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The effect of manganese and carbon on the mechanical properties of the welded layer of the bucket teeth of the Hadfield steel excavator

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Abstract

The paper investigates the effect of the surfacing composition's chemical structure (the manganese and carbon concentrations' ratio) on the mechanical properties of the surfacing layer on Hadfield steel for increasing the durability of the products made from it, namely the excavator bucket's teeth. Two criteria, namely the impact toughness and wear resistance of the coating, were chosen as optimization parameters. The assessment of the impact strength of the deposited coating was carried out on the Sharpie samples on the pendulum copra, and the wear test was carried out according to the Brinly-Haworth scheme in the conditions of samples' abrasion with quartz sand. Wear resistance of Hadfield steel, containing 1.1% *C* and 13% *Mn*, was taken as a unit of wear resistance in these experiments. To determine the optimal coating modes, the active experiment with the application of mathematical planning methods was conducted. The obtained response surfaces and graphs of equal output lines make it possible to establish the level of studied factors' influence on the optimization parameter. In order to analyze the influence of given factors on the optimization criteria, scatter plots with histograms were constructed, which make it possible to determine the rational values of the selected optimization criteria graphically - impact toughness and wear resistance of the coating.

Key words: teeth of the excavator bucket, Hadfield steel, deposited layer, manganese, carbon, impact toughness, wear resistance, optimal parameters

Introduction

Meeting the requirements for soil treatment largely depends on the efficiency and condition of the tillage machines' working bodies. Increasing their durability and ensuring proper recovery are critically important for the agro-industrial complex (AIC) of Ukraine. This task becomes especially vital taking into account the specific operating conditions of the tillage machines, which work in environments that contribute to rapid wear and huge production scales (millions of pieces).

Open pit mining is the most efficient way of extracting minerals. The most important part in the technological chain of open-pit mining is the excavation process; its continuity is largely determined by the durability of the replaceable bucket teeth of quarry excavators that experience direct interaction with the rock. When excavating a planted mass of particularly strong and abrasive rocks, the teeth of the excavator bucket work in extreme conditions of abrasive wear (a large number of favorably oriented cutting edges on the surface of planted rock's fragments, the dominant role of metal micro-cutting, intense shock loads, etc.), which causes their rapid failure. The intensity of tillage machines' wear is significantly influenced by the type of cultivated soil, its granulometric composition, stress-strain state, and the material of the tillage machines [1].

The destruction of a piece of rock occurs during collision and abrasion with the working body and they are used for the destruction of materials with a compressive strength limit of up to 125 *MPa*.

The investigation of the wear process of bucket teeth made of steel 45, 85, Hadfield steel, high-strength cast iron, showed that their outer surface (ends and side walls) perceive the impact of abrasive particles at the angle from 5 to 60°, and the working surface - at a straight angle [2].

During wear and tear, a characteristic microrelief is formed on their surface. When struck at an angle from 5 to 60°, the pits and streaks have a distinct directionality, and at 90° - a uniform bumpy appearance with traces of repeated direct introduction of abrasive particles of different weights.

In most cases, the performance of working bodies is determined by time. Therefore, the most important task for increasing labor productivity in the processing is to increase the wear resistance of parts in conditions of shock-abrasive wear. The amount of bucket tooth loss due to wear can reach up to 1/3 of its initial weight.

During the development of ferruginous quartzites, the service life of a set of bucket teeth of quarry excavators with a total weight of 1 ton makes up 2-3 days, and the weight of worn metal relative to the total weight of the teeth does not exceed 15%. Increasing their durability will give a significant economic effect and, therefore, is quite vital [2].

The bucket teeth of quarry excavators are a defining product representing a whole group of parts made of Hadfield steel, hardened to austenite and possessing a unique combination of viscosity and wear resistance. Since its creation, this steel has not found worthy substitutes in the production of solid-cast parts that work in extreme conditions of abrasive wear with shock loads.

The high wear resistance of this steel is explained by the exceptional ability of manganese austenite to undergo plastic deformation by means of homogeneous and multiple sliding and to strong hardening during slander, which occurs simultaneously with plastic deformation (without yielding). But in the conditions of the absence of dynamic or large specific static loads, the wear resistance of steels of this type is low, approximately the same as that of steel 45. Therefore, the teeth of excavators' buckets which work under weak shock loads have low wear resistance.

