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# Prediction Of The Strengthened Layer Depth At Electroerosive Alloying Of Steel Samples With Graphite Electrode

*Приведена формализованная методика определения констант уравнения прогнозирования глубины упрочненного слоя при электроэрозионном легировании стальных образцов графитовым электродом. Определены корреляционные зависимости глубины упрочненного слоя для поверхностей армко-железа, стали 12Х18Н10Т, 30Х13 и 40Х, от длительности обработки и энергии разряда.*

***Ключевые слова:*** *электроэрозионное легирование, цементация, методика, прогнозирование, глубина упрочненного слоя*

*Наведена формалізована методика визначення констант рівняння прогнозування глибини зміцненого шару при електроерозійному легуванні сталевих зразків графітовим електродом. Визначено кореляційні залежності глибини зміцненого шару для поверхонь армко-заліза, сталі 12Х18Н10Т, 30Х13, і 40Х, від тривалості обробки і енергії розряду.*

***Ключові слова:*** *електроерозійне легування, цементація, методика, прогнозування, глибина зміцненого шару*

*There is represented a formalized method for determining the constants of the equation for predicting the depth of a strengthened layer in the course of electroerosive alloying steel samples with a graphite electrode. There are determined correlation dependences of strengthened layer depth for surfaces of Armco-iron, 12X18H10T, 30X13, and 40X steels on processing duration and discharge energy values.*

***Keywords:*** *electroerosive alloying, carburizing, method, forecasting, depth of the hardened layer*

**Introduction**

The essence of the process of electroerosive alloying (EEA) consists in the fact that surfaces of anode (electrode) and cathode (part) are subjected to local action of high pressures of shock wave and temperatures [1]. In this case, the anode is instantaneously heated and a droplet or solid particle of the anode material moves to the cathode. Fragments flying from the anode to the cathode are heated to a high temperature. The spark discharge occurs in microscopically small volumes and lasts of 50 to 400 microseconds. On the cathode, there are formed wells and microwaves, wherein the anode and cathode particles interact with each other and with the surrounding medium. There are activated diffusion processes there resulting in creating new phases and changing surface layer structures.

Based on the essence of the EEA process, it can be assumed that there are opened wide possibilities for predetermined changes of steel surface properties when graphite is used as an anode. It has been found [2] that in the case of EEA processing iron alloys with a graphite electrode, there is formed a strengthened layer, which combines viscous austenite and solid carbide. The EEA method with a graphite electrode is based on the process of diffusion (saturation of a part surface layer with carbon), and it has some similarity with a kind of a chemical-thermal treatment, that is, a process for carburizing a surface of a part.

The EEA process by graphite electrode can be isolated creating a separate area in technique, and this process allows forming machine part surface layers of increased wear resistance without changing the original size of the part. Carburizing steel parts by electroerosive alloying (CEEA) has a number of advantages, the main ones of which are: achieving 100% continuity of strengthening the part surface layer; increasing hardness of the surface layer of the part due to diffusion-hardening processes; the alloying process can be carried out in strictly specified places without protecting the rest of the surface of the part; the absence of volumetric heating of the part as well as the part deformation and/or warpage associated therewith; the simplicity in technology application; flexible binding to existing equipment; the strengthening process requires no special preparation and high qualification of an executer. With CEEA processing of steel parts, the thickness of the strengthened layer depends on the values of discharge energy and alloying process period of time (process productivity).

The aim of the research was to improve quality of working surfaces of parts by predicting depth of a strengthened by means of controlling energy parameters of a CEEA process.

**Research Methodology**

To obtain the initial experimental data, there were carried out the processes for controlling, measuring and recording the parameters under fixed alloying conditions. Figure 1 shows the dependence of the strengthened layer depth on the CEEA discharge energy for the samples made of 40X, 12X18H10T, 30X13 steels and Armco iron.

