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MATHEMATICAL MODELING OF THE DEVELOPMENT OF RATIONAL CHARGE CHARGES WHEN STRENGTHENING SCREWS OF PRESSURE MECHANISMS

МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ РОЗРОБКИ РАЦІОНАЛЬНИХ ШИХТ ПРИ ЗМІЦНЕННІ ГВИНТІВ НАТИСКНИХ МЕХАНІЗМІВ

This research analyzes technological approaches to increasing the wear resistance and operational durability of machine-building components by surface hardening. The paper considers the peculiarities of hardening the threaded elements of the pressing unit of a 600/1500×2500 cold deformation mill made of 40X steel. The hardening process was implemented using functionally active composite charges under non-stationary temperature conditions. The main structural elements of such pressing mechanisms are a steel screw interacting with a bronze nut, which is fixed in the transverse assembly of the frame. The screw is rotated by a separate drive unit. To ensure high accuracy of the roll gap adjustment and stable operation of the mill, this screw pair must be characterized by increased strength, rigidity and durability. The surface hardening of the screw of the cold rolling mill's pressure mechanism was carried out using the developed functional-active charge based on chromium alloyed with titanium. During the research, thermodynamic modeling was performed, which made it possible to establish the phase composition of the gas and condensed phases. Using mathematical modeling methods, regression equations were constructed that reflect the influence of the main alloying elements on the wear resistance parameters under sliding friction conditions.

Keywords*: modeling, regression equation, rolling, durability, charge, pressing mechanism, coating, wear resistance, microhardness*.

У даному дослідженні проаналізовано технологічні підходи до підвищення зносостійкості та експлуатаційної довговічності елементів машинобудівних вузлів шляхом поверхневого зміцнення. Розглянуто особливості зміцнення різьбових елементів натискного вузла прокатного стана холодного деформування 600/1500×2500, виготовленого зі сталі марки 40Х. Процес зміцнення реалізовано із застосуванням функціонально-активних композиційних шихт при нестаціонарних температурних умов. Основними елементами конструкції таких натискних механізмів є сталевий гвинт, що взаємодіє з бронзовою гайкою, яка фіксується у поперечному вузлі станини. Обертання гвинта відбувається за допомогою окремого приводного пристрою. Для забезпечення високої точності регулювання міжвалкового зазору та стабільної роботи стана, ця гвинтова пара повинна характеризуватися підвищеними показниками міцності, жорсткості та довговічності. Поверхневе зміцнення гвинта натискного механізму стану холодного прокатування, проводились з застовуванням розробленоих функціонально-активні шихти на основі хрому легованих титаном. У процесі дослідження виконано термодинамічне моделювання, що дало змогу вста-

новити фазовий склад газової та конденсованої фаз. За допомогою математичних методів моделювання було побудовано рівняння регресійної залежності, які відображають вплив основних легуючих елементів на параметри зносостійкості в умовах тертя ковзання. Результати дослідження не тільки підтверджують ефективність застосування зазначених покриттів, але й мають широкі практичні та наукові значення, включаючи покращення виробничих процесів та підвищення конкурентоспроможності підприємств металургійної галузі.

Ключові слова: *моделювання, рівняння регресії, прокатка, довговічність, шихта, механізм пресування, покриття, зносостійкість, мікротвердість.*

Problem's Formulation

Research focuses on the systematic identification of key technological and structural factors that influence the operational longevity of mechanical systems employed in metallurgical production environments. A central technical issue is the limited durability of machine components and structural elements subjected to the intensive mechanical and thermomechanical loading regimes characteristic of cold rolling processes, where surface degradation due to friction and elevated contact stresses is particularly severe. To mitigate such degradation phenomena, advanced surface engineering techniques—particularly functional protective coatings and diffusion-based surface alloying—are increasingly utilized to enhance the tribological behavior of working surfaces and significantly improve their resistance to wear. Notwithstanding the notable advancements achieved in the development and implementation of such coatings, unresolved questions persist regarding the identification of dominant parameters influencing their protective efficacy. This includes the need for further clarification of the relationships between coating composition, structural evolution, and resulting mechanical performance under varying operational regimes.

