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MATHEMATICAL MODELING OF THE DEVELOPMENT OF RATIONAL CHARGES WHEN STRENGTHENING MECHANICAL EQUIPMENT OF PARALLEL KNIFES

МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ РОЗРОБКИ РАЦІОНАЛЬНИХ ШИХТ ПРИ ЗМІЦНЕННІ МЕХАНІЧНОГО ОБЛАДНАННЯ НОЖИЦЬ З ПАРАЛЕЛЬНИМИ НОЖАМИ

Our research focused on improving the operational durability of mechanical equipment for cutting metal on parallel shears of mill 1680, which is used in the cold rolling process, is described in this article. Research covers various methods of strengthening machine components and assemblies that ensure high reliability and durability of equipment used in metallurgy. Particular attention is paid to functionally active coatings created by self- propagating high-temperature synthesis to increase wear resistance and reduce energy consumption during the operation of parallel knife shears. The article also provides a detailed description of the design and operating principles of the 1680 rolling mill stand, including the features of rolls, support mechanisms, pressure devices, balancing systems, as well as drive mechanisms and rolled thickness control. Finally, the paper presents experimental results on the wear resistance of A473 (440C) steel with protective wear-resistant chromium-boron coatings, as well as mathematical modeling of the optimal composition of the SHS charge. During the study on the friction machine MT-5, samples with a coating obtained under isothermal conditions and with a coating under SHS conditions were tested for 5 hours of experiment. The amount of wear of chromium-doped boron coatings obtained under SHS conditions is 35-40·10^{-4} g/m^{2}.

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

У статті розглянуто дослідження, спрямоване на підвищення експлуатаційної довговічності механічного обладнання для різання металу на паралельних ножицях стана 1680, що застосовується в процесі холодної прокатки. Робота охоплює різні методи зміцнення компонентів машин і вузлів, що забезпечують високу надійність і довговічність обладнання, яке використовується в металургії. Особливу увагу приділено функціонально-активним покриттям, створеним методом саморозповсюджувального високотемпературного синтезу, з метою збільшен-

ня зносостійкості та зниження енергоспоживання в процесі роботи ножиць з паралельними ножами. Стаття також містить детальний опис конструкції та робочих принципів кліті прокатного стану 1680, розглядаючи особливості валків, опорних механізмів, натискних пристроїв, систем врівноваження, а також приводних механізмів і регулювання товщини прокату. На завершення представлено експериментальні результати щодо зносостійкості сталі 5ХНМ із захисними зносостійким хромоборованим покриттям, а також наведено математичне моделювання отримання оптимального складу СВС-шихти. Під час проведення дослідження на машині тертя МТ-5 за 5 годин експерименту, зразки з покриттям отриманим в ізотермічних умовах та з покриттям в умовах СВС. Величина зносу легованих хромом борованих покриттів отриманих в умовах СВС становить 35-40 · 10^{-4} г/м^{2}.

Ключові слова: *високотемпературний синтез, ножиці, захисні покриття, зносостійкість, математичне моделювання, оптимальний склад.*

Problem's Formulation

Problem is to identify and address the key factors affecting the durability of mechanical equipment used in metallurgical production. The main challenge is to extend the service life of equipment involved in cold rolling processes, where it is subjected to significant mechanical and thermal stresses that accelerate wear, especially during metal cutting with parallel knives. To solve this problem, functional coatings and alloying methods are being actively developed and applied to improve surface properties and wear resistance. However, the factors determining the effectiveness of such coatings, as well as ways to optimize the processes of their application remain not fully understood at the moment. It is also important to consider the influence of production parameters such as temperature, pressure, speed and chemical composition of the material on the durability and quality of the coatings. The objective of the study is to identify and analyze the key factors determining the effectiveness of functional coatings and alloyed materials in metallurgical production conditions.

