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MATHEMATICAL SIMULATION OF WELDED DEPOSIT LAYERS AS FOR ADAPTATION OF MATERIALS TO FAILURE IN QUASIDISSIPATIVE TRIBOSYSTEMS

Purpose. To establish mathematical models for the adaptation of materials under conditions of activation of a metastable structural-phase state of quasi-dissipative tribosystems. Determination and substantiation of factors for planning an active experiment due to which it is possible to create mathematical models of stable forecasts for increasing the wear resistance of materials.

Research methods. When conducting the experiments, a priori data were used in combination with our own scientific developments of mathematical models of the dependences of the influence of the chemical composition of alloys during manual and automatic electric arc surfacing on the physical and mechanical properties of the surface layer of the material, which is destroyed under tribosystem conditions. It was decided to use mathematical planning of research on the basis of an active experiment with the creation of models for the numerical description of the mathematical expectation in the form of regression equations.

Obtained results. On the basis of theoretical and practical scientific research with planning a passive and active experiment, a set of relevant knowledge has been obtained, which makes it possible to determine the main criterion requirements for the sensitivity of deposited steels and alloys to adaptation under the action of external mechanical and energy influences and allows to mathematically describe the characteristics of the alloy and provide a numerical estimate of the correlation parameters among themselves. On the basis of the theory of scientific mathematical planning of the experiment, a set of corresponding experiments was carried out, which made it possible to build spatial graphic models.

Scientific novelty. For the first time, theoretical and practical scientific research is presented with the reproduction of a systemic multivariate analysis of the parameters of mathematical models and processes leading to the martensitic ($\gamma \rightarrow \alpha$) transformation and determines the substantiation of the chemical composition of the deposited materials to increase fracture resistance under conditions of quasi-dissipative and dissipative tribosystems.

Practical meaning. The obtained results of the above studies allow, within the framework of technical and technological accuracy, which is necessary within the framework of practical engineering forecasts, to determine the physical and mechanical properties of wear-resistant deposited alloys under conditions of quasi-dissipative and dissipative tribosystems.

Key words: wear resistance, alloy, weld metal, mathematical model, prediction, regression equation, martensite, austenite, ($\gamma \rightarrow \alpha$) transformation, hardness.

Formulation of the problem

Alloys with high initial hardness generally have high wear resistance, but the exception to this general rule are alloys, in the structure of which a significant amount of retained austenite is formed. In the process of wear of such steels with a metastable austenitic structure under the influence of the energy of abrasive grains on the friction surface, deformation martensite may form.

This process is closely related to the redistribution of energy costs, that is, its dissipation, which triggers

mechanisms that strengthen the working surface of the parts.

The sensitivity to the adaptation of steels and alloys to external mechano-energetic influences, leading to the martensitic ($\gamma \rightarrow \alpha$) transformation, depends on the temperature of the martensite point, which is largely determined by the content of carbon and alloying elements in the solid solution.

The formation of deformation martensite is accompanied by a complex shear in the crystal lattice of metastable austenite. With an external force during wear,

the metal of the working surface receives the energy necessary for the ($\gamma \rightarrow \alpha$) transformation [2, 3].

Analysis of the dependence of the mass fraction of martensite on the magnitude of the deformation stresses (Fig. 1) showed that an increase in the mass fraction of martensite is observed in proportion to the deformation stresses of the material.

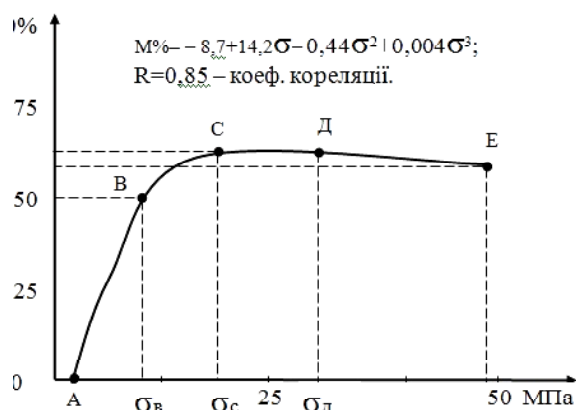


Fig. 1. Dependence of the mass fraction of martensite on the strain stress

A further increase in stresses in the B-C section causes a slight increase in the mass fraction of deformation martensite. And with an increase in stress over 20 MPa, the deformation martensite content on the material surface practically does not increase. Dangerously high voltages can be reproduced in this area, which can provoke destruction of the metal. An increase in deformations above critical ones will always cause destruction of the material [1].