Of particular importance is the examination of the influence of technological parameters—namely, thermal conditions, applied pressures, deformation rates, and compositional variability of alloying systems—on the microstructural features and functional characteristics of the protective layers. Research main objective is to perform a detailed analysis of the interaction between processing conditions and material response, with the aim of optimizing surface treatment strategies for enhanced performance and extended service life of critical components in metallurgical machinery.

Analysis of recent research and publications

A review of current research in the domain of functional protective coatings and surface alloying technologies, aimed at enhancing the operational longevity of mechanical systems in steelmaking, reveals a range of leading trends and technological advancements. In recent years, numerous investigations have focused on optimizing the composition and microstructure of protective layers to improve their adhesion strength, hardness, and resistance to various forms of wear. Among the most promising directions is the application of alloying elements such as chromium, silicon, and titanium, which substantially enhance the operational characteristics of coatings, particularly their resistance to both abrasive and adhesive wear—making them suitable for use under severe service conditions typical of metallurgical equipment.

Significant attention has been devoted to the analysis of tribological wear mechanisms, enabling a more in-depth understanding of the factors influencing the durability of surface coatings. The molecular-mechanical theory of friction plays a key role in interpreting the physicochemical nature of interfacial processes during contact interaction, as well as in identifying strategies to mitigate wear. A valuable outcome of such research is the determination of optimal technological parameters—temperature, applied pressure, and material feed rate—that contribute to the formation of coatings with superior functional properties. These insights are instrumental in increasing the efficiency of coating technologies and improving the quality of industrial products.

Formulation of the study purpose

The purpose of this research is to develop and improve methods of surface hardening of machine and mechanism parts to increase the reliability and durability of metallurgical equipment. In particular, the research is aimed at studying the processes of strengthening the screw of the pressure mechanism of the cold rolling mill 600/1500×2500, made of 40X steel, using functionally active charges under non-stationary temperature conditions.

Presenting main material

Improving the operational reliability and service life of machine and mechanism parts in the industrial engineering industry for the needs of metallurgy is a priority area of scientific and technological development. In particular, the problem of strengthening the elements of the pressure mechanism of cold rolling mills, such as rolling mill 2500, is relevant. To ensure efficient operation under significant mechanical and thermal loads, it is necessary to improve the physical and mechanical properties of the surface layers of these elements by forming wear-resistant coatings with high hardness and minimal thermokinetic impact. One of the effective ways to achieve these goals is to use functionally active blends that not only reduce energy consumption but also achieve increased surface hardening efficiency.

The application of functionally active charge compositions under non-isothermal conditions represents an advanced approach for the formation of protective coatings, utilizing powder mixtures capable of initiating highly exothermic interactions within the condensed phase. During the reaction, spontaneous combustion occurs and the combustion front propagates, accompanied by the generation of high temperatures (up to 4000 °C) [1—2]. The essence of the technology is the realization of exothermic reactions in the frontal combustion mode, which results in the formation of functional materials with valuable properties. This approach is fundamentally different from traditional methods of powder metallurgy, where synthesis occurs by prolonged sintering of inert compounds [3].

The advantages of obtaining protective coatings using functionally active charges under non-stationary temperature conditions include the formation of highly reactive thermal and chemical zones that contribute to the intensification of chemical transformations, the use of internal chemical energy of the exothermic reaction instead of external heat sources, the use of simple technological equipment, and the possibility of rapid multilayer heating of large volumes of reagents. This makes the use of functionally active charges effective in areas where economic or resource constraints are critical. Today, these processes are successfully used to produce refractory compounds, boride and carbide materials, superhard alloys, refractory building elements, oxide raw materials, single crystals, phosphors, and even high-temperature superconductors. Most of these materials are already produced on an industrial level with high technical and economic efficiency [4,5].

Most rolling mills are equipped with screw pressure mechanisms. The main structural elements of such mechanisms are a bronze nut placed in the bed cross member and a steel screw screwed into the nut using a separate mechanism.

