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Preliminary communication

Determination of Optimal Hardfacing Modes for Recovering Electric Motor Shafts

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Abstract: The research aims to determine the optimal modes of hardfacing when restoring the shafts of electric motors, taking into account the resulting hardness of the deposited layer for further machining. When conducting a full-scale experiment on hardfacing, samples (200 × 100 × 10 mm) of steel 3 were used, which were preliminarily ground. For hardfacing, such hardfacing materials were used as 1/S - 7018, Sv-08G2S.The advantages and disadvantages of various surfacing methods are established. The hardness values of the deposited layer with material 1/S - 7018.1 were determined in manual hardfacing, with Sv08G2S material - in semi-automatic hardfacing in a protective gas environment (CO_2 - 100%), with Sv-08G2S material - automatic surfacing under the layer flux. It has been established that the most effective and economical method of surfacing during the restoration of electric motor shafts is a semi-automatic method in a carbon dioxide environment. Regression analysis was used to build a mathematical model for determining the optimal hardfacing modes, taking into account the hardness of the deposited layer. The correlation coefficients are determined, which indicate a strong linear relationship between the hardness of the deposited layer and such technological parameters as current strength, welding arc voltage, and effective power. For the first time, a mathematical model was obtained for the dependence of the hardness of the deposited layer on the technological parameters of the coating - current strength, voltage, and arc power. The existence of a connection between the technological parameters of surfacing has been established.

Keywords: current strength; hardfacing; hardness; mode; power; voltage

1 INTRODUCTION

Guided by the requirements of resource-saving technologies, a special place is given to the restoration and repair of parts [1, 2], which form the basis of the secondary production of parts [3, 4].

At present, in the machine-building, mining, and construction industries, electric motors are widely used that are excellent in terms of power output, torque, and design parameters. Often there is a situation of failure of the electric motor due to excess load on the main unit - the motor shaft, leading to jamming of the electric motor, or partial or complete destruction of the shaft [5]. First of all, the keyed and splined surfaces of the shaft are subjected to destruction, which leads to the appearance of such defects as: crushing of the splines, tearing out of the edges, scuffing on the shaft surface, and crushing of the groove faces [6]. Such phenomena lead to increased wear of the connected units, increased runout, and the development of abrasive wear [7].

It should be noted that the cost of restoring the motor shaft is 30% of the cost of a new shaft, and the resource, respectively, is from 70 to 80% of the resource of a new shaft.

Restoration of parts is technically justified and economically justified, primarily due to the possibility of reuse and repeated use of worn parts. In this regard, hardfacing technologies are of particular importance, which are most widely used in the repair and restoration of worn shafts. Of the available variety of restoration and repair methods, the most widely used in the repair industry is surfacing, which provides more than 70% of the restoration volume.

Since new shafts are expensive, often damaged and worn shaft surfaces are repaired by hardfacing.

Hardfacing is the application of a layer of metal to the surface of a workpiece or product by fusion welding [8].

When repairing any type of equipment, restoration surfacing is mainly used, which is used to restore the original dimensions of worn or damaged parts. In this case, the deposited metal is close in composition and mechanical properties to the base metal [9].

Important in the process of surfacing is the selection of technological parameters that would ensure the quality of the deposited metal for the purpose of its subsequent machining.

2 LITERATURE REVIEW

In the study and analysis of the state of the problem, including the enterprises of Kazakhstan, Russia, Ukraine, Germany, India, Poland, and China, it was found that the following types are most widely used for recovering parts by hardfacing: manual arc surfacing, semi-automatic in shielding gases and automatic surfacing under a flux layer [10-13].

Each type of hardfacing has advantages and disadvantages.

The advantages of various types of hardfacing are [14, 15]:

- manual arc hardfacing (simplicity and versatility of the method; the ability to perform complex surfacing work in hard-to-reach places);
- semi-automatic hardfacing in shielding gases (economical, good adhesion between the base and deposited metals);
- automatic hardfacing under a layer of flux (high productivity, high quality of the deposited metal).