Thus, we need to provide such deformation stresses that do not exceed the stresses corresponding to point C, and are included in the interval B-C.

At high temperatures in the contact zone, the formation of deformation martensite will be difficult; therefore, heterogeneous wear-resistant alloys with a large amount of a hardening phase are used.

Research methods

It is very important for the study of this topic the construction of a multicriteria mathematical model of the tribosystem based on an active experiment [6].

Planning a multiobjective equation should have a clear algorithm. The first stage includes the analysis of each of the systems: metallurgical, tribotechnical, technological, operational, economic. After that, they are differentiated and the main criteria are selected, which to the greatest extent determine the process of metal destruction in this particular case of the operation of parts. After checking the factors for compatibility and correlation, they are encoded and the variation intervals are selected. The model can be of several types: differential, fractional rational, trigonometric, or polynomial. The design matrix of the experiment can be full factorial or fractional factorial, which takes into account the number of interactions between factors.

Next, it is necessary to find out the deviation of the results from the arithmetic mean, that is, the total variance of the reproducibility of the experiment. It characterizes the dispersion of the results of experiments at a certain combination of factor levels. If the comparative number of variances is more than two and one variance significantly exceeds the others, then Cochran's test can be used to determine their homogeneity. If this criterion is not met, it is necessary to increase or decrease the number of parallel experiments.

After calculating the matrix, it is necessary to check the adequacy of the model according to Fisher's criterion and to assess the significance of the coefficients of the equation. Compliance with all criteria allows you to build a linear equation. An insignificant coefficient at a factor means that this factor does not affect, or does not significantly affect the optimization parameter. However, the value of the regression coefficient is influenced not only by the role of this factor, but also by the selected interval of variation. This means that with very narrow limits, the change in the optimization parameter can indeed be very small. However, this alone cannot yet conclude that the factor is insignificant. Therefore, the statistical signal of the factor should be verified, if possible, or at least analyzed from a technological point of view. That is, before the full factorial experiment, star or null points are added, followed by a central compositional orthogonal or rotatable second order planning. At the end, a quadratic equation is obtained. With the further insignificance of the coefficients, the degree of the equation is increased to the third order plan, and so on.

An attempt was made to reproduce the mathematical equation of the dependence of wear resistance, hardness and the amount of the hardening phase on external conditions. The regression equations were made with a certain tolerance, because we used the data of standard materials such as Cr12 and Cr12V (these steels are already studied) with certain assumptions, so that we can identify the effect of the chemical composition on the parameters we have chosen.

In abrasive wear with semi-fixed abrasives, there is no clearly expressed nature of the destruction mechanism, since the particle constantly changes its position in space, alternating cutting edges, the contact area, the angle of attack at which it interacts with the friction surface. As a result, the wear mechanism consists of microlocal loads, plastic deformation and microcutting. When certain conditions coincide, the abrasive particle is temporarily jammed, and the destruction of the friction surface is carried out under the influence of the fixed abrasive. This mechanism of force interaction of the abrasive with the surface layer is typical for most parts of road construction equipment - mixer blades, runner scrapers, grinder knives, feeder augers, et al. [4, 5, 7-9].

Therefore, the optimization parameter is assumed to be relative wear resistance ε , hardness of the deposited metal HRC, amount of hardening phase,%. And as the main

independent factors were chosen: the content of carbon, manganese and boron in the deposited metal. Steel 45 in the annealed condition was chosen as the standard. The relative wear resistance of this steel: $\varepsilon = 1.00$.

Optimization of the chemical composition of the deposited metal makes it possible to find the maximum values of the relative wear resistance under specific wear conditions.

The complexity of the abrasive fracture mechanism is associated with the lack of clear criteria and methods by which it is possible to reliably assess the ability of materials to resist wear, referring to its physical and mechanical properties, chemical composition and structural state.