Such a screw pair must have sufficient strength and rigidity to ensure the required reliability and accuracy of adjusting the gap between the rolls. In particular, flat-rolled steel mills are designed to allow for the possibility of changing the gap during the rolling process (if there is metal in the rolls). Such pressing mechanisms must have sufficient rigidity and drive power, and in addition, ensure the required accuracy of roll installation.

For crimping mills, the peculiarity of the pressing mechanisms is the need to ensure a high speed of movement of the upper roll because the gap changes after each pass. In addition, such mills are characterized by a significant movement of the rolls in the process of changing the gap.

For long products mills, the change in gap during the rolling process is unacceptable, so the mechanism may not be as powerful. However, for long products mills, it is necessary to ensure a constant rolling level. For this reason, such stands are equipped not only with upper but also with lower pressure mechanisms. The speed of roll movement during gap adjustment in long products mills is not essential because it is insignificant and occurs periodically (several times per shift). For flat-rolling mills, low-speed pressing mechanisms are used. The 2500 cold rolling mill uses a mechanism with a total gear ratio of 1122. The kinematic diagram of this mechanism, which consists of two worm gears for each screw, is shown in Fig. 1. Depending on the required speed of the screw (or, more precisely, the rolls) and the amount of movement, a stop or trapezoidal thread is used.

For existing rolling mills, in most cases, a verification calculation of the screw and nut, which have certain dimensions (Fig. 1), is performed [6,7]. Such a calculation is reduced to determining the stresses in the elements of the pressing mechanism from the action of working loads, and comparing the calculated values with the permissible.

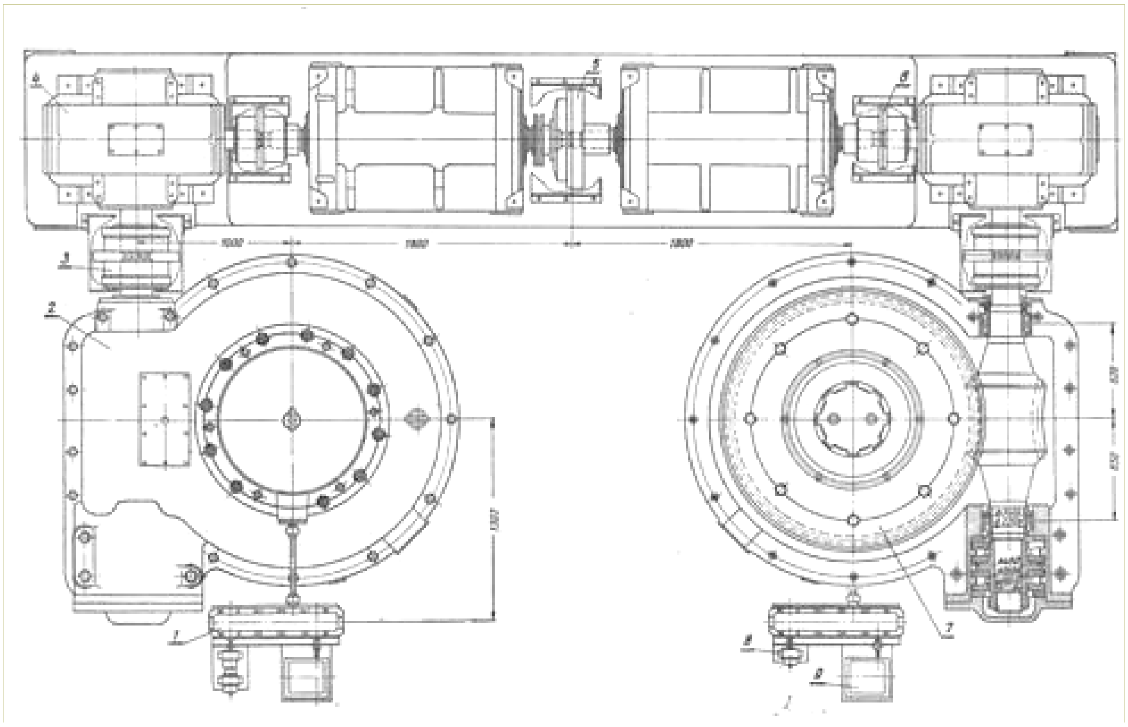

Fig. 1. Kinematic diagram of the pressure mechanism of the cold rolling mill 600/1500x2500

Tension in a pressure screw is defined as the ratio of the force acting on the screw to its cross-sectional area, using the formula:

$$\sigma_{2b} = \frac{4 \cdot F_1}{\pi \cdot d_1^2},$$

where F_1 — force acting on the screw, Н; d_1 — minimum screw diameter, мм.