Analysis of recent research and publications

Analysis of modern research in the field of functional coatings and alloying to increase the service life of mechanical equipment in metallurgy allows us to highlight a number of main directions and achieved results. In recent years, many studies have been carried out to improve the composition and structure of functional coatings in order to increase their adhesion, hardness and resistance to wear. One of the most promising methods is the use of alloyed coatings containing such elements as chromium, silicon and titanium. These materials are characterized by high hardness and resistance to abrasive and adhesive wear, which makes them optimal for the conditions of metallurgical production. Considerable attention is also paid to the study of wear mechanisms and interaction of contact surfaces, which allows to determine more accurately the factors affecting the durability of coatings. Molecular mechanical theory of friction is used to understand the processes occurring during friction and to develop techniques for reducing wear of surfaces.

An important outcome of the research is the identification of optimal production parameters such as temperature, pressure and speed that maximize the efficiency of the coatings and alloyed materials. This contributes to optimizing coating processes and improving product quality. Thus, a review of recent research indicates significant progress in the field of functional coatings and alloying to increase the durability of mechanical equipment, which opens new perspectives for improving the efficiency of metallurgical production processes. The method of self-propagating high-temperature synthesis (SHS) for the application of protective coatings is based on the use of powdered exothermic sums, in which chemical elements interact in the condensed phase, creating a combustion helix, which is self-propagating [1]. SHS is one of the highest-temperature combustion processes, capable of reaching temperatures in the range from 800 to 4000 °C.

Presenting main material

Ensuring the reliability and long service life of rolling mill parts is one of the priorities in strengthening the components of industrial machinery and mechanisms, particularly in metallurgical production. To increase the reliability of mechanical equipment for cutting metal with parallel shears in the 1680 continuous cold rolling mill, it is necessary to strengthen the surface layer of parts, which reduces thermokinetic load and increases surface hardness, thereby improving wear resistance. The use of functionally active charges helps to increase the wear resistance of pressure screws, reduce hardening costs and significantly reduce energy consumption.

The essence of the SHS method is the implementation of exothermic reactions in the mode of combustion wave propagation with the formation of materials with unique properties that are valuable in terms of practical application [2]. This process differs significantly from traditional powder metallurgy methods based on sintering chemically inert compounds and has the following advantages

– creation of active chemical and thermal zones that intensify the transformation of reagents and promote the formation of the required products;

– the use of cheaper chemical energy (heat generated during exothermic reactions) instead of electrical energy to achieve the high temperatures required to produce the products;

– use of simple equipment (instead of furnaces and other heating devices);

– rapid layer-by-layer heating of large volumes of reagents, as opposed to slow heating through walls from external heat sources.

Thus, SHS processes can be widely used in all cases where there are no restrictions related to raw materials or economic considerations. Among the materials in which SHS processes already play an important role are refractory compounds, carbide and boride materials, hard alloys, refractory and construction materials, oxide charge and single crystals, phosphors and high-temperature superconductors [3]. Many of these materials are produced on an industrial scale with high technological and economic efficiency.

For transverse cutting of hot rectangular metal undergoing the slabbing stage, shears with parallel blades are used. During cutting, the plane in which the knife moves (i.e., the cutting plane) remains constant (Fig. 1). The main parameters of the scissors are: the maximum cutting force *P*, knife stroke *H*, knife length *L* and the number of strokes (cuts per minute (scissor productivity)