As for the teeth of the quarry excavators' buckets, the design and material of wear-resistant areas, in addition to their direct purpose, must provide an acceptable level of bearing capacity of the teeth of the quarry excavators' buckets as a whole.

Increasing the operational characteristics of the steel surfaces of the teeth of excavators working in difficult conditions of abrasive wear and significant shock loads can be achieved by electric arc welding of coatings with highly alloyed floatings. When developing electrode materials for surfacing, an important aspect is to ensure a chemical composition that matches the basic material as much as possible. Chromium, nickel, manganese, molybdenum are key alloying elements that help increase the hardness and wear resistance of the deposited layer. Coatings obtained by electric arc deposition have a structure consisting of solid carbide particles that provide resistance to abrasive wear. Self-strengthening of coatings (slander effect) during operation under shock loads is especially important for high-manganese steels. Prospects for the application of electric arc surfacing are the following:

- the development of the new electrode materials and improvement of surfacing technologies in order to reduce cracks and internal defects;
- optimization of the coatings' composition to improve their wear resistance with simultaneous maintaining impact toughness, which is critically important for work surfaces operating in extreme conditions.

Thus, electric arc surfacing remains the leading method in the field of surface engineering for increasing the wear resistance of steel surfaces operating under difficult conditions of abrasive wear and shock loads.

The purpose of this paper is to study the influence of manganese and carbon content on the impact toughness and wear resistance of the deposited layer on Hadfield austenitic manganese steel in order to increase the durability of the excavator bucket teeth.

Literature review

The problem of the optimal ratio of manganese and carbon concentrations specifically in the deposited layer on Hadfield steel is not fully investigated, although research in this direction was carried out by V. A. Loktionov-Remizovskyi, N. V. Kiryakova, G. E. Fedorov and their colleagues [3]. A comparative analysis of topographic projections of mechanical properties (strength limits, yield limits and impact toughness) of austenitic manganese steels with their structural diagrams has been made in the research. This allows us to understand the relationship between the structural characteristics of the material and its mechanical properties. The concentration range of Hadfield steel (in particular, the content of manganese and carbon regulated by Ukrainian standards) has been compared with the structural diagram of manganese steels. These analyzes help to evaluate how changes in the chemical composition and structure of the steel affect its performance characteristics, such as strength and toughness. It was found out that in order to increase the stability of the structure, as well as to achieve constant levels of properties of Hadfield steel (such as strength, viscosity and other important characteristics) from melting to melting, it is necessary to optimize the carbon content. In particular, it is proposed to raise the lower limit of carbon content to 0.95% and lower the upper limit to 1.25%. Meanwhile, according to DSTU (National Standard of Ukraine) 8781:2018, the carbon and manganese content can vary from 0.9 to 1.5% and from 11.5 to 15.0%, accordingly. This will ensure better repeatability of the properties of cast parts in the entire range of carbon and manganese content regulated by the Ukrainian standard.

It is considered that the most optimal materials for depositing coatings on high-manganese steel parts are those whose component composition can provide a significant amount of manganese austenite in the coating [4].

However, despite the wide selection of electrode materials, such as EN14700 T Fe 9, OK Tubrodur 14 and others, intended for the application of wear-resistant coatings by the electric arc deposition method, the range of materials suitable for operation under conditions of shock loads is quite limited. Such materials are mainly represented by alloys of the Fe-13Mn-1C system (iron-manganese alloys with a content of 13% manganese and 1% carbon). The best mechanical properties of these alloys are achieved under the conditions of formation of a single-phase austenite structure. As described in the studies [5] of the cast steel microstructure without heat treatment, the ferrite-carbide mixture is released mainly along the boundaries of austenite grains; this makes these boundaries more brittle and prone to destruction. The mixture of ferrite and carbide has a high dispersion and lamellar structure, where the interlamellar distance is 30±7 nm. This indicates that such a structure is eutectoid and is usually observed during cooling of steel, which contributes to a decrease in its plasticity. The presence of a ferrite-carbide mixture in the structure leads to a significant decrease in plasticity, and with its amount ~20 wt. %, the relative elongation decreases by 7 times.

