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MATHEMATICAL MODELING FOR IMPROVING THE RELIABILITY HOT ROLLING MILL 1680 MECHANICAL EQUIPMENT

МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ЩОДО ПІДВИЩЕННЯ НАДІЙНОСТІ МЕХАНІЧНОГО ОБЛАДНАННЯ СТАНА ГАРЯЧОГО ПРОКАТУВАННЯ 1680

This research investigates the surface strengthening of critical elements of metallurgical equipment using functionally active charges under non-stationary temperature conditions, which is aimed at increasing their operational reliability and service time. The object of research is the kingpin of the flying shear of a 1680 hot rolling mill, made of 40X steel. The surface of this element was hardened using functionally active chromium-based mixtures alloyed with boron under non-stationary temperature conditions. Structurally, the flying shear assembly of this type implements a crank-lever kinematic scheme, in which the pin acts as an axial hinge between the swing lever and the knife holder, ensuring the accuracy and stability of its movement during high-speed cutting. Modeling and experimental studies have made it possible to determine the influence of the composition of the alloying components of the functionally active charge on the wear resistance parameters under sliding friction conditions. Regression dependencies describing the relationship between the concentration of alloying elements and the tribotechnical characteristics of the hardened layer were obtained, which creates scientific prerequisites for optimizing the composition of powder mixtures and heat treatment modes while increasing the durability of hot rolling unit parts.

Keywords*: self-propagating high-temperature synthesis, thermodynamic modeling, kingpin, scissors, protective coatings, wear resistance, mathematical modeling.*

У статті досліджено поверхневе зміцнення відповідальних елементів металургійного устаткування, з використанням функціонально активних шихт при нестаціонарних температурних умовах, яке спрямовано на підвищення їх експлуатаційної надійності та ресурсу роботи. Як об'єкт дослідження обрано шворінь поворотного важеля летючих ножиць стана гарячої прокатки типу 1680, виготовлений зі сталі 40Х. Зміцнення поверхні шворня поворотного важеля, здійснювали із застосуванням функціонально активних шихт на основі хрому, легова-

них бором при нестаціонарних температурних умовах. Конструктивно вузол летючих ножиць цього типу реалізує кривошипно-важільну кінематичну схему, у якій шворінь виконує функцію осьового шарніра між поворотним важелем і тримачем ножа, забезпечуючи точність та стабільність його руху під час високошвидкісного різання. Проведене моделювання та експериментальні дослідження дозволили визначити вплив складу легуючих компонентів функціонально-активної шихти на параметри зносостійкості при умовах тертя ковзання. Дослідження фазового складу отриманих хромованих покриттів легованих бором дифузійних шарів, дозволило визначити, що на поверхні оброблюємого шворня поворотного важеля, формуються дифузійні шари, що мають у своєму складі фази $(Fe,Cr,Al)_2B$ з вкрапленням FeB, Fe_3Al і тв. розчин B, Cr, Al в α-залізі. При T більше 800 K мольна частка конденсованої фази стабілізується на постійному рівні, що вказує на перебіг реакцій у інтервалі 800–1600 K з утворенням виключно конденсованих продуктів без зміни стехіометричного балансу газової фази. Варіюючи вміст бору та амонієвих газотранспортних агентів у порошковій шихті, формуються сполуки (BH, BH_2, BH_3, BF, BF_2, BF_3, BHF, BH_2F, BI, BI_2, BI_3) та конденсовані фази ($B(c)$, $Al_2O_3(c)$, $BN(c)$, $AlF_3(c)$, $AlN(c)$, $Cr(c)$). Отримано регресійні залежності, що описують взаємозв'язок між концентрацією легувальних елементів та триботехнічними характеристиками зміцненого шару, що створює наукові передумови для оптимізації складу порошкових сумішей і режимів термообробки при підвищенні довговічності деталей вузлів гарячої прокатки.

***Keywords**: саморозповсюджувальний високотемпературний синтез, термодинамічне моделювання, шворень, ножиці, захисні покриття, зносостійкість, математичне моделювання.*

Problem's Formulation

The research problem consists in identifying key factors that influence the increase in durability and reliability of machines and mechanisms used in metallurgical production. One of the main problems is the need to extend the service life of parts that are subjected to intense mechanical and thermal loads during hot rolling processes, where accelerated wear of surface layers occurs. To minimize these negative phenomena, surface alloying and functional protective coatings are used to improve the tribological characteristics of the material and increase its wear resistance [1]. However, despite significant progress in this area, issues related to the identification of the main factors that determine the effectiveness of coatings, as well as the optimization of the technological parameters of their application, remain insufficiently studied. Particular attention should be paid to analyzing the influence of technological conditions—temperature, pressure, deformation rate, and material composition—on the formation of the structure and operational characteristics of the hardened layer. Thus, the main objective of the study is to comprehensively study and systematize the factors that determine the effectiveness of functional coatings under the conditions of real load on metallurgical equipment components.