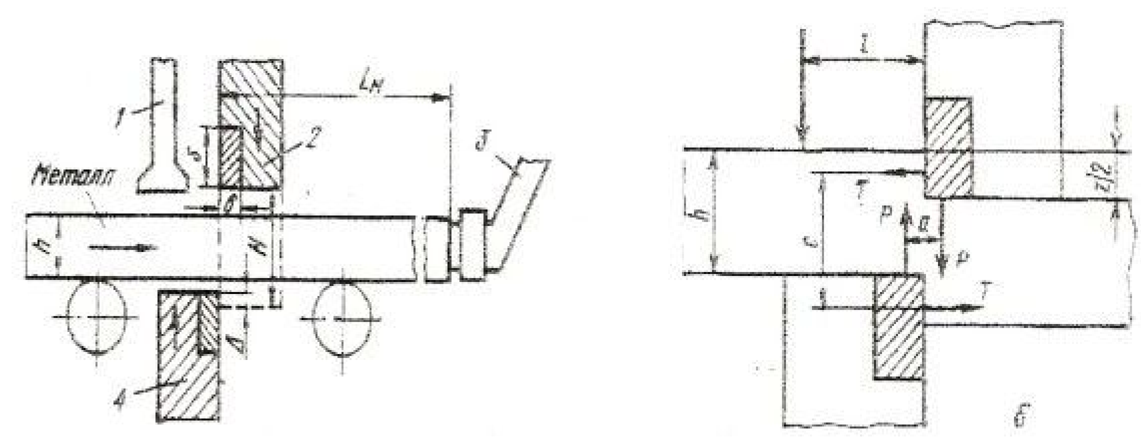

Fig. 1. Scheme of scissors with parallel blades: 1 — clamp; 2 — upper caliper with a knife; 3 — movable stop; 4 — lower caliper with a knife [5]

Depending on the depth of penetration of the knives $\varepsilon_x = \frac{z_x}{h}$

$$k_1 = \frac{\tau_{\max}}{\sigma_B} = 0{,}6...0{,}7\ ,$$

for soft metals $-\ k_1 = 0{,}7$, for hard metals $-\ k_1 = 0{,}6$.

The calculation formula for the maximum cutting force will be as follows:

$$P_{\max} = k_1 k_2 k_3 \sigma_\sigma sh - \varepsilon_6\ ,$$

where k_2 — coefficient that takes into account the increase in cutting force when the blades become dull during prolonged operation of the scissors; k_3 — the same if the lateral gap between the knives is increased.

Based on practical data, the following values of these coefficients can be accepted [4]:

when hot cutting $k_2 = 1{,}10 \ldots 1{,}20$, $k_3 = 1{,}15 \ldots 1{,}25$;

when cold cutting $k_2 = 1{,}15 \ldots 1{,}25$, $k_3 = 1{,}20 \ldots 1{,}30$.

To cut metal with a non-rectangular cross-section (e.g., round), its cross-section must be brought to an equivalent rectangular cross-section. There are two main types of scissor designs: top cut and bottom cut. In the first type, only the upper knife is movable, while in the second type, both knives are movable, although the main cutting is done by the movement of the lower knife [5].

Top-cut scissors have certain design disadvantages, including the need to use a special roller table in the form of a lifting and swinging table, since a stationary roller table prevents the movement of the upper knife. In addition, when cutting, a burr is inevitably formed at the bottom of the roll, which prevents further movement of the material along the roller conveyor. Thanks to the elimination of these drawbacks, shears with a lower cut have become more widely used.

Permissible cross-sectional dimensions of metal that can be cut with a particular type of shear are determined by the maximum cutting force for which the shear is designed. The stroke of the blades is selected taking into account the possibility of unobstructed passage of the material with a maximum cross-section under the mechanical or hydraulic clamping foot, as well as the overlap of the blades at the end of the cut (usually by 10—20 mm). The length of the knives is taken equal to that of slitting shears with a cutting force of up to 20 MN — 150—200 mm more than the maximum width of the slabs. The cross-section of the knives is usually taken from the ratio s/д = 2.5—3, where s is the height and д is the thickness of the knife.

Knives are shaped like a symmetrical rectangle, which allows you to use all four corners when cutting. The blade's sharpening angle is 90°. The knives are made of A473 (440C) steel or St6 carbon steel with a hardness after heat treatment of up to 400 HB. To increase the service life of the knives, the cutting edges are surfaced with hard alloys (e.g., sormite) [6].

According to the design, shears for cross-cutting with parallel blades are divided into two main groups:

a) shears with an upper moving blade (top cut), which are used at metallurgical plants;

b) shears with a lower moving blade (lower cut).