In the research [6], in order to reduce the influence of the cementite phase on the formation of coatings of the Fe-12Mn-1.1C system during electric arc welding, a complex alloying of the electrode charge with vanadium (V) and silicon (Si) in amounts of 1.2% and 2 .4% by weight, accordingly. As a result, multilayer coatings were obtained, which consisted of austenite, which formed dendritic crystallites, and ferrite, which was located in the interdendritic space. Vanadium carbide (VC) in the amount of about 5.6% was localized in the central regions of austenitic dendrites in the form of faceted phases up to 2 μm in size. This carbide phase increased the hardness of coatings to the level of 31–34 HRC, which is 10 HRC units higher than the hardness of coatings with an unalloyed manganese austenite structure. However, a significant amount of ferrite (~28 vol. %) negatively affected the possibility of operational strengthening of coatings. The conclusion is that although alloying with carbide-forming elements such as vanadium ensures the absence of undesirable cementite phases and increases hardness, the presence of ferrite reduces the effectiveness of strain hardening. This indicates the need for further optimization of the composition to minimize the effect of the ferrite phase on the coating characteristics.

Results

In this workpaper, the influence of the chemical structure of the surfacing composition (the ratio of manganese and carbon concentrations) on the mechanical properties of the surfacing layer on Hadfield austenitic manganese steel was investigated in order to increase the durability of the products made from it, namely the teeth of the excavator bucket.

To assess the optimal ratio of manganese and carbon, and in a wider interval compared to DSTU (National Standard of Ukraine) 8781:2018, a number of laboratory tests of surfacing samples with manganese concentrations of 6.36...17.64% were carried out. The carbon content in each series was varied from 0.60 to 1.60%. For all samples, impact tests at + 20 ^{0}C were carried out, as well as wear tests according to the Brinly-Haworth scheme under the conditions of abrasion of samples with quartz sand. The wear resistance of Hadfield steel, containing 1.1% C and 13% Mn, was taken as a unit of wear resistance in these experiments.

The task of planning the experiment was mathematically formulated as follows: it is necessary to get an idea of the response surface of the factors, which can be shown in the form of a function or a mathematical model [7]:

$$M\{y\} = \eta = \varphi(x_1, x_2, x_3, ..., x_k), \tag{1}$$

where y – is the optimization parameter (in our case, the impact toughness (KCU) and wear resistance (I) of Hadfield steel, which is used to make the teeth of the excavator bucket); x_i – variable factors, that have strong impact on the response and which can be changed during the experiment (content in percent of carbon and manganese). Accordingly, the task is reduced to determining the dependence of the mathematical expectation of the process result on the parameters (factors).

Finding the functions that determine the relationship between the factors (carbon and manganese content in percentages) and the impact viscosity (KCU) and wear resistance (I) parameters, the area of homogeneity of the processes can be conveniently described by an expression in the form of a polynomial.

Since it is necessary to evaluate two factors, the task of conducting a two-factor experiment [7] arises, the factor levels are shown in Table 1.

Table 1

Levels of factors are intervals of variation

Factors	Levels				
	1,41	+1	0	– 1	– 1,41
x_1 – carbon content, %	1,6	1,45	1,1	0,75	0,6
x_2 – manganese content, %	17,64	16	12	8	6,36

According to the planning matrix, experiments are performed with provided factors. The test results are shown in Table 2.

Table 2

Experiment planning matrix in real values and test results

№	*C*, %	*Mn*, %	*KCU*, J/ cm²	*I*, relat. units
1	0,75	8	75	0,9
2	0,75	16	316	0,85
3	1,45	8	133	1,25
4	1,45	16	170	0,98
5	0,6	12	232	0,88
6	1,6	12	151	0,8
7	1,1	6,36	108	1,36
8	1,1	17,64	270	0,89
9	1,1	12	215	1,01
10	1,1	12	218	1,01

Data processing of the experiment and search for optimal values were made in the Statistica 6.0 program.