Analysis of recent research and publications

An examination of contemporary investigations into functional surface layers and element-enrichment techniques designed to prolong the operational lifespan of steelmaking machinery reveals several dominant trajectories and milestones. Over the past decade, extensive experimental efforts have focused on refining the phase composition and microstructure of these layers to enhance interfacial bonding energy, Vickers microhardness, and resistance to erosive degradation. A particularly efficacious strategy involves doping with refractory metals and metalloids—chromium, silicon, boron—yielding coatings that exhibit superior tolerance to galling, fretting, and third-body abrasion under the severe mechanical regimes typical of metallurgical plants.

Substantial emphasis has been placed on elucidating tribokinetic failure modes, enabling precise identification of variables governing coating longevity. Central to this analysis is the molecular-kinetic friction paradigm, which elucidates the physicochemical interactions at contacting asperities and informs strategies for minimizing dissipative energy losses.

Key empirical outcomes include the establishment of critical process windows — thermodynamic temperature, partial pressure, and precursor flux — that maximize the resultant coating's multifunctional attributes. Such parameter refinement elevates deposition throughput and elevates the integrity of engineered components. Collectively, this synthesis of recent literature underscores transformative advances in protective surface engineering and substrate alloying, thereby catalyzing innovations in metallurgical workflows and bolstering the dependability of associated capital assets [2].

In order to increase the service life and working parameters of steel products, hard protective films are deposited. Such films transform the surface characteristics of the substrate, ensuring chemical passivity, increased microhardness, and reduced abrasive wear. Most traditional surface alloying technologies are energy-intensive and time-consuming. In the context of Ukraine, the priority is to create innovative options for chemical-thermal treatment (CTT) that allow controlling the phase composition and microstructure of protective layers, ensuring the required performance indicators with a reduced formation cycle [3].

Diffusion saturation with chromium is used to modify cast irons, various types of steel (carbon, alloy, tool), heat-resistant intermetallics based on Ni, Mo, Nb, B, Co, as well as sintered composites. Powder and vacuum chromium plating technologies are dominant [4]. The presence of carbon in the matrix complicates Cr migration, as carbon blocks diffusion channels. When processing medium- and high-carbon alloy steels (0.3–1% C), a continuous carbide barrier ($Cr_{23}C_6$, Cr_7C_3) forms at the interface, providing extreme wear resistance [5]. Underneath it, a gradient transition zone with an uneven distribution of alloying components is formed. To thicken the chromium-containing layer, preliminary decarburization in an H_2 atmosphere is used, which activates the penetration of Cr.

In low-carbon alloy steels, an intermetallic σ-phase crystallizes on the surface, which increases the brittleness of the diffusion layer. Experiments show that α-structure stabilizers (V, Nb, B, Mo, W, Cr) accelerate chromium diffusion, while γ-stabilizers (Mn, Ni) inhibit Cr flow [6]. The addition of carbide-forming elements to low-carbon matrices promotes the formation of voluminous Cr solid solution zones, since C is fixed in carbide inclusions without hindering diffusion. Kinetics analysis showed parabolic growth of the layer under isothermal conditions and exponential dependence when varying the saturation temperature. This is due to an increase in the equilibrium concentration of the CrI_2 carrier in the gas phase; the limiting stage is intracrystalline diffusion in the substrate [7]. Thus, parametric optimization allows the synthesis of coatings with predictable properties, expanding the scope of industrial application.

Presenting main material

The design and operation of the pivot pin in the mechanism of the hot-rolled flying shears with a width of 1680 mm is implemented on a wide-strip hot rolling mill with a nominal strip width of ≈ 1680 mm. A four-bar crank-rocker linkage mechanism is used in the flying shear assembly, which is designed for dynamic strip trimming without stopping the technological flow. The shear lever is connected to the spindle or cutting tool holder via a hinge assembly. The pin acts as the axial element of the hinge connection between the pivot lever and the holder (or crank); it is made in the form of a steel cylindrical pin, rigidly fixed in the lever body using a mounting sleeve or a radial sliding/rolling bearing. This design ensures controlled relative angular movement (rotation or oscillation) of the lever relative to the holder under cyclic working loads, minimizing friction and wear in the assembly.