Top cut shears have a simpler design. The principle of their operation is as follows: the lower knife is fixed in the frame, while the upper knife is fixed in the caliper (slider) and is driven by a crank or hydraulic mechanism, moving down and cutting the metal. It should be noted that in order to cut metal on these scissors, a roller table is required, which can oscillate after cutting, which complicates the overall design [7].

Protective coatings on A473 (440C) steel are widely used in mechanical engineering, so assessing the wear resistance of steel with boron coatings alloyed with chromium, silicon and titanium is of considerable scientific and practical interest. These coatings, due to their high hardness and ability to retain lubricants on the surface, increase the material's resistance to wear. The main objective of the study is to determine the optimal operating conditions for parts hardened by the developed technology using SHS charges.

The nature and rate of wear of friction surfaces depend on the operating conditions of the product and the properties of the working surface, such as roughness, hardness, and the presence of a protective coating. In the contact zone of a friction pair, complex processes of mechanical and physicochemical interaction occur that determine the type of wear of the surfaces. These include strengthening and weakening of contact areas due to repeated deformation, heat generation, changes in structure, oxidation, micro-welding of irregularities with subsequent erosion, and other phenomena. The molecular mechanical or adhesion- deformation theory of friction, which takes these processes into account to the fullest extent, allows us to explain the mechanisms of wear and interaction of materials in the friction zone.

Deformation interaction occurs at the points of contact of rough surfaces, causing multiple deformation of the surface layer. Depending on the mechanical impact, the interaction can be elastic, plastic, or micro-cutting. Adhesive interaction, in turn, is associated with the formation of micro-welded bridges in the contact zone. Molecular mechanical theory suggests that reducing or inhibiting wear helps prevent the formation of strong adhesive bonds in friction pairs and increases the hardness of friction surfaces.

The application of a resistant coating to the friction surfaces creates a barrier that prevents adhesion of the contacting surfaces and increases hardness, which in turn prevents plastic deformation and micro-cutting. This contributes to the elastic interaction of the friction surfaces, which is optimal for increasing wear resistance. Therefore, the hardness (microhardness) of the coated surface can serve as an important criterion for assessing its performance properties.

The task of the mathematical planning of the experiment was to study the effect of the technological mode of processing and the composition of the SHS charges on the wear resistance indicators in order to optimize the mode of thermal spontaneous combustion and select the optimal SHS charges for boring samples from L6,T61206 steel.

Based on the results of the experiment, find the values of the unknown model coefficients. The model coefficients are calculated by the formula:

$$B_j = \frac{\sum_{i=1}^{N} x_{ji} \cdot y_i}{N},$$

where $j = 0,1,Z,...,$

Let's use this formula to calculate the coefficients B_1 and B_2:

$$\in_1 = \frac{(-1)y_1 + (+1)y_2 + (-1)y_3 + (+1)y_4}{4};$$

$$\in_2 = \frac{(-1)y_1 + (-1)y_2 + (+1)y_3 + (+1)y_4}{4}.$$

To calculate the coefficients, a column vector is used x, and for b, the vector is valid, so it is also valid for the arithmetic averages of the variables $\bar{y} = \sigma_0 + \sigma_1 \bar{x}_1 + \sigma_2 \bar{x}_2$. Because of the symmetry property $\bar{x}_1 = \bar{x}_2 = 0$.

So, $\bar{y} = t_0$, is the arithmetic mean of the optimization parameter. To obtain it, it is necessary to add up all U and divide by the number of experiments. To bring this procedure in line with the formula for calculating the coefficients, we introduce a column vector of the dummy variable into the planning matrix, which is equal to +1 in all cases. Therefore, the linear model $y = \sigma_0 + B_1 x_1 + \sigma x_2$ visualize

$$y = B_0 x_0 + B_1 x_1 + B_2 x_2.$$

The coefficients of the independent variables indicate the strength of the influence of the factors: the larger the numerical value of the coefficients, the greater the influence of the factor. If the coefficient has a plus sign, then the optimization parameter increases with the increase of the factor value, and if it has a minus sign, it decreases.