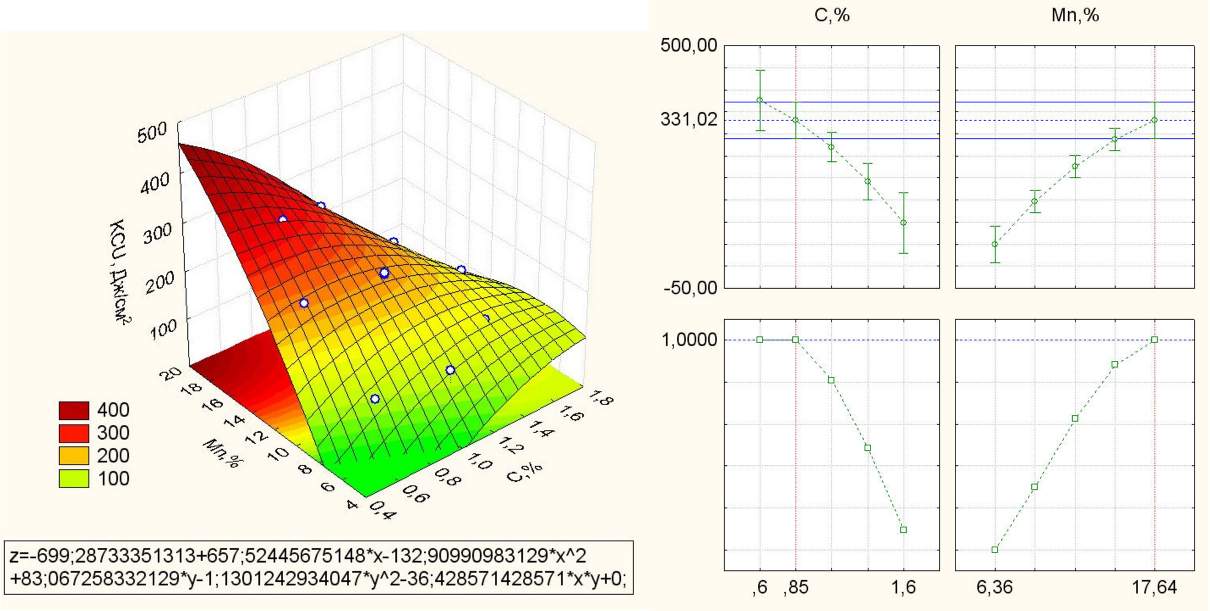
Thus, thanks to the two-factor experiment, a regression equation was obtained for the impact toughness (*KCU*) of the deposited layer depending on the carbon and manganese content, it is as follows:

$$KCU = -699{,}3 + 657{,}5C - 132{,}9C^2 + 83{,}1Mn - 1{,}1Mn^2 - 36{,}4C \cdot Mn\,. \tag{2}$$

And the regression equation for the intensity of wear of the deposited layer depending on the content of carbon and manganese is the following:

$$I = 0{,}46 + 2{,}05C - 0{,}66C^2 - 0{,}08Mn + 0{,}004Mn^2 - 0{,}04C \cdot Mn\,. \tag{3}$$

By means of the "Design Analysis of Experiments" module (experimental project) of this program, the influence of each of the factors on impact toughness (*KCU*) Picture 1 and wear resistance (*I*) Picture 2 was determined, and the optimal values of the factors were obtained.



a) b)

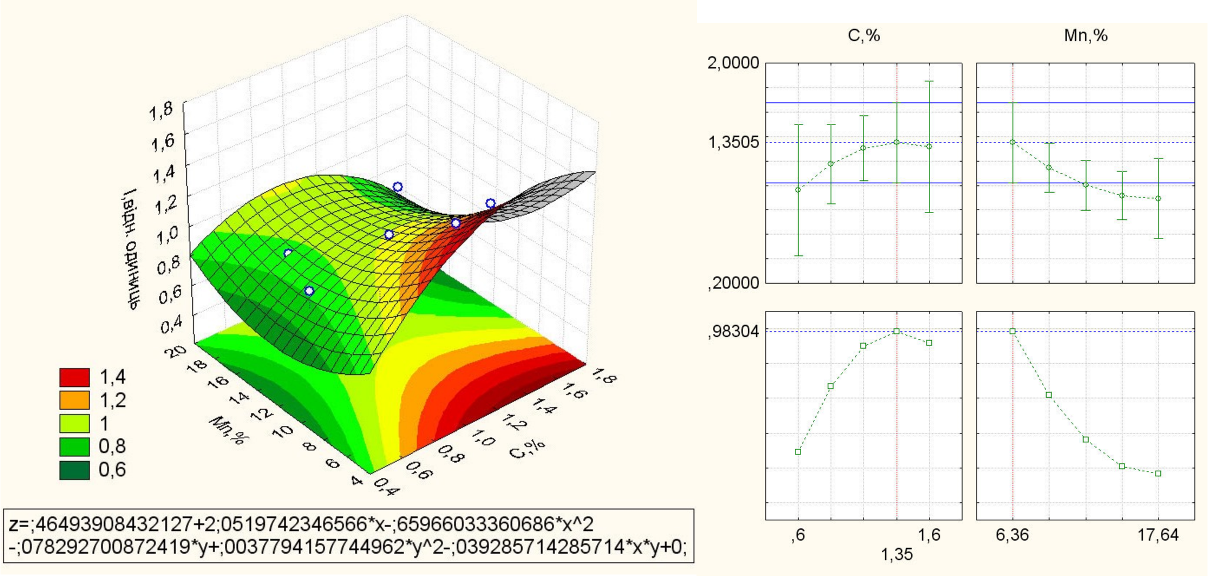
Fig.1. The influence of the ratio of manganese and carbon on the impact toughness of the deposited layer: a) response surface of the impact toughness (*KCU*) of the deposited layer; b) dot graphs with histograms characterizing the impact of the studied factors for impact toughness