The disadvantages of various types of hardfacing are [16, 17]:

- manual arc hardfacing (depending on the qualification of the welder, low productivity, harm to the environment);
- semi-automatic hardfacing in shielding gases (increase in metal spatter by 10-12%, organic change in metal composition);
- automatic hardfacing under a layer of flux (high heating of the part during surfacing; the need for heat treatment to increase wear resistance).

The method and modes of hardfacing affect the quality of surface-modified layers [18-20]. By varying the surfacing parameters, it is possible to obtain a deposited layer with different microstructure, residual stresses, surface topography, hardness, and wear resistance of surface layer materials [21-24].

The restored shafts are subject to further machining to ensure the geometric dimensions, the surfaces' relative posi the roughness. Since the deposited layer has a high hardness due to the presence of high-hardness carbides and a viscous metal base [25], this causes difficulty in milling and grinding [25, 26], high tool consumption [27], and in connection with this, the hardness parameter of the deposited layer considered as the main one.

As we see from the literature [6-27], the problem of controlling the hardness of the deposited layer due to the selection of modes was not considered.

In this regard, it is necessary to choose such a hardfacing method and its technological modes that would provide a deposited layer with the desired hardness for resource-saving machining with less cutting tool consumption.

3 RESEARCH METHODOLOGY

During the theoretical and practical study of the most common methods for restoring worn surfaces, as well as surfacing materials, the possibility of using and obtaining the required hardness index without additional heat treatment of the restored shaft was revealed.

To determine the most effective hardfacing method, the following were used:

- method of manual arc hardfacing using stick electrodes;
- method of semi-automatic hardfacing in a protective gas environment;
- method of automatic hardfacing under a layer of flux.

For manual arc surfacing, electrodes of grade 1/S - 7018.1 were used. These are coated electrodes of the basic type with a low hydrogen content. Tab. 1 shows the chemical composition of the surfacing material 1/S - 7018.1.

Table 1 Expected duration of work at the design stage of the program

C / %	Mn / %	Si / %	S / %	P / %
0,06	1,20	0,50	Max 0,017	Max 0,011

For a comparative analysis, the method of semi-automatic hardfacing in a shielding gas environment (CO_2 - 100%) was used with the use of hardfacing material brand ESABSTOODY 102-G Ø1,6 mm.

To study the characteristics of automatic hardfacing under a flux layer, hardfacing material Sv-08G2S Ø2 mm was used. Tab. 2 shows the chemical composition of the Sv-08G2S hardfacing material.

Table 2 Chemical composition of welding material Sv08G2S Ø2 mm

C / %	Mn / %	Si / %	S / %	P / %
0,05-0,08	1,80-1,95	0,70-0,95	max 0,025	max 0,020

The selected materials have the necessary characteristics to obtain a high-quality deposited layer with desired properties.

The technique for studying the hardness of the obtained samples is similar to the previously published methods in articles [27] and [28].

For the hardfacing experiment, 3 specimens were prepared, which are shown in Fig. 1.

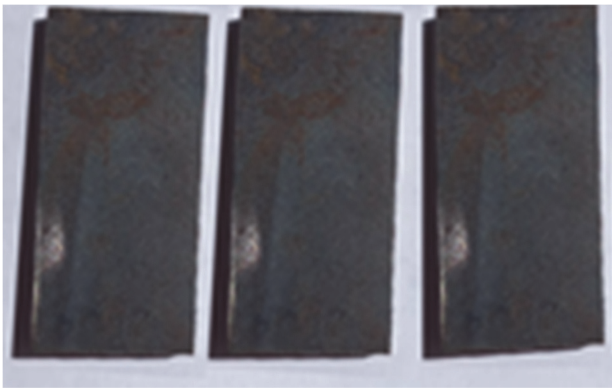

Figure 1 Samples for hardfacing

The material of the samples used is St3, 10 mm thick. Hardness HV-140-170 kgf/mm^2. [6]

