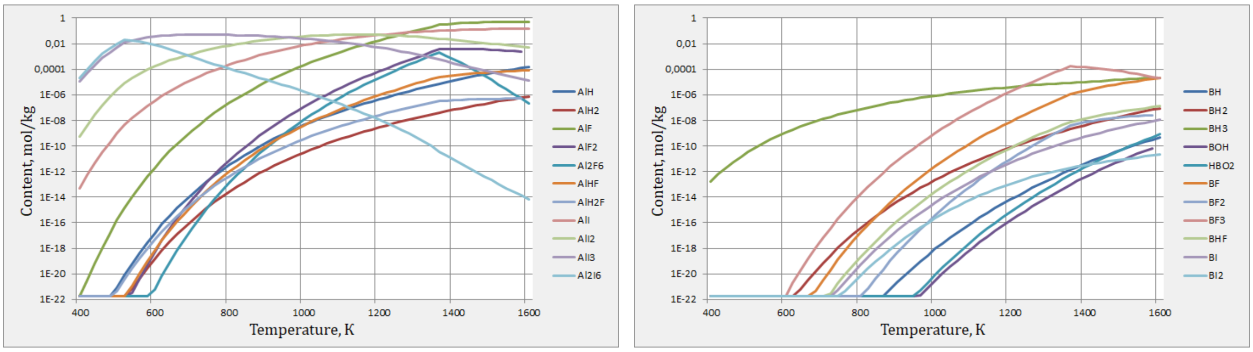


a) b)

Fig.1. Content of condensed products (a) and gaseous chromium compounds (b) in the reactor for the Cr-B system

Thermodynamic modeling, combined with the analysis of kinetic mechanisms, serves as a powerful tool for not only forecasting the outcomes of chemical reactions but also for optimizing the process parameters of synthesis technologies. This predictive capability is particularly valuable in the design and development of advanced materials, as it enables a substantial reduction in both the duration and financial investment typically associated with experimental research. Furthermore, the approach provides a reliable means of accurately estimating the physicochemical properties of final products, thereby facilitating more efficient process control and quality assurance. Unlike conventional combustion synthesis, which is constrained by the need for strict control over thermal conditions to ensure stable reaction propagation, thermally-induced spontaneous combustion offers enhanced flexibility in process adjustment. Specifically, the intentional dilution of the reactive powder mixture with inert additives—up to 45–50 wt.%—allows for effective modulation of the peak process temperature, thereby tailoring it to meet the requirements of particular technological applications.