In the course of the study, it was found out that the impact toughness (*KCU*) of manganese steels depends on the carbon content and changes along a curve with a maximum. This means that for each value of the manganese content there is an optimal carbon concentration at which the impact toughness reaches its peak. In particular, for steels with a manganese content of 13%, a carbon content of 0.85...1.0% is optimal. At the same time, an increase in the manganese content in general contributes to an increase in impact toughness at all carbon concentrations, except for the highest carbon concentrations (1.5...1.7%). The maximum values of impact toughness were obtained for steel containing 17...18% manganese and 0.6...0.7% carbon.

This indicates that the correct selection of carbon and manganese content is a key to achieving the maximum impact toughness of steel, which is an important factor in ensuring high mechanical stability of the material. It should be noted that even with a reduced manganese content (10.3...11.0% or 8.6...9.2%), the impact toughness of the samples can remain high provided that the carbon concentration is chosen correctly. In particular, with a carbon content of 1.0% for steel with 10.3...11.0% manganese and 1.3% for steel with 8.6...9.2% manganese, the impact toughness exceeds 150 J/cm². This suggests that such coatings can be economically viable for applying as cheaper materials, while maintaining the sufficiently high impact toughness required for many industrial applications.

The maximum wear resistance is observed in deposits with a manganese content of 6%. In such deposits, during abrasion, a surface martensite is formed, which significantly increases the hardness of the surface, providing increased resistance to wear. However, with a further increase in the manganese content, wear resistance begins to decrease.

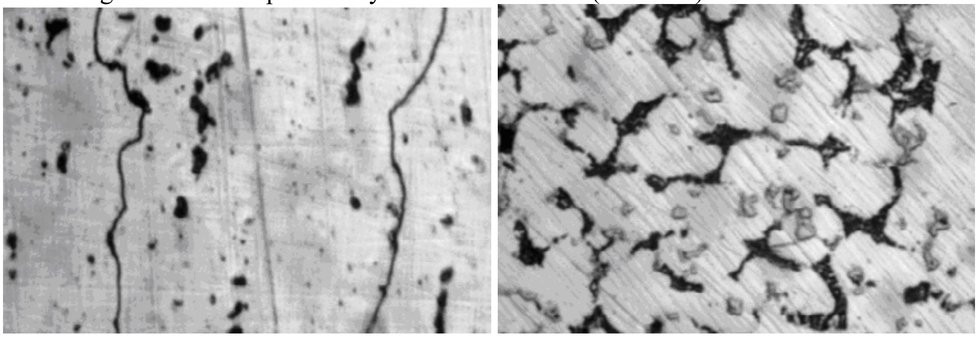
On the other hand, an increase in carbon concentration has a positive effect on wear resistance, which makes the carbon content an important factor for improving the performance characteristics of surfacing. Thus, the correct ratio of manganese and carbon is a key to achieving optimal wear resistance.



a) b)

Fig.2. The effect of the ratio of manganese and carbon on the impact wear resistance of the deposited layer: (a) response surface of the wear intensity of the deposited layer; (b) dot graphs with histograms characterizing the influence of the investigated factors on the intensity of wear

The investigation of the deposited layer's microstructure (Picture 3) showed the absence of hot cracks.



a) b)

Fig.3. Microstructure of the deposited layer: a) content: carbon – 0,85 %; manganese – 17,64 %; b) content: carbon – 1,35 %; manganese – 6,36 %.