The surface of the pin is ground, anti-corrosion coating is allowed, and the fit is made with minimal backlash, which is controlled during operation. The pivot pin is made of alloyed structural steel 40X with heat treatment, which provides increased hardness, wear resistance, and resistance to dynamic impact loads characteristic of high-speed shears in continuous rolling. During the cutting cycle, when the knife follows the moving strip, the lever transmits the load through the pin, which ensures the direction and accuracy of the knife holder's movement relative to the material. The pivot is located on the swivel lever of the shear mechanism, usually in the middle of the lever closer to the top of the crank, where it connects to the knife holder: this is where the transmission of torsional/translational motion between the crank and the knife takes place [8].

This decision is critical in terms of reliability: in case of wear or play in the pin, the knife movement becomes inaccurate, which can lead to uneven cutting, vibration, or emergency shutdown. Therefore, during maintenance, the pin play, seat wear, corrosion, lubricant condition, and the presence of cracks or burrs on the pin surface are checked.

In the 1680 machine, the use of a crank-lever transmission in the shears is justified by the need for synchronous movement of the knife at the speed of the rolling strip. Thus, the pivot pin of the swing lever in the flying shear mechanism of condition 1680 is a small but absolutely necessary part that is responsible for the hinge connection, correctly transmits dynamic loads, and ensures the accuracy of the strip cut at high rolling process productivity [9].

Self-igniting high-temperature synthesis (SHS) is a promising method for forming protective coatings from powder mixtures that react exothermically in the condensed phase. The reaction initiates spontaneous combustion with flame front propagation and local temperatures up to 4000 °C. SHS is based on the frontal mode of exothermic reactions that generate functional materials with high performance characteristics. Unlike classical powder metallurgy with prolonged sintering of inert precursors, SHS uses internal chemical energy.

Advantages of SHS: creation of zones with increased reaction activity, replacement of external heat sources with reaction energy, simplicity of equipment design, rapid multilayer heating of large volumes of reagents. This ensures efficiency in industries without strict resource constraints. Refractory compounds, borides, carbides, superhard alloys, refractory elements, oxide raw materials, single crystals, phosphors, and high-temperature superconductors [10] are industrially produced with high technical and economic returns.

To derive optimal formulations for the reactive SHS powder charge ensuring adequate coating thickness and enhanced service life, experimental design methodologies were employed, incorporating a full factorial analysis based on a 2^3 matrix [11]. The independent variables were defined as follows: X_1 — concentration of the primary alloying element (chromium); X_2 — boron content; X_3 — chromium component. The response variable selected for optimization was Y — the wear resistance metric for the Cr–B system (tabl. 1).

Table 1. Factors for the Cr-B system

Characteristic	Factors		
	Cr %, wt.	B %, wt.	Chromium component %, wt.
Code	X_3	X_2	X_1
Basic level	20	10	10
Variation interval	5	5	5
The lower level	15	5	5
The upper level	25	15	15

The determination of the baseline level and the variation intervals was carried out considering that the addition of the chromium-containing component below 10 wt.% does not significantly influence the course of the SHS reaction. Based on the analysis of characteristic temperature changes during the self-propagating high-temperature synthesis process, the optimal amount of the chromium component was established. To ensure a complete 100 wt.% composition of the powder SHS charge, aluminum oxide (Al_2O_3) was introduced as an inert ballast additive.

As a result, an empirical equation was derived, describing the combined effect of the technological parameters and the charge composition on the optimization criteria of physical, mechanical, and performance characteristics of the obtained coatings. The regression equation takes the following form:
$Y = 94 – 3.5X_1 – 8.2X_2 + 0.9X_3 – 7.3X_1^2 + 2.1X_2^2 + 1.6X_3^2 – 0.475X_1X_2 + 2.125X_1X_3 – 0.125X_2X_3$.

The resulting mathematical model was visualized in the form of three-dimensional response surfaces, which graphically illustrate the influence of the investigated factors and their interactions on the target response parameter (fig. 1).

Boron-doped chromium coatings on 40X steel increase the reliability of machine parts. The high microhardness of the coatings and the retention of lubricant on the surface reduce the intensity of wear during friction. Thermodynamic modeling of SHS reactions was performed in the TERRA software package by calculating the equilibrium composition of the products. A complete thermodynamic analysis covers the equilibrium state of the system, taking into account heat and power exchange with the environment (fig. 2, 3). Equilibrium is determined by minimizing the isobaric-isothermal potential or maximizing entropy, taking into account all potentially equilibrium individual substances [12].