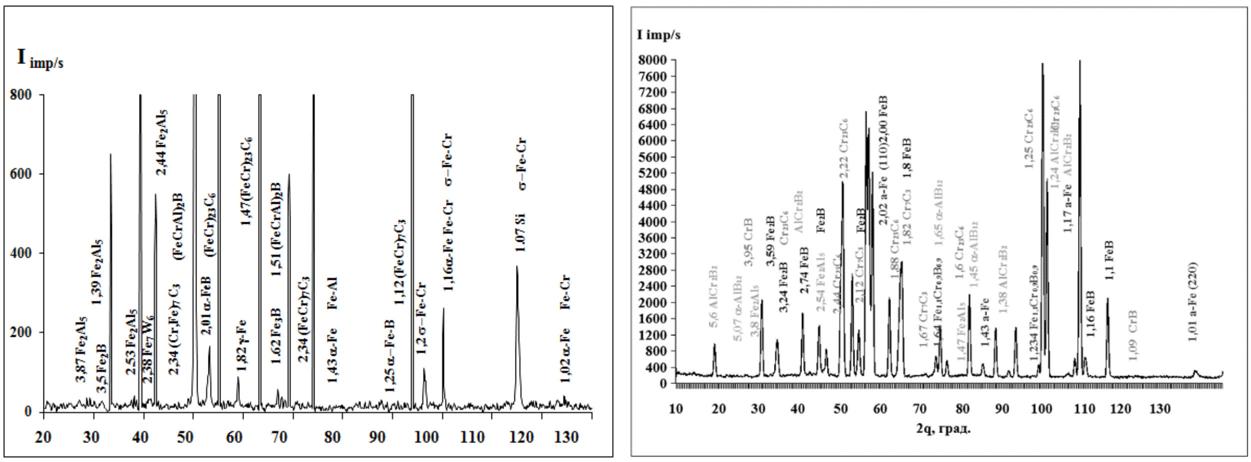
As the system temperature increases, there is a notable shift in the product distribution, characterized by a rising fraction of gaseous products alongside the concurrent release of condensed species. Within the temperature interval of 400–1600 K, a progressive decline in the condensed phase content is observed. This phenomenon is largely attributed to the thermal evaporation of auxiliary materials or carriers integrated into the reactive system. Notably, when the temperature exceeds 800 K, a series of decomposition reactions are initiated, resulting in the evolution of secondary gaseous products and a pronounced increase in the overall molecular count of the gas phase (fig 1, 2). A thermodynamic system is conceptually defined as a physically bounded region of matter that exchanges only heat and mechanical work with its surroundings. Employing modern thermodynamic simulation techniques enables a rigorous, quantitative prediction of the behavior of complex heterogeneous, multi-phase, and multi-component systems across broad temperature and pressure ranges. Such models incorporate the influence of chemical equilibria and phase transitions, making them indispensable for detailed thermochemical assessments. These methods significantly improve the efficiency of high-temperature process design, assist in the evaluation of interaction outcomes, and substantially decrease the dependence on repetitive empirical experimentation.



a) b)

Fig.2. Content of gaseous aluminum (a) and boron (b) compounds for the system Cr-B

Equilibrium calculations for arbitrary systems—encompassing all relevant thermodynamic parameters, physical properties, and the complete chemical and phase composition—are typically performed by minimizing the Gibbs free energy (at constant pressure and temperature) or by maximizing the system's entropy. This comprehensive approach ensures highly accurate forecasts of system behavior under prescribed environmental conditions. At temperatures exceeding 800 K, the relative amount of condensed phase products becomes nearly constant, which suggests that within the temperature range of 800–1600 K, chemical transformations occur without a significant change in the total molecular count of the system. This behavior is indicative of reaction mechanisms that predominantly involve condensed-phase dynamics, such as decomposition, disproportionation, and solid–substrate-mediated exchange reactions. These types of processes typically proceed without introducing additional gaseous species into the system, thereby maintaining molecular balance.



a) b)

Fig. 3. Diffraction pattern of a sample made of 45 steel (a) and 40X (b) with a protective chromium coating doped with boron

Such transformations often represent fundamental pathways for the chemical transport of elements within reactive media, especially in high-temperature powder metallurgy and self-propagating synthesis systems. The stabilization of the condensed phase in this regime also implies that the system has reached a thermodynamically favorable configuration, where the nature of chemical bonding and the structural stability of intermediate or final solid products become the dominant factors influencing phase evolution. Depending on the amount of boron and ammonium gas transport agents, gaseous compounds (AlH, AlH_2, AlF AlF_2, Al_2F6, AlHF, AlH_2F, AlI, AlI_2, AlI_3, Al_2I_6, Cr, Cr_2, CrH, CrOH, CrF, CrF_2, CrF_3, CrI, CrI_2, CrI_3, BH, BH_2, BH_3, BOH, HBO_2, BF, BF_2, BF_3, BHF BI, BI_2) and condensed phases (Al(c), B(c), Al2O3(c), AlI_3(c), AlN(c), Cr(c)).

The task of the mathematical planning of the experiment was to study the effect of the technological mode of processing and the composition of functionally active charges on the wear resistance of protective coatings in order to optimize the mode of thermal spontaneous combustion and select the optimal composition of the powder charge.