Fig. 2 shows the equipment for preparing samples for the study of macrostructure and hardness.

a) b) c)

Figure 2 Equipment for preparing samples and measuring the hardness of the deposited layer: a - automatic desktop cutting machine "UNITOM-2"; b - automatic machine for grinding and polishing samples "LABOPOL-5"; c - ultrasonic hardness tester "MET-U1"

Preparation of samples for further research was carried out using the equipment shown in Fig. 2a and 2b, provided by the testing laboratory of the engineering profile "Integrated Development of Mineral Resources" (IIP "KORMS") at Abylkas Saginov Karaganda Technical University. Further measurements of the obtained hardness of the deposited layer and the boundaries of the transition between the deposited and the base metal were made using an ultrasonic hardness tester, shown in Fig. 2c.

The surfacing of the test specimens was carried out using the following equipment:

- manual arc hardfacing - with a VDM-1202 multi-station welding rectifier, equipped with a welding current frequency controller of the ChPR-315 URAL brand (04);
- semi-automatic hardfacing in a shielding gas environment - by a semi-automatic device PDG-252 of the SELMA company with a built-in wire feed mechanism, a universal welding carriage with magnetic clamps;
- automatic hardfacing under a layer of flux - welding tractor ADF-1005 URAL with a power source brand VDU-1205 URAL.

The equipment used was provided by the laboratory of the Kazakhstan Institute of Welding at Abylkas Saginov Karaganda Technical University.

Before hardfacing, the test specimens were cleaned with grinding wheels to a metallic sheen and degreased, excluding the occurrence of weld defects [30].

The modes for hardfacing of the previously considered surfacing methods were selected empirically. The main requirement for the deposited seam was to obtain the greatest height of the deposited layer while ensuring the fusion of the deposited metal with the test specimen.

4 RESULTS AND DISCUSSIONS

The hardfacing modes when using the surfacing materials described above were selected empirically. In the process of surfacing, both rectilinear movement without vibrations by the electrode, and with transverse vibrations was used. Fig. 3 shows the samples obtained with manual arc hardfacing.

Figure 3 Samples made by manual arc welding: 1 - 80 A, 20 V; 2 - 85 A, 21,2 V; 3 - 95 A, 22 V; 4 - 105 A, 22,8 V; 5- 110 A, 23 V

When choosing the optimal surfacing modes, the main criterion was the width and height of the weld, as well as the average allowable penetration depth.

Technological parameters of the optimal mode for performing manual arc hardfacing with a stick electrode are presented in Tab. 3.

Table 3 Optimum manual arc welding

Hardfacing material: 1/S - 7018,1	
Welding current, I_d	95 A
Arc voltage, U_d	22 V
Electrode diameter, d_{el}	2,6 mm

To ensure the best quality of the weld obtained during semi-automatic hardfacing, a welding carriage was used, which makes it possible to exclude vertical oscillations of the burner during its movement.

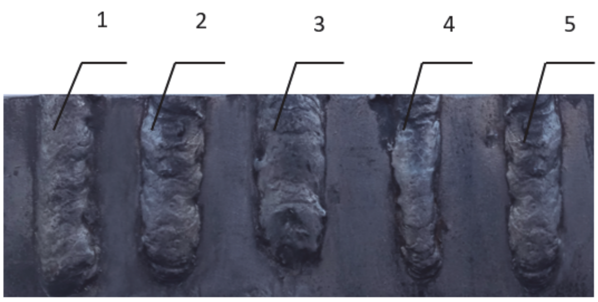

Figure 4 Samples made by semi-automatic hardfacing in a protective gas environment (CO_2 - 100%): 1 - 135 A, 20 V; 2 - 180 A, 19,5 V; 3 - 220 A, 20 V; 4 - 240 A, 22 V; 5 - 260 A, 22 V

Fig. 4 shows the welds obtained under various modes and the presence of oscillations of the welding head during semi-automatic hardfacing in a protective gas environment.

Based on the analysis of the parameters of the obtained welds under various modes Tab. 4 presents the most optimal hardfacing mode.