Of primary importance is the property of the material to resist the penetration and movement of abrasive particles along the friction surface. This set of characteristics is determined by the resistance of the metal to elastic and plastic deformation. In this case, an indicative characteristic is the aggregate hardness of the alloy, as well as the hardness of its individual structural components, initial, or obtained in the process of operation.

Optimization of the chemical composition of the deposited metal makes it possible to find the maximum values of the relative wear resistance under specific wear conditions.

At the same time, the regression equation does not allow investigating the mechanism of the influence of individual factors on the physical and mechanical properties of alloys, therefore, in this case, when planning the experiment, such alloying elements were taken as variables, the influence of which on the properties of wear-resistant materials was studied, and it is only necessary to establish their mutual influence on the wear resistance of materials specified in the conditions of abrasive wear.

The mass fraction of chromium in all experiments remained constant and equal to 14 %. This is due to the fact that the introduction of chromium into the deposited metal is necessary

for the formation of chromium carbides, borides or carboborides, while its content in the alloy must be limited to 13–16%, since it has been established that an increase in the chromium content of more than 15–20 % does not lead to a significant increase in wear resistance.

The lower doping level with carbon (C) and boron (B) was set to 1.0 and 0.5%, respectively. A lower level of alloying with these elements determines a significant decrease in the amount of the hardening excess phase or its complete absence, causes an unreasonable increase in the factor space in the region of alloys with due to low wear resistance under conditions of abrasive wear without significant shock loads.

The upper level of carbon doping was limited to 3.5 %. A further increase in the carbon content in the alloys is impractical, since this leads to an increase in the eutecticity of the alloys, an increase in the size of the excess phase, and the appearance of free carbon in the alloys, which is located along the grain boundaries between the excess and strengthening phases and the matrix. All this causes significant embrittlement of the metal and a decrease in performance and wear resistance.

The maximum wear resistance of alloys of the Fe-C-Cr system doped with boron corresponds to a boron concentration of 2.5...5 %. Since at present the task was to study the question of the possibility of reducing the boron content in alloys of the Fe-C-Cr-B system, without reducing their wear resistance, the upper level of boron alloying was limited to 3.0 %.

The choice of variation intervals with manganese 0...1.3% is due to the fact that at a content of more than 1.5 %, it stabilizes the austenite γ - region and significantly reduces the position of the martensite point.

The average values of the mass fraction of elements in the deposited metal and the results of the experiment are shown in Table 1.

The results of the statistical check are shown in Table 2.

Table 1 – Average values of the mass fraction of elements in the deposited metal and the results of the experiment

№	The name of the alloy	The average mass fraction of elements in the weld metal, %					Hardness HRC	Phase composition, %				Relativ. wear resistance, ε	Strengthening phase, %
		C	Cr	B	Si	Mn		Before the test		After the tests			
								α	γ	α	γ		
1	ЭН-ИТС-01	3,50	14	0,50	-	-	60	75	25	90	10	5,90	65
2	КБХ-45	2,30	14	1,90	-	0,36	65	90	10	95	5	6,20	70
3	ЭН Т-620	3,25	14	1,20	2,20	1,10	55	65	35	80	20	5,60	55
4	ЭН Т-590	2,75	14	1,50	0,65	1,30	52	90	10	100	-	5,40	50
5	III-AH104	1,80	14	0,50	3,00	0,60	50	60	40	65	35	3,60	15
6	ЭН-180Cr14B3	1,60	14	3,00	-	-	63	70	30	75	25	7,10	65
7	III-Cr12V1	1,35	14	0,50	1,93	0,65	45	50	50	60	40	2,15	12
8	III-AH170	1,00	14	2,70	0,60	0,65	61	45	55	60	40	6,50	50

Table 2 – The results of statistical verification of regression equations

For the equation	Cochren's criterion		Fisher's criterion		Confidence interval $\pm \Delta b_{ij}$	Dispersion	
	$G_{p \text{ розр}}$	$G_{\text{табл}}$	$F_{p \text{ розр}}$	$F_{\text{табл}}$		Adequacy, $S^2_{\text{ад}}$	Reproducibility, $S^2_{\text{в}}$
ε	0,22	0,68	0,24	5,32	0,21	0,062	0,259
HRC	0,30	0,68	0,74	5,32	24,53	22,41	30,00
K	0,52	0,68	0,07	5,32	13,90	1,238	17,00