Table 1. Experiment planning matrix

Characteristic	Factors		
	CC %, wt.	B %, wt.	Al %, wt.
Code	X_3	X_2	X_1
Basic level	20	12	17
Variation interval	5	4	5
The lower level	15	8	12
The upper level	25	16	22

Wear parameter (ΔI) was evaluated by measuring the mass loss of a steel 50 specimen, upon which the coating was deposited under process conditions defined by a peak temperature tp = 1100°C and an isothermal holding time τ = 30 min. The selection of both the baseline values and the variation intervals of the technological parameters was guided by empirical data, which established that the inclusion of less than 10 wt.% of chromium does not yield coatings with the requisite mechanical and physical performance. Consequently, the threshold value of chromium content was set to ensure structural integrity and functionality of the protective layer.

By analyzing the evolution of characteristic temperature values during processing under non-isothermal conditions, the optimal proportion of the chromium-containing component was empirically determined. Additionally, aluminum oxide (Al_2O_3) was employed as an inert ballast phase to ensure a stoichiometric completion of the powdered functional mixture. This approach guarantees the reproducibility and thermal stability of the coating formation process by maintaining a controlled heat balance and phase distribution.

As a result of the conducted investigations, a regression model was derived that quantitatively describes the influence of technological parameters and charge composition on the resulting structural, mechanical, and service properties of the coatings. The empirical model is expressed by the following equation:

$$\Delta I = 72{,}711 - 0{,}4X_1 - 1{,}1X_2 - 0{,}1X_3 + 0{,}1111X_1^2 + 5{,}6111X_2^2 - 5{,}3889X_3^2 - 5{,}5X_1X_3 + 0{,}25X_2X_3$$

This expression enables a detailed evaluation of the contribution of individual factors and their mutual interactions to the overall wear resistance and performance of the coating. The inclusion of quadratic terms and cross-factor interaction components significantly enhances the fidelity of the model by capturing nonlinearities inherent in real thermochemical systems.

The effectiveness of thermodynamic and statistical modeling for predictive analysis and optimization is thus convincingly demonstrated. This methodology facilitates the rational design of novel functional coatings by minimizing experimental effort and expediting process development. To visualize the influence of each factor on wear resistance, a set of three-dimensional response surface plots was constructed (fig. 4), enabling intuitive analysis and informed decision-making in material selection and process tuning.

Drawing upon comprehensive thermodynamic assessments and phase composition analyses of boron-enriched chromium-based protective layers, a detailed physicochemical model has been developed to describe the formation mechanism of such coatings under conditions of thermal self-propagating combustion of functionally active charges.

Stage 1. The process initiates with a steady temperature rise, during which the steel substrate is subjected to thermal exposure. As the temperature surpasses threshold values, the decomposition of volatile gas transport agents—specifically ammonium fluoride (NH_4F) and ammonium iodine (NH_4I)—is triggered. This decomposition results in the generation of chemically active species that will subsequently contribute to halide-mediated transport processes.

Stage 2. A self-sustaining combustion reaction of the functional powder blend is ignited, releasing a substantial amount of thermal energy. This exothermic reaction causes further elevation of the system temperature and leads to the formation of a halide-rich gaseous phase. The primary gaseous products at this stage include chromium and aluminum halides such as CrF, CrF_2, CrF_4, AlI, AlI_2, AlI_3, and volatile boron species like BF_3. These volatile halides serve as key agents in transporting the coating-forming elements toward the substrate.

Stage 3. The generated thermal energy begins to dissipate, primarily through conduction into the steel substrate, causing the local temperature to decrease toward the designed steady-state value. Under these thermal conditions, the formation of a chromium-, aluminum-, and boron-doped α-solid solution initiates, serving as the structural basis for the protective layer.