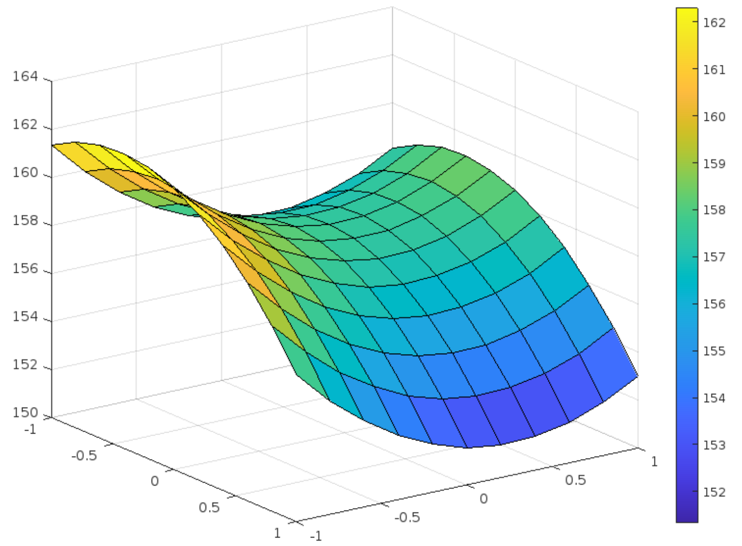

Fig. 1. Optimization of wear resistance for the system Cr-B

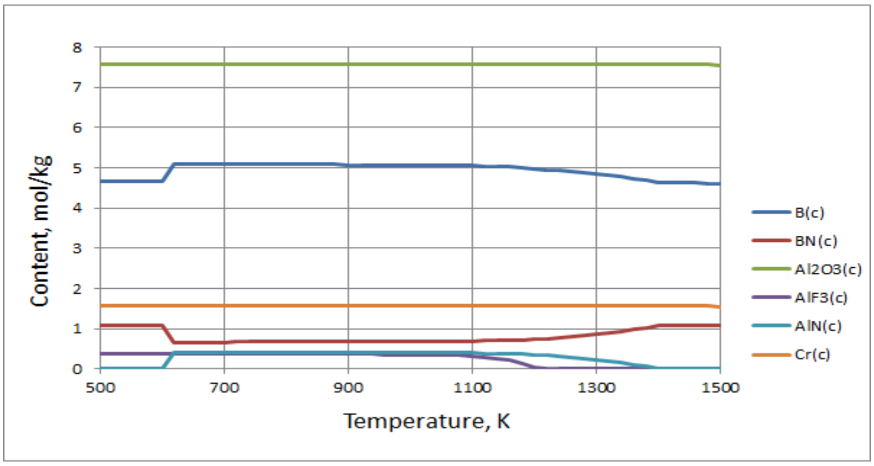

Fig. 2. The content of condensed products in the reactor of the charge for the system: Cr-B

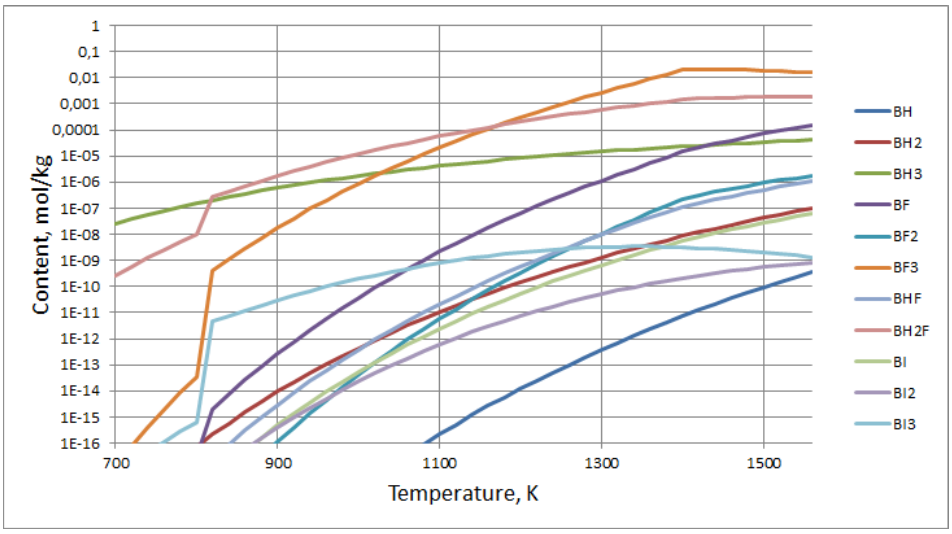

Fig. 3. The content of boron gaseous compounds in the reactor of the charge for the system: Cr-B

The kinetic patterns of reactions in the self-propagating high-temperature synthesis mode are determined by thermodynamic conditions and diffusion barriers. Under conditions of minimal diffusion inhibition in the gas phase during heating and a relatively low rate of temperature change compared to the kinetics of gas-phase transformations, thermodynamic equilibrium of the products is established at each isothermal level. A sequential calculation of the equilibrium composition in the temperature range allows the phase transformation of the system to be reconstructed.