Thus, as a result of processing the results of the experiment planning matrix after testing, as a result of the static nature of the dependencies, the following adequate regression equations were obtained:

$$\begin{cases} \varepsilon = 0.695 + 1.47C + 2.36B - 2.07Mn - 0.64CB + 0.546CMn + 0.573BMn - 0.208CBMn \\ HRC = 38.7 + 5.8C + 7.6B - 5.77Mn - 1.66CB + 0.846CMn + 3.46BMn - 1.69CBMn \\ K = -39.25 + 29.5C + 33.5B + 3.808Mn - 9CB - 2.846CMn - 4.154BMn + 0.31CBMn, \end{cases} \quad (1)$$

where C is the mass fraction of carbon, %; B – mass fraction of boron, %; Mn – mass fraction of manganese, %.

To study the entire factor space of the influence of alloying elements C, B and Mn on the physical and mechanical properties of the alloys, spatial diagrams (response surfaces) of the mutual influence of the chemical composition for the relative wear resistance ε were built (Figure 2).

Analysis of calculations and sections of response surfaces (Fig. 2) showed that the maximum value of the relative wear resistance is achieved at the following mass fraction of the deposited metal, %: Cr = 12; C = 1.6; B = 3 Its phase composition to the test was 70/30 % and 75/25 % of the α and γ phases, respectively. The microhardness of the hardening phase is 21 GPa.

As we can see, the martensitic transformation is very weak and almost insignificant. The increased stability of austenite, in comparison with the optimal one, reduces the resistance to fracture, which is explained by the fact that in this case, martensitic transformations cannot provide the required degree of stress relaxation and energy consumption of external interaction.

A significant effect on the strengthening of austenite, its stability with respect to dynamic deformation martensitic transformations and, accordingly, the properties of alloys with unstable austenite are carried out by the previous cold and warm plastic deformations. Depending on the mode of their implementation, they can stabilize or destabilize austenite and ambiguously affect the properties [5].

To reduce the amount of austenite and its stability, the following technological methods are used:

- decrease in heating temperature for hardening;
- cold treatment;
- aging for phase separation;
- deformation to obtain stacking faults, a small amount of martensite phases and depletion of austenite in alloying elements [4].

Findings

The task of adapting materials to external wear conditions is to predict the effect of external load conditions in combination with $\gamma \rightarrow \alpha$ transformation processes, at which the maximum production of deformation martensite in the working metal layer will be achieved.

Analysis of the data, when comparing the initial and final amounts of retained austenite, shows that it is decreasing. At the same time, the degree of this hardening under the most favorable conditions, when the volume of transformations of unstable austenite is maximum, still does not provide a sufficiently high microhardness. However, the use of an unstable austenitic structure in combination with martensite and a hardening solid phase is the optimal solution.

Therefore, it is very important to control the structure and development of martensitic transformations in alloys, because this will significantly improve their technological properties. But the process of scientific research and proof of these phenomena requires a deeper study.