The value of the coefficient corresponds to the contribution of this factor to the increase in the optimization parameter when the factor moves from zero to the upper or lower level. By replacing the variables x_i and subsequently reducing the similar ones, we obtain natural equations characterizing the effect of the thermal self-ignition mode and the content of alloying elements on the wear resistance of protective coatings (I):

$$I = 110{,}44 - 1{,}27B - 6{,}51Al - 1{,}43XC + 0{,}6B^2 + 0{,}26Al^2 + 0{,}075BAl.$$

In order to determine the composition of the SHS charge, which ensures the optimal wear resistance of coatings, three-dimensional graphical dependences were constructed (Fig. 2)

Recommended optimum composition of the SHS charge for obtaining wear-resistant chromium-borated protective coatings: 22% XC + 12% Al + 11% B + 50% Al_2O_3 + 2% I_2+ 3% NH_4F;

Testing of tribological processes of materials in the practice of laboratory research is widely used on the MT-5 friction machine was carried out under conditions of boundary sliding friction with lubrication with motor vehicle oil. The results of the wear test of steel samples on the MT-5 friction machine are shown in Fig. 3.

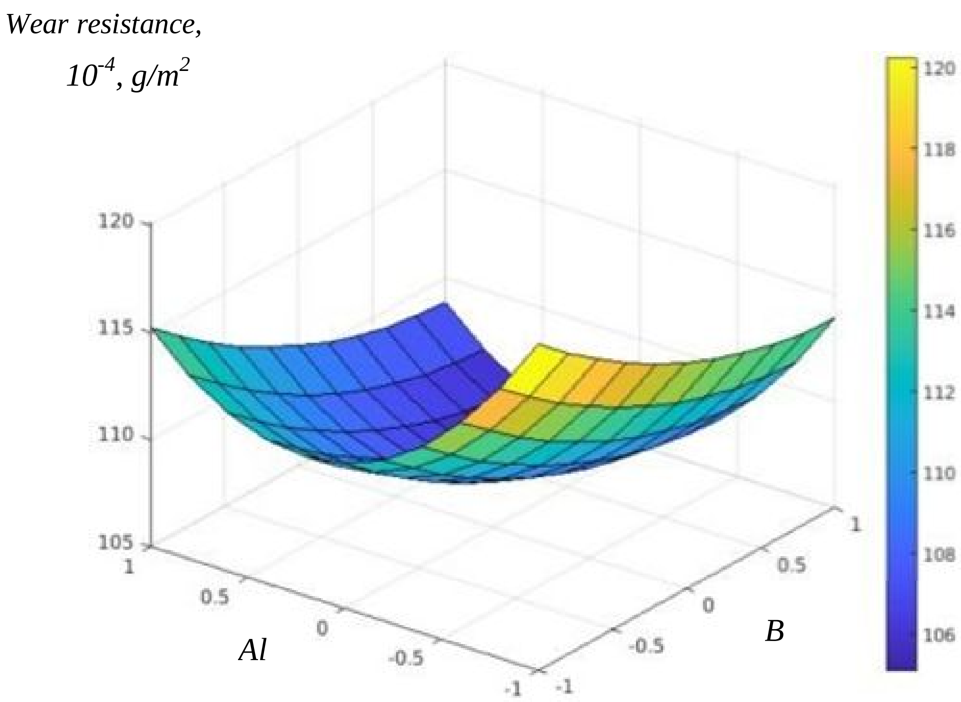

Fig. 2. Effect of Al and B content on wear resistance

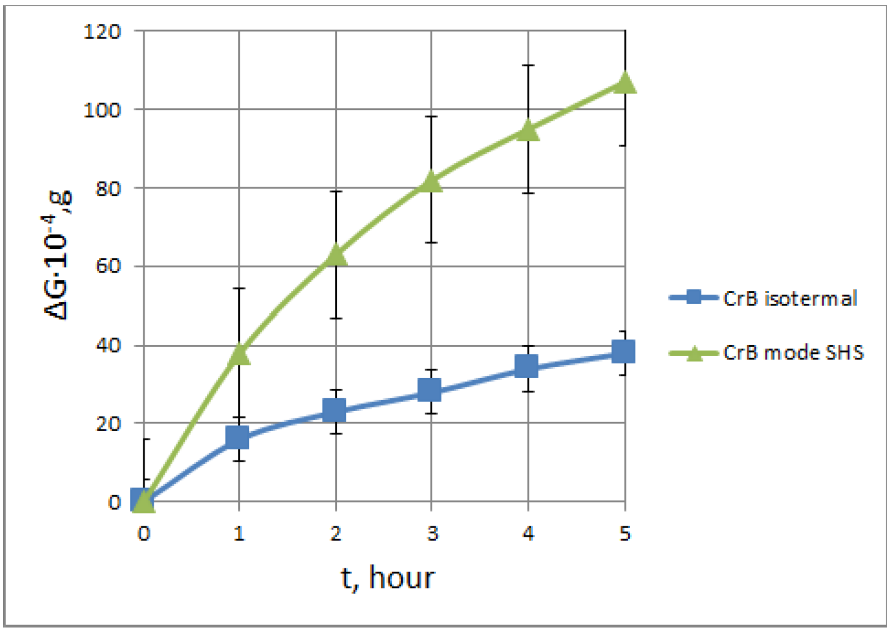

Fig. 3. Test results on the MT-5 friction machine

The counter body was made of G52986 steel with heat treatment to a hardness of 60—62 HRC. The load on the test specimen was P = 50N. The average speed of the test specimen was 0.19 m/s. During the first 30 minutes, the specimens were prefabricated, and then the specimens were tested for 5 h. At each entry of the sample, its impact dynamic loading was performed. The machine is designed for testing metals, alloys and rigid structural plastics with data recording in a PC. The machine consists of a test setup, a control panel and a data acquisition system for PC registration.