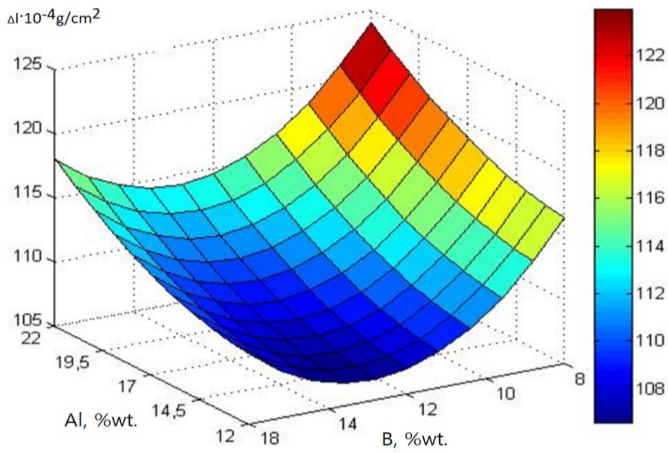
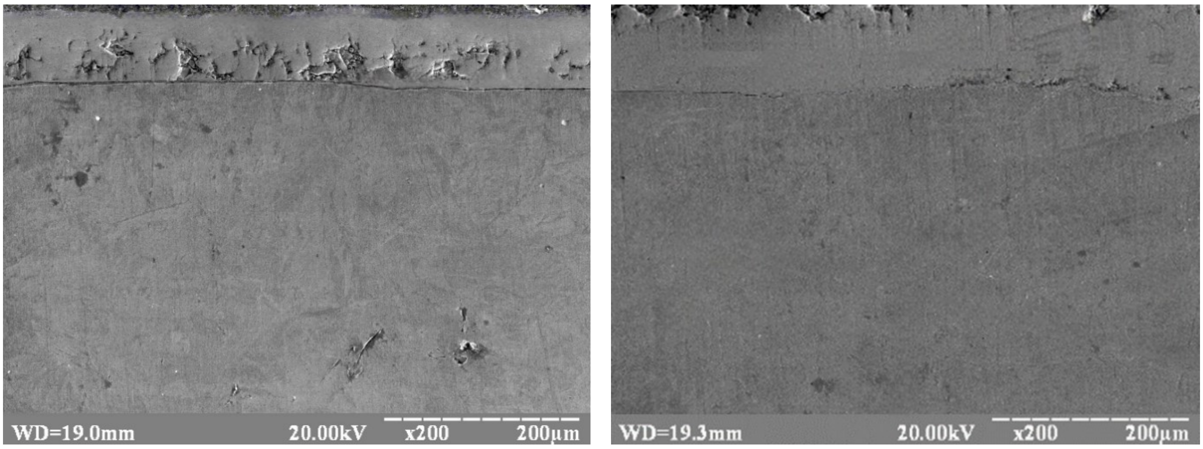


Fig.4. Influence of boron and aluminum content on the wear resistance of coatings

Stage 4. This stage is characterized by active interdiffusion processes. Thermally activated atoms of Cr, Al and B, begin to diffuse into the iron matrix of the steel component. As a result, a multicomponent solid solution enriched with these elements is formed, along with complex alloyed intermetallic phases A continuous and directed diffusion flux is established, promoting the development of thick, uniform coatings. Compared to conventional isothermal processes, coatings formed under transient thermal regimes exhibit significantly increased thickness. This is attributed to the fine-grained, submicron-block microstructure of austenite that forms under rapid heating. The austenitic matrix, developed under non-equilibrium conditions, features a high dislocation density localized at grain boundaries and a branched intergranular structure, enhancing the material's diffusion responsiveness. This stage is the most prolonged, extending up to 60 minutes, during which the bulk of the coating is synthesized.