Table 4 Optimum conditions for semi-automatic welding in shielding gas (CO_2 - 100%)

Hardfacing material: Sv-08G2SØ1,6 mm	
Welding current, I_d	220 A
Arc voltage, U_d	20 V
Electrode diameter, d_{el}	1,6 mm

Automatic hardfacing under a flux layer was carried out on a sample of large overall dimensions, to achieve the best quality of the deposited layer and a true picture of the geometric parameters of the deposited weld. Fig. 5 shows the obtained samples with automatic hardfacing under a layer of flux under various modes.

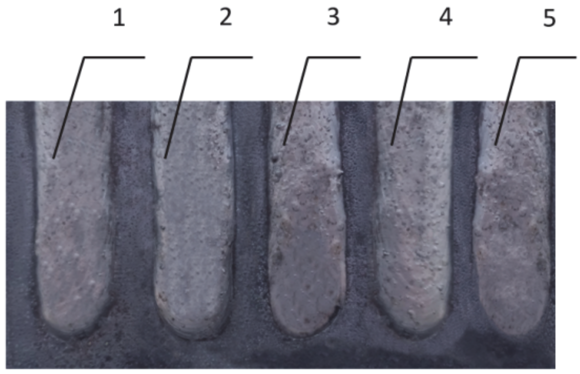

Figure 5 Samples made by automatic hardfacing under a layer of flux: 1 - 200 A, 32 V; 2 - 220 A, 32 V; 3 - 235 A, 33 V; 4 - 240 A, 33 V; 5 - 260 A, 34 V

Based on the obtained geometric parameters of the welds, the most optimal mode for automatic submerged arc hardfacing is determined, which is presented in Tab. 5.

Table 5 Optimum mode of automatic submerged arc welding

Hardfacing material: Sv-08G2S	
Welding current, I_d	200 A
Arc voltage, U_d	32 V
Electrode diameter, d_{el}	2 mm
Flux	AH-348-A

The following operations were carried out to prepare and analyze the samples under study:

1. Samples with surfacing for further analysis were cut transversely to the surfacing direction. For cutting the samples, an automatic cutting machine UNITOM-2 was used, equipped with water cooling of the cut zone. The use of cooling in the process of cutting the samples made it possible to exclude the effect of overheating on the weld structure and, accordingly, the distortion of the study results. The cutting process was carried out in a closed chamber, equipped with local illumination of the cutting zone, which made it possible to control the entire process;

2. The cut specimens were ground and polished using a LABOPOL-5 automatic machine. The process of preparation of microsections of the studied samples is carried out according to the standard procedure [29].

The main stages of preparation of microsections include the process of leveling the surface by coarse grinding with water cooling, fine grinding of the surface using fine-grained grinding discs, polishing using a diamond suspension of various grit fractions (from 9 µm to 1 µm), and polishing discs, etching using nitric acid.

Polished and etched samples are shown in Fig. 6.

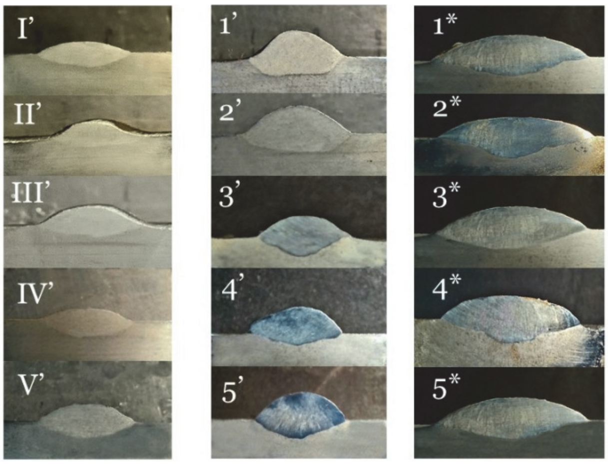

Figure 6 Prepared microsections of the studied samples: I', II', III', IV', V' - Manual arc hardfacing, 1', 2', 3', 4', 5' - Semi-automatic hardfacing in a protective gas environment, 1*, 2*, 3*, 4*, 5* - Automatic hardfacing under a layer flux

The determination of the hardness values of the studied samples was carried out using an ultrasonic hardness tester MET-U1. According to the passport data of the hardness tester, when analyzing the hardness of the surface under study, the sensor develops a force equal to 9,8 N. The hardness tester recorded the surface hardness according to the Vickers scale. Fig. 7 shows the layout of controlled points on the weld section.