The screws of the pressure mechanisms are made of structural steel grades, such as 40Х, 40ХН. The safety margin for pressure screws is at least 5. Therefore, the permissible stresses for screws are $[\sigma]_{28} = 120 \div 150 Н/ММ^2$. For mills with increased requirements for stand stiffness, for example, to ensure increased rolling accuracy, the allowable stresses are $[\sigma]_{2\varepsilon} = 60 \div 80 Н/ММ^2$.

For the nut of a clamping mechanism, the most stressed elements are the thread and the bearing surface (in the bed cross member) [8,9]. The stress in the nut thread is calculated as the ratio of the force transmitted from the screw to the area of the thread turns

$$\sigma_p = \frac{F_1}{S_p \cdot n},$$

where S_p — contact area of the nut and screw by one thread turn, мм²; n — number of thread turns. The contact area for one thread turn is

$$S_p = \frac{\pi}{4}(D_4^2 - D_1^2),$$

where D_4, D_1 — respectively, internal and external diameter of the nut thread, mm.

The number of turns is determined as the quotient of the nut height H_2 divided by the thread pitch P

$$n = \frac{H_2}{P}.$$

Permissible stresses for bronze nuts are $[\sigma]_{зм.\ op} = 15 \div 20 Н/mm^2$. Compression stress of the nut material in the area of contact with the support surface of the bed is determined by the formula:

$$\sigma_{3M} = \frac{F_1}{S_{on}}..$$

The bearing surface area is defined as:

$$S_{on} = \frac{\pi}{4}(d_z^2 - d_s^2),$$

where d_2, d_6 — respectively, the diameters of the holes in the cross member of the frame for placing the nut and passing the pressure screw, mm. The permissible compression stresses for bronze are: $[\sigma]_{зм.бр} = 45 \div 60\text{Н/mm}^2$.

Protective coatings applied to 40X steel are extensively utilized in the machine-building sector because they enhance the operational reliability of components. Consequently, it is essential to investigate the wear-resistant characteristics of steel after the application of boride coatings infused with elements such as chromium, silicon, and titanium. The exceptional microhardness of these coatings, combined with their capacity to hold lubricants on the surface, significantly lowers the wear rate during frictional interactions. The primary goal of this study is to identify the ideal operating conditions for machine parts strengthened through this advanced surface modification technique under fluctuating temperature conditions, utilizing specially formulated functionally active charges.

For the thermodynamic simulation of chemical reactions involving functionally active charges under dynamic temperature conditions, the equilibrium composition of the system's products was determined using the TERRA software. To develop the optimal formulations of powder-based functionally active charges that ensure adequate coating thickness and enhanced durability, experimental design methods were employed, incorporating a full factorial analysis based on a 2^3 experimental plan. Thermodynamic modeling of these processes involves a comprehensive thermodynamic analysis of the system's equilibrium state. Thermodynamic systems are defined as isolated material regions whose interaction with the surroundings is limited to the exchange of heat and mechanical energy. The computation of thermodynamic equilibrium for complex systems—encompassing the determination of all equilibrium parameters, thermodynamic properties, and chemical and phase compositions—is achieved by minimizing the isobaric-isothermal potential or maximizing the system's entropy, while accounting for all potentially equilibrium individual substances [13].

The kinetic patterns of chemical reactions involving functionally active under non-stationary temperature conditions are influenced by both thermal and diffusion factors. If we assume that during the heating phase, the suppression of diffusion processes in the gas phase is minimal, and the temperature change rate is significantly slower compared to the speed of gas-phase chemical reactions, we can infer that the reaction products reach an equilibrium composition at each temperature. By determining the equilibrium composition of these products across a range of temperatures, we can effectively map out the chemical dynamics of the process.