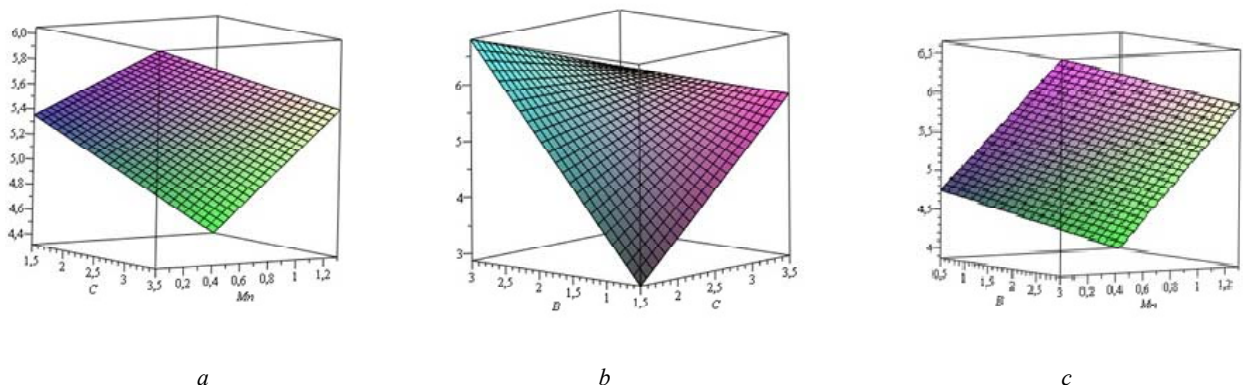


Fig. 2. Dependence of the relative wear resistance at a constant content of boron (a), manganese (b) and carbon (c)

Bibliography

1. Попов С. М. Триботехнічні та матеріалознавчі аспекти руйнування сталей і сплавів при зношуванні: Навчальний посібник / С. М. Попов, Д. А. Антонюк В. В. Нестребо. – Запоріжжя : ЗНУ, ВАТ «Мотор Січ», 2010. – 368 с.
2. Тененбаум М. М. Износостойкость конструкционных материалов и деталей машин при абразивном изнашивании / Тененбаум М. М. – М. : Машиностроение, 1966. – 332 с.
3. Малинов Л. С. Ресурсосбережение за счет применения экономнолегированных сплавов и упрочняющих технологий, обеспечивающих получение многофазных метастабильных структур и управление структурными и фазовыми превращениями (обзор) / Л. С. Малинов, В. Л. Малинов // Нові матеріали та технології в металургії та машинобудуванні. – 2011. – № 1. – С. 93–105.
4. Аналіз характеру зношування і визначення основних критеріїв працездатності скребків бетонозмішувачів / С. М. Попов, С. О. Шумикін, І. М. Білоник, Є. Я. Губар // Нові матеріали і технології в металургії та машинобудуванні. – 2018. – №2. – С. 84–92.
5. Popov S. N. Study of the features of the wear of a friction pair of a drive wheel with a mover caterpillar under abrasive conditions / S. N. Popov, S. O. Shumykin // Нові матеріали і технології в металургії та машинобудуванні. – 2020. – №1. – С. 49–54.
6. Баратокритеріальний підхід до аналізу визначення основних критеріїв зношування деталей / С. М. Попов, С. О. Шумикін, І. М. Білоник, О. М. Захаренко // Scientific achievements of modern society. Abstracts of the 6th International scientific and practical conference (February 5–7, 2020). Cognum Publishing House. Liverpool, United Kingdom. 2020. – P. 1048–1053.
7. Popov S. Technology for increasing abrasive wear resistance of parts of road construction machines / S. Popov, S. Shumykin, R. Sule // Perspectives of world science and education. Abstracts of the 8th International scientific and practical conference (April 22–24, 2020). CPN Publishing Group. Osaka, Japan. – 2020. – P. 129–132.
8. Popov S. The process of contact interaction on the friction surface as for blades of coal fans / S. Popov, S. Shumykin, I. Mozgovaya // Modern science: problems and innovations. Abstracts of the 3rd International scientific and practical conference (June 1–3, 2020). SSPG Publish. Stockholm, Sweden. – 2020. – P. 178–181.
9. Popov S. Fracture analysis of friction surfaces of tracks of caterpillar mechanisms during abrasive wear / S. Popov, S. Shumykin, N. Kotov // Actual trends of modern scientific research. Abstracts of the 5th International scientific and practical conference (November 8–10, 2020). MDPC Publishing. Munich, Germany. – 2020. – P. 131–135.

Одержано 21.12.2020

Попов С. М., Шумикін С. О., Лаптева А. М. Математичне моделювання наплавлених шарів при адаптації матеріалів до руйнування в квазідисипативних трибосистемах

Мета роботи. Встановлення математичних моделей адаптації матеріалів за умов активації метастабільного структурно-фазового стану квазідисипативних трибосистем. Визначення та обґрунтування чинників для планування активного експерименту за рахунок яких можливе створення математичних моделей стабільних прогнозів щодо підвищення зносостійкості матеріалів.