The existence of critical temperature limits for a stable combustion front imposes restrictions on the use of the combustion mode in industrial processes. In contrast, the thermal self-ignition mode has no such limitations. By diluting the initial powder mixture with an inert filler to 85—90 % of the mass, it is possible to reduce the peak temperature to a specified technological value.

As the temperature rises, the yield of volatile components increases, and condensed phases are formed in parallel. In the range of 400—1600 K, the proportion of the condensed phase decreases due to the volatilization of transport agents. Starting at 800 K, the destruction of primary products is initiated, manifested in the formation of secondary decomposition compounds and a sharp increase in the molar volume of the gas phase.

At temperatures exceeding 800 K, the molar fraction of the condensed phase attains a steady-state value, indicating that reactions within the 800—1600 K interval proceed with the exclusive formation of solid-phase products without alteration in the total molecular count of the gaseous phase. This behavior is typical of decomposition, disproportionation, or metathetic interactions involving the substrate, which underpin the chemical vapor transport mechanisms operative in the system. Depending on the boron loading and the concentration of ammonium-derived gaseous transporters within the powder charge, volatile intermediates are generated (BH, BH_2, BH_3, BF, BF_2, BF_3, BHF, BH_2F, BI, BI_2, BI_3) alongside condensed phases ($B(c)$, $Al_2O_3(c)$, $BN(c)$, $AlF_3(c)$, $AlN(c)$, $Cr(c)$).

Phase analysis of the boron-alloyed chromized diffusion coatings revealed that on the surface of the treated pivot pin in the rocker arm, multilayer diffusion zones form comprising $(Fe,Cr,Al)_2B$ as the dominant phase, with dispersed inclusions of FeB, Fe_3Al, and solid solutions of B, Cr, and Al in α-iron.

Conclusions

As a result of theoretical and experimental studies, it has been established that the use of functionally active charge based on chromium alloyed with boron during the formation of diffusion coatings in non-stationary temperature conditions provides a significant increase in wear resistance and operational durability of metallurgical equipment parts. The most pronounced strengthening effect is observed on the surface of the pivot pin of the hot rolling mill type 1680, which is due to the formation of diffusion layers of complex phase composition resistant to abrasive and adhesive wear on the surface.

Phase analysis showed that at temperatures above 800 K, a complex of solid solutions and boride phases of the type $(Fe,Cr,Al)_2B$ with inclusions of FeB, Fe_3Al, and solid solutions of B, Cr, Al in α-iron is formed in the surface zone. This phase ratio ensures high microhardness, thermal stability, and chemical inertness of the diffusion layer, which significantly reduces the wear rate during sliding friction. An increase in temperature above 800 K is accompanied by stabilization of the molar fraction of condensed phases, indicating that the system has reached thermodynamic equilibrium and that reactions proceed within the range of 800–1600 K without disturbing the stoichiometric balance. This indicates the predominance of destruction mechanisms, disproportionation, and exchange reactions with the metal substrate, which determine the efficiency of chemical transport of elements in the coating formation process.

It has been established that varying the concentration of boron and ammonium-type gas transport agents in powder mixtures allows for controlled changes in the ratio of volatile intermediates (BH, BH_2, BH_3, BF, BF_2, BF_3, BHF, BH_2F, BI, BI_2, BI_3) and condensed phases ($B(c)$, $Al_2O_3(c)$, $BN(c)$, $AlF_3(c)$, $AlN(c)$, $Cr(c)$), which determines the mass transfer kinetics and the depth of the diffusion layer. The obtained regression dependencies confirm the existence of a close correlation between the concentration of doping elements, heat treatment parameters, and tribotechnical characteristics of the hardened layer, which creates a scientific basis for optimizing the composition of powder mixtures and processing modes.

Thus, the results of the study not only prove the effectiveness of using functionally active charges under non-stationary temperature conditions, but also open up prospects for further improvement of technologies for strengthening metallurgical equipment components. The practical implementation of the proposed approach will contribute to increasing the reliability, stability, and service time of hot rolling units, which will ultimately reduce operating costs and increase the competitiveness of metallurgical enterprises.

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