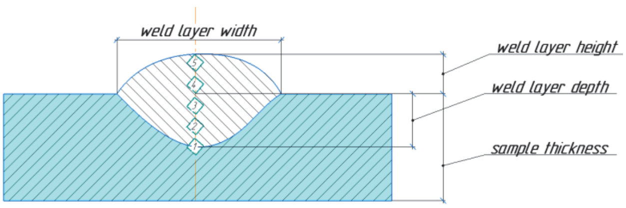

Figure 7 Layout of the hardness control points of the deposited layer: 1, 2, 3, 4, 5 - control points

According to the scheme presented above, the hardness of the deposited layer on the samples was controlled for each hardfacing mode at 5 points. The results obtained are presented in Tab. 6.

Based on the experiments carried out, the following conclusions were drawn: the most optimal method of surfacing is semi-automatic surfacing, which combines high productivity, and optimal manufacturability parameters, which provides the required characteristics of the deposited layer for subsequent machining of the restored surface. The manual surfacing method is characterized by high labor costs, and automatic surfacing gives high hardness values of the deposited layer, in the range from 555-826 HV. The hardness obtained by semi-automatic surfacing is in the range of 296-393 HV, which is preferable since it is closest in characteristics to the hardness (236 HV) of the base metal ST 45.

Table 6 Results of measuring the hardness of the deposited layer of the test samples

Weld number	Hardness
Manual arc hardfacing with stick electrode	
Hardfacing material: 1/S - 7018.1 Ø2,6 mm	
I'	301 HV
II'	316 HV
III'	407 HV
IV'	446 HV
V'	455 HV
Semi-automatic hardfacing in shielding gas (CO_2 - 100%)	
Hardfacing material: Sv-08G2S Ø1,6 mm	
1'	393 HV
2'	382 HV
3'	372 HV
4'	309 HV
5'	296 HV
Automatic hardfacing under a layer of flux	
Hardfacing material: Sv-08G2S Ø2 mm	
1*	555 HV
2*	748 HV
3*	760 HV
4*	826 HV
5*	780 HV

Based on the obtained experimental data using multiple regression, a mathematical model (regression equation) was constructed that describes the degree of influence of the initial parameters of the surfacing mode (X_i factors) on the hardness index of the deposited layer (response Y). Input data for determining the mathematical model are presented in Tab. 7.

Table 7 Initial values of the parameters of the semi-automatic surfacing mode in a protective gas environment (CO_2 - 100%)

Mode number	Hardness of the deposited layer / HV (Y)	Effective power / cal/sec (X_1)	Welding current strength / A (X_2)	Welding voltage / V (X_3)
1	393	486	135	20
2	382	631,8	180	19,5
3	372	792	220	20
4	309	950,4	240	22
5	296	1029,6	260	22

The establishment of dependencies between the hardness of the deposited layer and the technological parameters of the hardfacing are shown in Figs. 8, 9, 10.

The dependencies were determined based on the obtained partial correlation coefficients, which differ from simple linear pair correlation coefficients in that they measure the pair correlation of the corresponding features. This is especially important, provided that the influence of other factors (x_j) on them is eliminated. Based on partial coefficients, a conclusion is made about the validity of including variables in the regression model.

The dependence of the hardness on the parameter of the effective power of the welding arc is shown in Fig. 8.

Analyzing the graph of the first factor sign (X_1), it is possible to give a qualitative interpretation of the approximation reliability value R^2 = 0,8885 on the Chadok scale, which indicates the presence of a strong relationship between hardness and the effective power of the welding arc.