Методи дослідження. При проведенні дослідів були використані апріорні данні в комплексі з власними науковими розробками математичних моделей залежностей впливу хімічного складу сплавів при ручному і автоматичному електродуговому наплавленні на фізико-механічні властивості поверхневого шару матеріалу, що руйнується в умовах трибосистем. Було вирішено використовувати математичне планування досліджень на основі активного експерименту зі створенням моделей чисельного опису математичного очікування в вигляді рівнянь регресійних залежностей.

Отримані результати. На основі проведених теоретико-практичних наукових досліджень з плануванням пасивного та активного експерименту отримано комплекс відповідних знань, який дозволяє визначити основні критеріальні вимоги чутливості наплавлених сталей і сплавів до адаптації під дією зовнішніх механо-енергетичних впливів та дозволяє математично описати характеристики сплаву і надати чисельну оцінку кореляції параметрів між собою. На основі теорії наукового математичного планування експерименту проведено комплекс відповідних дослідів, який дозволив побудувати просторові графічні моделі.

Наукова новизна. Вперше наведено теоретико-практичні наукові дослідження з відтворенням системного багатofакторного аналізу параметрів математичних моделей та процесів, що приводять до мартенситного ($\gamma \rightarrow \alpha$) перетворення та обумовлює обґрунтування хімічного складу наплавлених матеріалів для підвищення здатності до опору руйнуванню в умовах квазідисипативних та дисипативних трибосистем.

Практичне значення. Отримані результати наведених досліджень дозволяють в рамках технічної і технологічної точності, що необхідна в рамках практичних інженерних прогнозів, визначити фізико-механічні властивості зносостійких наплавлених сплавів в умовах квазідисипативних та дисипативних трибосистем.

Ключові слова: зносостійкість, сплав, наплавлений метал, математична модель, прогнозування, рівняння регресії, мартенсит, аустеніт, ($\gamma \rightarrow \alpha$) перетворення, твердість.

Попов С. Н., Шумикин С. А., Лаптева А. Н. Математическое моделирование наплавленных слоев при адаптации материалов к разрушению в квазидиссипативных трибосистемах

Цель работы. Установление математических моделей адаптации материалов в условиях активации метастабильного структурно-фазового состояния квазидиссипативных трибосистем. Определение и обоснование факторов для планирования активного эксперимента за счет которых возможно создание математических моделей стабильных прогнозов по повышению износостойкости материалов.

Методы исследования. При проведении опытов были использованы априорные данные в комплексе с собственными научными разработками математических моделей зависимостей влияния химического состава сплавов при ручной и автоматической электродуговой наплавке на физико-механические свойства поверхностного слоя материала, который разрушается в условиях трибосистем. Было решено использовать математическое планирование исследований на основе активного эксперимента с созданием моделей численного описания математического ожидания в виде уравнений регрессионных зависимостей.

Полученные результаты. На основе проведенных теоретико-практических научных исследований с планированием пассивного и активного эксперимента получено комплекс соответствующих знаний, который позволяет определить основные критериальные требования чувствительности наплавленных сталей и сплавов к адаптации под действием внешних механо-энергетических воздействий и позволяет математически описать характеристики сплава и предоставить численную оценку корреляции параметров между собой. На основе теории научного математического планирования эксперимента проведен комплекс соответствующих опытов, который позволил построить пространственные графические модели.

Научная новизна. Впервые приведены теоретико-практические научные исследования с воспроизведением системного многофакторного анализа параметров математических моделей и процессов, приводящих к мартенситному ($\gamma \rightarrow \alpha$) преобразованию и обуславливают обоснование химического состава наплавленных материалов для повышения сопротивляемости разрушению в условиях квазидиссипативных и диссипативных трибосистем.

Практическое значение. Полученные результаты приведенных исследований позволяют в рамках технической и технологической точности, которая необходима в рамках практических инженерных прогнозов, определить физико-механические свойства износостойких наплавленных сплавов в условиях квазидиссипативных и диссипативных трибосистем.

Ключевые слова: износостойкость, сплав, наплавленный металл, математическая модель, прогнозирование, уравнение регрессии, мартенсит, аустенит, ($\gamma \rightarrow \alpha$) преобразования, твердость.