The principle of operation of the machine is the abrasion of a pair of samples pressed against each other with a given force. The samples were weighed every hour of the test, on an analytical balance VLR-200 with an accuracy of 10^{-4} g. When testing the disk-disk pair, both samples rotate, both with and without slippage, and in the disk-pad and shaft-bushing pairs, the samples-pad and sleeve are stationary [8].

During the research on the MT-5 friction machine, samples with a coating obtained under isothermal conditions and with a coating under SHS conditions were tested for 5 hours of experiment. The amount of wear of chromium-doped boron coatings obtained under SHS conditions is $35\text{-}40{\cdot}10^{-4}$ g/m^2, and with a coating obtained under isothermal conditions is 2.5-2.7 times higher, and is $105\text{-}115{\cdot}10^{-4}$ g/m^2.

Conclusions

1. Research has been conducted to increase the operational durability of mechanical equipment for cutting metal on parallel shears of rolling mill 1680 used in the cold rolling process.
2. Various methods of strengthening the elements of machines and mechanisms that provide increased reliability and durability of metallurgical equipment are considered and evaluated. Efficiency of application of functionally active coatings obtained by self- propagating high-temperature synthesis to increase wear resistance and reduce energy consumption in the operation of parallel blade shears was determined.
3. Design features and principles of operation of the rolling mill stand 1680, including rolls, support mechanisms, pressure devices, balancing systems, drive mechanisms and rolled thickness control, were studied.
4. Experimental studies were conducted on the wear resistance of A473 (440C) steel with a protective chromium-boron coating. During tests on the MT-5 friction machine, it was found that the wear resistance of coatings obtained in the SHS process is significantly higher than that of coatings obtained under isothermal conditions. The wear rate of the coatings created by the SHS method is $35\text{-}40 \cdot 10^{-4}$ g/mI.
5. Mathematical modeling was performed to determine the optimal composition of the SHS charge, which ensures the formation of coatings with high wear-resistant properties.

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