A graph of the dependence of the hardness on the welding current strength parameter is shown in Fig. 9.

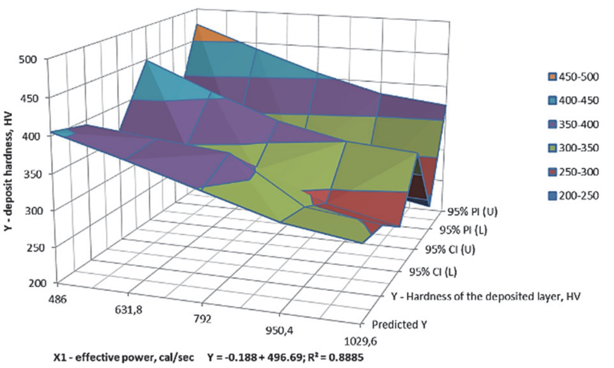

Figure 8 Dependence of hardness on the effective power of the welding arc

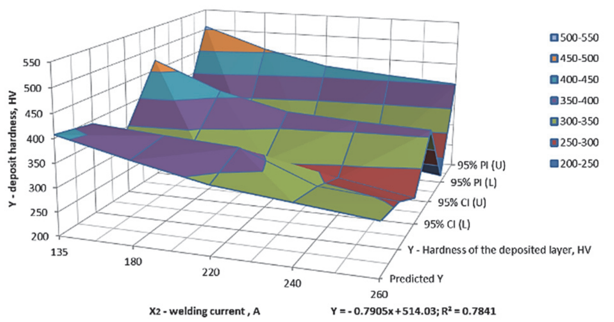

Figure 9 Dependence of hardness on welding current

Analyzing the graph of the dependence of hardness on the strength of the welding current, we determine a strong connection, since R^2 = 0,7841 and this value fulfills the condition $-0{,}7 \le R \le 0{,}9$.

The graph of the dependence of the hardness of the deposited layer on the voltage parameter of the welding arc is shown in Fig. 10.

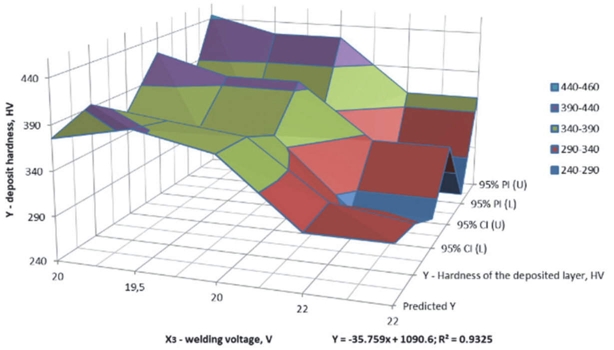

Figure 10 Dependence of hardness on arc voltage

When analyzing the graph of the dependence of hardness on arc voltage, a very strong relationship was established, since the coefficient R^2 = 0,9325.

When comparing the reliability values of the approximation of the coefficient R^2 for all three dependences, it is obvious that the factor X_3 has the greatest influence on the response Y. In this regard, the X_3 factor (R^2 = 0,9325) has the greatest influence on the effective attribute. This means that when building a mathematical model, it will enter the regression equation first.

To check the dependence of the hardness of the deposited layer on the selected parameters of the surfacing mode, regression analysis was used with the compilation of a multiple regression equation and subsequent proof of its adequacy. The multiple regression equation used in the calculation can be represented by the formula:

$$Y = f\left(\beta, X\right) + \varepsilon \tag{1}$$

where $X = X(X_1, X_2, \ldots, X_m)$ are vectors of independent (explanatory) variables; β is the vector of parameters (to be determined); ε is the random error (deviation); Y is the dependent (explained) variable.

Therefore, the theoretical linear multiple regression equation is:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_m X_m + \varepsilon \tag{2}$$

where β_0 is a free term that determines the value of Y if all explanatory variables X_j are equal to 0.