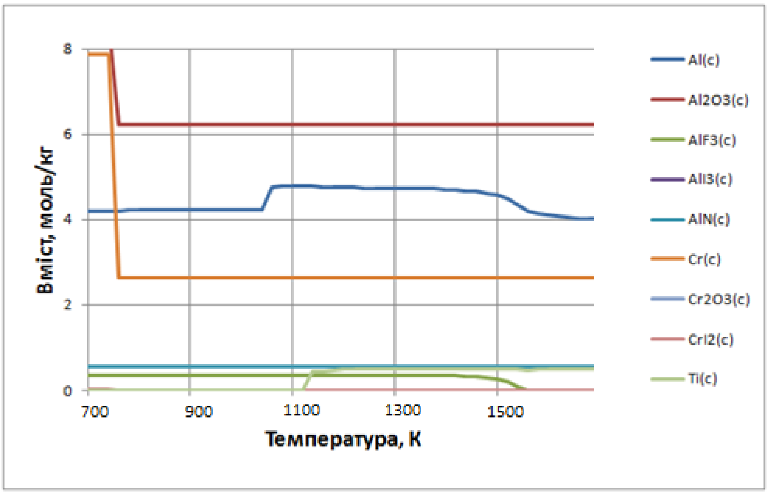

Fig. 2. The content of condensed products in the reactor of the charge

The presence of threshold temperatures required for sustaining combustion front propagation imposes certain technological constraints on the practical use of combustion-based synthesis modes. In contrast, thermal autoignition offers greater flexibility, as it is not subject to such limitations. The dilution of the initial reactive powder mixture with inert components up to 85—90 % by mass enables precise regulation of the maximum temperature, bringing it within a range suitable for technological processes.

As temperature increases, there is a notable rise in the proportion of reaction products in the gaseous phase, accompanied by the formation of condensed species. Within the temperature interval of 400—1600 K, a reduction in the condensed phase fraction is observed due to the volatilization of carrier substances. Additionally, beginning at approximately 800 K, decomposition reactions are initiated, leading to the emergence of secondary gaseous products and a sharp increase in the total number of gas-phase molecules.

The resulting gaseous species undergo interactions with metallic components of the powder system, such as Al, Ti, and Cr, promoting their transition into the gas phase in the form of volatile compounds like AlJ, AlJ_2, AlCl, $AlCl_2$, $CrCl_2$, CrF, CrF_2, CrF_4, $TiCl_2$, $TiCl_3$, $TiCl_4$ etc. At temperatures exceeding 800 K, the condensed phase content remains relatively constant, suggesting that chemical transformations occur with the formation of condensed products in the 800–1600 K range without a net increase in molecular quantity. This behavior is characteristic of decomposition, disproportionation, or exchange reactions with the substrate, which collectively underpin the mechanism of chemical transport of elements.

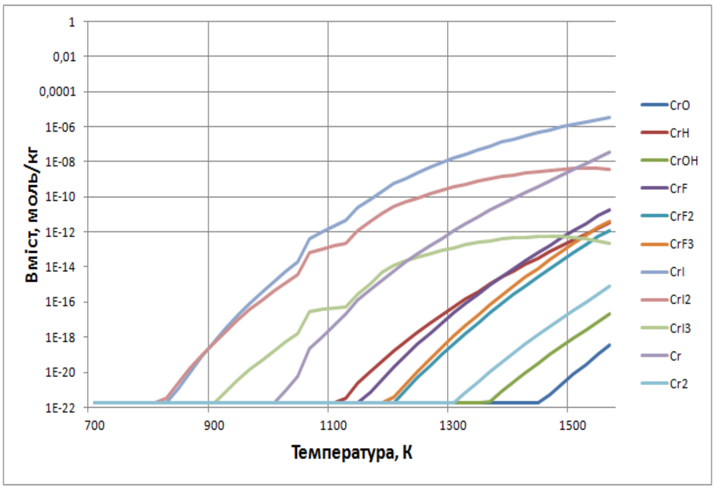

Fig. 3. The content of chromium gaseous compounds in the reactor of the charge

Mathematical planning of experiments was performed to develop optimal charge compositions The factors of the experiment were selected: (X_1) — content of alloying elements (chromium), (X2) — content of titanium, (X3) — content of chromium component. Optimization parameters selected Y1 — wear resistance indicator for the Ti-Cr system (Tabl. 1).