Stage 5. In the final stage, the system undergoes cooling, and the temperature of the functionally active charge drops. As a consequence, the diffusion fluxes weaken, and the rate of coating formation diminishes. The protective layer solidifies with a stabilized phase composition comprising: $(Fe,Cr)_{23}(C,B)_6$, $(Fe,Cr)_7(C,B)_3$, (Fe,Cr,Al)B, $(Fe,Cr,Al)_2B$. Metallographic and X-ray spectral analysis of boron-doped chrome protective coatings obtained on 45 and 40X steel samples (fig. 5) showed that the following phases were formed on the surface: $(Fe,Cr)_{23}(C,B)_6$, $(Fe,Cr)_7(C,B)_3$, (Fe,Cr,Al)B $(Fe,Cr,Al)_2B$, and zones of α-solid solution of Cr, Al, B in Fe. Boron-modified chromium-based protective coatings deposited on steel grade 45 have gained substantial relevance in tribological applications due to their pronounced ability to reduce friction and significantly enhance resistance to wear. These coatings are especially valued in engineering systems subjected to intense mechanical contact, where surface durability and lubrication retention are crucial. As such, a key aspect of current research lies in assessing the wear resistance of steel 45 substrates following surface modification with boron-containing chromium coatings.

Experimental investigations conducted under dry sliding friction conditions using the SMT-1 tribometer revealed a pronounced enhancement in wear resistance when coatings were synthesized via thermal self-propagating modes using functionally active powder mixtures. Specifically, the coatings formed under dynamic temperature regimes demonstrated wear resistance approximately 1,4–1,6 times greater than their counterparts fabricated using conventional isothermal processes (fig. 6). This performance enhancement is attributed primarily to the superior microhardness of the thermally activated coatings.



a) b)

Fig. 5. Boron-alloyed, chromium coatings on steel 40X(a) and 45 (b) (tp - 1050 ^{o}C, τ = 30 min).

Quantitatively, the microhardness values (measured under a 100 g load) for boron-doped coatings produced under steady-state thermal conditions were observed in the range of H100 = 15,000–15,500 MPa. In contrast, coatings formed under non-isothermal conditions utilizing exothermically reactive powder blends exhibited significantly higher microhardness, reaching values between H100 = 16,500–17,500 MPa. This substantial increase in surface hardness is one of the main factors contributing to the improved wear performance of the coatings. The increase in microhardness for coatings obtained using functionally active mixtures is due to an increase in the amount of chromium, aluminum, and boron alloying elements by 5-11% compared to known coatings obtained under isothermal conditions.

It is important to note, however, that although a clear trend correlating increased surface hardness with enhanced wear resistance exists, the relationship is not strictly linear. The wear behavior of metallic materials is inherently complex and influenced by numerous interacting variables, including contact pressure, sliding velocity, lubrication conditions, and surface topography. As a result, microhardness alone cannot fully account for all variations in wear behavior.

From a mechanistic perspective, wear under sliding friction conditions predominantly involves elastic and plastic deformation of the surface layer, along with subsurface fatigue processes that eventually lead to material removal. These processes manifest through microcrack initiation, propagation, and detachment of surface fragments. In contrast, when subjected to impact-dynamic loading, different wear mechanisms dominate, including brittle fracture, chipping, shearing of individual particles, and localized plastic deformation. These distinctions underscore the necessity of tailoring coating composition and structure to the specific mechanical and tribological demands of the intended application.