According to the theoretical linear Eq. (2), an empirical multiple regression equation was presented, according to the formula:

$$Y = b_0 + b_1 X_1 + b_2 X_2 + \cdots + b_m X_m + \varepsilon \tag{3}$$

where b_0, b_1, …, b_m are the parameters for estimating the theoretical values β_0, β_1, β_2, …, β_m of the regression coefficients; e is the estimate of deviations ε.

In the process of regression analysis based on Eq. (3), a strong dependence of the influencing factors on the result of the obtained hardness of the deposited layer was revealed. Based on this, the resulting hardness regression equation will look like this:

$$Y = -522{,}1949 - 1{,}772 X_1 + 5{,}9427 X_2 + 47{,}3686 X_3 \tag{4}$$

According to the resulting regression equation for the hardness index of the deposited layer, it follows that the constant evaluates the aggregated influence of the considered factors on the result Y. In the absence of X_1, the variable Y would be –522,1949. The coefficient β_1 indicates Y that with an increase in X_1 by 1, the value of the variable Y decreases by 1,72. According to the coefficient β_2, with an increase in X_2 by 1, the value of the variable Y increases by 5,9427. Accordingly, with an increase in the X_3 index by 1, the value of the variable Y increases by 47,3686.

To confirm the degree of influence of the considered factors on the independent variable Y, the derived pair correlation coefficient was calculated according to the formula:

$$r_{xy} = \frac{\overline{xy} - \overline{x}\overline{y}}{s\left(x\right)s\left(y\right)} \tag{5}$$

where $s(x)$, and $s(y)$ are standard deviations for y and x_i; $\overline{xy}$ are the arithmetic mean values of factors and response.

Based on Eq. (4), the obtained correlation coefficients of factors and variable Y are presented in Tab. 8.

Analyzing the obtained values of the correlation coefficient, it follows that the selected parameters of the surfacing mode have a strong linear relationship both with the hardness index of the deposited layer and concerning each other, because the value of the indicator R is in the region of $-0,7 \le R \le 0,9$.

Table 8 Matrix of pairwise correlation coefficients R

R	Y	X_1	X_2	X_3
Y	1	–0,9426	–0,8855	–0,9657
X_1	–0,9426	1	0,9892	0,8557
X_2	–0,8855	0,9892	1	0,7710
X_3	–0,9657	0,8557	0,7710	1

To check the adequacy of the proposed mathematical model of the dependence of the hardness of the deposited layer on the parameters of the surfacing mode, the multiple correlation coefficient, the coefficient of determination and the Fisher criterion was determined, the values of which are presented in Tab. 9.

Table 9 Criteria for assessing the adequacy of the mathematical model

Name criteria	Numeric value	Adequacy condition	Conclusion
Multiple correlation coefficient, R	0,9987	$R \rightarrow 1$	A strong influence on the Y variable
Determination coefficient, R^2	0,9974	$R^2 \rightarrow 1$	
Fisher criterion, F	2,59 (F_{cr}(3; 1) = 9,01)	$F < F_{cr}$	The model is adequate

The conclusions of Tab. 9 testify to the adequacy of the obtained model of the empirical multiple regression equation since with a value of R close to 1, the regression equation describes the actual data better and the factors have a stronger effect on the result.

5 CONCLUSION

1. For effective and high-quality restoration of electric motor shafts, providing the required hardness of the deposited layer, it is recommended to use semi-automatic welding in a shielding gas environment (CO_2 - 100%).

2. The hardness of the deposited layer depends on the strength of the welding current, voltage, and effective power of the welding arc.

3. It is determined that:
- an increase in the strength of the welding current leads to a decrease in hardness;
- an increase in stress leads to an increase in hardness;
- an increase in effective power leads to an increase in hardness.

4. Stress has the greatest effect on hardness.

5. The statistical significance of the equation was tested using the coefficient of determination and Fisher's test. It has been established that 99,74% of the total response variability is explained by a change in factors, i.e., technological modes of surfacing.

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