Table 1. Factors for the Ti-Cr system

Characteristic	Factors		
	Al %, wt.	Ti %, wt.	Cr %, wt.
Code	X_1	X_2	X_3
Basic level	22	17	6
Variation interval	5	5	2
The lower level	17	12	8
The upper level	27	27	4

The selection of the baseline level and the range of variation is based on the condition that the introduction of chemically active components (ChC) does not exceed 10 wt.%. This criterion was established through an investigation of the changes in characteristic temperatures during the application of functionally active charges additives under non-isothermal conditions. The optimal quantity of ChC was determined accordingly. Aluminum oxide (Al_2O_3) is employed as an inert diluent to ensure a complete 100 composition of the functionally active charges under non-isothermal conditions.

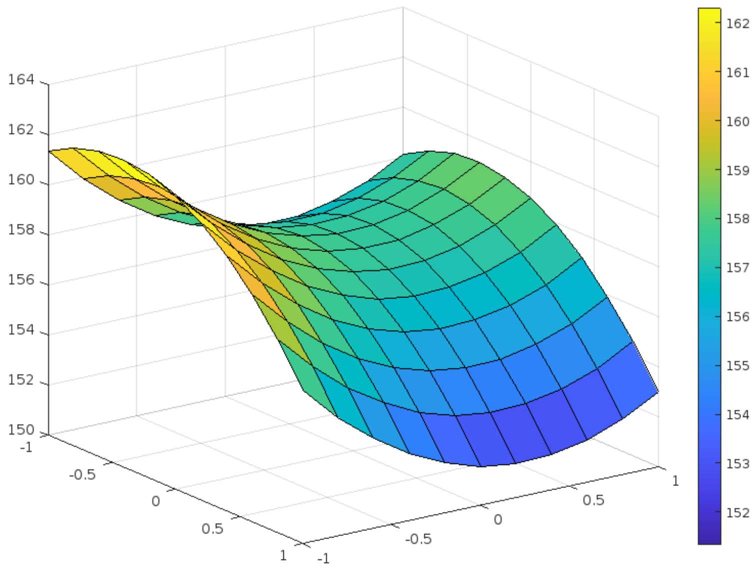

Fig. 4. Optimization of wear resistance for the system Cr-Al-Ti

The response surface corresponding to the developed mathematical models is presented in the form of three-dimensional graphical dependencies (fig. 4). The derived regression equation, which characterizes the influence of technological parameters and charge composition on the optimization criteria for physical, mechanical, and performance properties, is expressed as follows: $Y = 55{,}889 - 3X_1 - 2{,}4X_2 - 1{,}7X_3 + 3{,}8889X_1^2 + 5{,}8889X_2^2 - 3{,}6111X_3^2 + 0{,}625X_1X_2 + 1{,}625X_1X_3 - 0{,}375X_2X_3$

Conclusions

Method of diffusion saturation of the surface from the solid phase in an active gas environment wtih using functionally active charge compositions under non-isothermal conditions has proven to be promising for obtaining high-quality protective coatings. The proposed method enables the formation of protective coatings characterized by an elevated concentration of alloying components such as chromium, silicon, titanium, and other elements, which leads to enhanced functional properties and improved surface protection efficiency. Based on the results of the conducted research, it was established that employing functionally active powder charges under non-isothermal temperature conditions significantly increases the wear resistance of the screw component within the pressure mechanism of a 600/1500×2500 cold rolling mill. This finding demonstrates considerable potential for application in the metallurgical industry, offering viable approaches to minimize energy expenditures while simultaneously extending service life. Specialized chromium-based charges alloyed with titanium were developed and tested. Regression models were derived to quantify the influence of specific alloying additions on wear resistance during sliding friction processes. Consequently, the obtained results substantiate the practical viability and scientific value of the applied coating systems, contributing to production efficiency improvements and enhancing the competitive advantage of metallurgical enterprises.

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