As the manganese content decreases, hardness and wear resistance increase, but the structure tends to decrease the impact toughness.

Conclusions

By controlling the chemical composition of powder wire, it is possible to achieve different mechanical properties of the deposited layer of the excavator bucket teeth for different types of cultivated soil. So, to ensure the highest value of the impact toughness of the deposited layer (when processing hard soil rocks), the following concentration of powder wire elements is optimal: carbon - 0.85%; manganese - 17.64%, and to ensure the highest value of wear resistance of the deposited layer (when processing soft soil rocks), the optimal concentration of elements is as follows: carbon - 1.35%; manganese - 6.36%.

References

1. Posonskyi S., Babak O. (2017). Optimization of technological parameters of induction surfacing by composite powder of made from l53 steel working units of the soil-processing machines. *Problems of tribology*. Khmelnytskyi. KhNU, 85 (3). P.82-88.

2. Zagurskyi A. (2015). Increasing the wear resistance of the teeth of single-bucket excavators. *Student's Bulletin of NUVHP*. Rivne. NUVHP, 3 (5). P. 52-55.

3. Loktionov-Remizovskyi V., Kiryakova N., Fedorov G., Grybov M., Oleksenko I. (2020). Optimization of Carbon and Magganese Content in Steel 110G13L. *Casting processes*. Kyiv. NAS, 142 (4). P. 26-33, URL: https://doi.org/10.15407/plit2020.04.026

4. Prysiazhniuk P.M. Scientific basis of formation of wear-resistant coatings of the system "high-manganese steel - refractory compounds" by electric arc surfacing [dys. ... d-ra tekhn. nauk: 05.02.01]. 2024. 384 p. [Ukrainian]

5. S.H.M. Anijdan. (2018) The effect of heat treatment process parameters on mechanical properties, precipitation, fatigue life, and fracture mode of an austenitic Mn Hadfield steel. J. Mater. Eng. Perform. 27, P. 5246–5253. URL: https://doi.org/10.1007/s11665-018-3625-y

6. Rodríguez, M., Perdomo, L., Béjar, L., Moreno, J. A., Medida, A., Soriano, J. F., & Alfonso, I. (2017). Efecto del V y el Si sobre la microestructura de depósitos realizados con electrodos tubulares revestidos de alto contenido de Mn (Hadfield). *Soldagem & Inspeção*, 22(3), P. 249-257, URL: https://doi.org/10.1590/0104-9224/si2203.03

7. Vasylkovska K., Leshchenko S., Vasylkovskyi O., Petrenko D. Improvement of equipment for basic tillage and sowing as initial stage of harvest forecasting. *INMATEH – Agricultural Engineering*. 2016. 50 (3). P. 13-20. [English]

Посонський С.Ф. Вплив марганцю та вуглецю на механічні властивості наплавленого шару зубів ковша екскаватора зі сталі Гадфілда

В роботі виконано дослідження впливу хімічного складу наплавочної композиції (співвідношення концентрацій марганцю і вуглецю) на механічні властивості наплавленого шару на сталь Гадфільда з метою підвищення довговічності виготовлених з неї виробів, а саме зубів ковша екскаватора. За параметр оптимізації обрано два критерії, ударну в’язкість та зносостійкість покриття. Оцінку ударної в’язкості наплавленого покриття проводили на зразках «Шарпі» на маятниковому копрі, а випробування на знос за схемою Брінля-Хаворта в умовах стирання зразків кварцовим піском. За одиницю зносостійкості в цих експериментах прийнята зносостійкість сталі Гадфільда, що містить 1,1 % *C* і 13 % *Mn*. Для визначення оптимальних режимів нанесення покриття проводився активний експеримент з використанням методів математичного планування. Отримані поверхні відгуку та графіки ліній рівного виходу дають можливість встановити рівень впливу досліджуваних факторів на параметр оптимізації. Для аналізу впливу заданих факторів на критерії оптимізації побудовані графіки розсіювання з гістограмами, з яких можна графічно визначити раціональні значення обраних критеріїв оптимізації – ударну в’язкість та зносостійкість покриття.

Ключові слова: зуб ковша екскаватора, сталь Гадфільда, наплавлене покриття, марганець, вуглець, ударна в’язкість, зносостійкість, оптимальні параметри