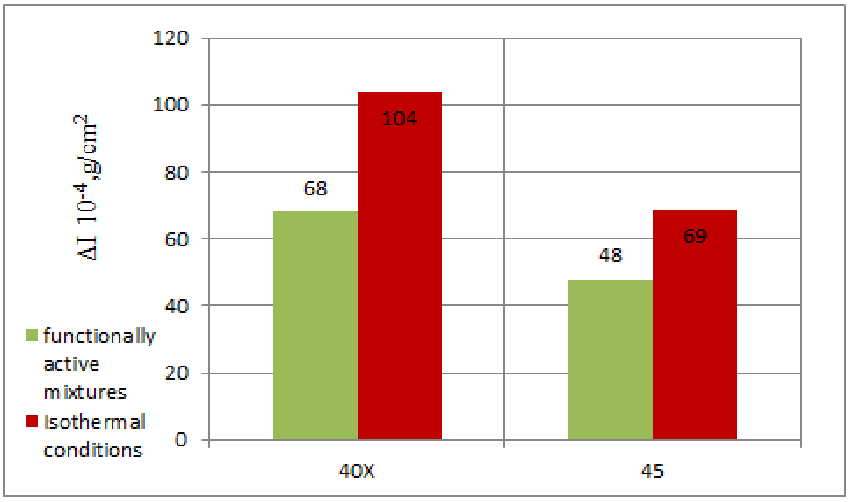


Fig.6. Comparative tribological tests on steel 40X and 45.

Consequently, the choice of coating technique and regime must be guided by a comprehensive understanding of the interaction between the operational environment and the mechanical behavior of the surface layer. The demonstrated ability of thermally generated boron-alloyed chromium coatings to resist wear under severe conditions positions this approach as highly promising for extending the service life of components in high-load, high-friction environments. Thus, the use of functionally active charges for the formation of boron-doped chromium coatings is a promising direction for improving the wear resistance of steel materials. The obtained results confirm the possibility of a significant improvement in the performance characteristics of steel 45 by optimizing the technological parameters and composition of coatings.

4. Conclusions

As a result of the research, the influence of boron alloying on the wear resistance of chrome coatings obtained using functionally active charges was determined. The effectiveness of the developed technology for applying multicomponent chrome coatings has been confirmed by both experimental and theoretical methods. The coatings formed under non-stationary temperature conditions demonstrated high characteristics in terms of wear resistance and thermal stability. A significant improvement in physical and mechanical properties was achieved on steel samples with a carbon content of 0.5% compared to traditional coatings, which was manifested in a reduction in wear under impact and dynamic loading. The amount of alloying compounds also depends on the initial composition of the material. Calculations of the thermodynamic equilibrium of reaction products and kinetic laws confirmed the possibility of forming coatings with specified properties at different temperature conditions. In the powdered, functionally active charge, gaseous compounds are formed (AlH, AlH_2, AlF AlF_2, Al_2F6, AlHF, AlH_2F, AlI, AlI_2, AlI_3, Al_2I_6, Cr, Cr_2, CrH, CrOH, CrF, CrF_2, CrF_3, CrI, CrI_2, CrI_3, BH, BH_2, BH_3, BOH, HBO_2, BF, BF_2, BF_3, BHF BI, BI_2) and condensed phases (Al(c), B(c), Al2O3(c), AlI_3(c), AlN(c), Cr(c)). The modeling showed that the selected powder mixtures and technological parameters ensure the effective formation of protective layers. Metallographic analysis confirmed the high quality and homogeneity of the coatings, their good adhesion to the steel base, and resistance to cracks and defects. According to the results of metallographic and X-ray spectral analysis, it was found that the following phases are formed on the surface of the chrome coatings of boron-doped coatings: $(Fe,Cr)_{23}C_6$, $(Fe,Cr)_7C_3$, Fe_3Al, $(Fe,Cr,Al)_2B$, as well as zones of α-solid solution of Cr, Al, B in Fe. During tests under sliding friction conditions on the friction machine SMT-1, it was found that the wear resistance of coatings obtained using functionally active charges was 1.9-2.1 times higher than that of coatings formed under isothermal conditions. A comparative analysis of wear resistance during tests on the friction machine MT-5 (under shock-dynamic loading) revealed that coatings obtained using functionally active charges have a 1.4-1.6 times lower wear than coatings obtained under isothermal conditions.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRediT author statement

Sereda D.B.: Conceptualization, Data Curation; **Kruglyak I.V. -** Writing Original Draft, Methodology; **Sereda B.P.**: Investigation, Writing Review & Editing, Supervision. The final manuscript was read and approved by all authors.

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