It is clear from Fig. 1 that the depth of the strengthened layer increases with increasing the discharge energy. At the first approximation, there is an exponentially increasing dependence between the depth of the strengthened layer and the discharge energy values. The minimum

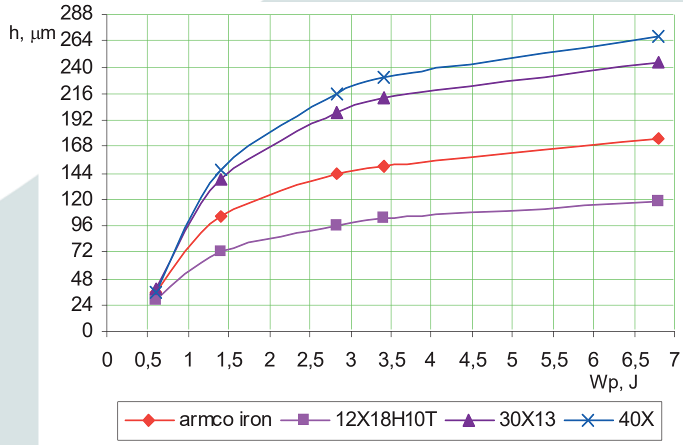



***Fig. 1. Dependence of the depth of the strengthened layer on the discharge energy value (processing period of time is 1 min.)***

depth of the strengthened layer for the CEEA processing 40X, 12X18H10T, 30X13 steels and Armco iron with the discharge energy Wp = 0.6 J is 35; 30; 34; 35 µm, respectively, and the maximum one at Wp = 6.8 J is 270; 115; 245; 180 µm, respectively. While alloying the surfaces for 5 and 10 minutes, the depth values of the strengthened layers increase, but the characters of the curves remain the same [3].

Besides the energy parameters of the used equipment, the processing period of time also significantly influences on the depth of the strengthened layer. The depth of the strengthened layer increases with increasing the processing period of time. At the first approximation, there is an exponentially increasing dependence between the values of the depth of the strengthened layer and the CEEA processing period of time. The minimum depth of the strengthened layer at CEEA processing with the discharge energy Wp = 0.6 J for 12X18H10T, 40X, 30X13 and Armco iron is, respectively: 30; 35; 30; 34 microns for 1 minute, 48; 50; 37; 48 microns for 5 minutes and 51; 55; 38; 50 microns for 10 minutes, and the maximum one at Wp = 6.8 J for the above mentioned materials is, respectively: 115; 270; 180; 245 microns for 1 minute, 250; 910; 310; 860 microns for 5 minutes and 275; 1060; 333; 1006 microns for 10 minutes.

On the basis of experimental studies, it has been found that at processing steel with the use of the CEEA process, there is an exponentially increasing dependence (1) between the depth of the strengthened layer (h) and the discharge energy (Wp) up to the saturation period occurrence, when $h = h_{max}$ [4].

$$h = a_1' \cdot e^{\frac{b_1}{Wp}} \qquad (1)$$

For all the sample materials, there are calculated coefficients in equation (1) (Table 1).

*Table 1. The coefficients values in equation (1) for materials being analyzed under different conditions of the CEEA process.*

| Processing period of time, min. | Materials for samples | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 12X18H10T steel | | 40X steel | | Armco-iron | | 30X13 steel | |
| | «a'1» | «b1» | «a'1» | «b1» | «a'1» | «b1» | «a'1» | «b1» |
| 1 | 131.381 | -0.8839 | 346.714 | -1.3551 | 211.199 | -1.057 | 310,816 | -1.3089 |
| 2 | 210.023 | -0.9724 | 760.035 | -1.7103 | 310.135 | -1.2420 | 770,013 | -1.7102 |
| 3 | 260.175 | -0.9717 | 1050 | -1.7012 | 360.218 | -1.2732 | 1050 | -1.8124 |
| 5 | 291.255 | -1.0835 | 1294 | -1.9239 | 401.939 | -1.0757 | 1221 | -1.9138 |
| 7 | 310.302 | -1.0911 | 1420 | -1.9417 | 420.213 | -1.4021 | 1370 | -1.9431 |
| 10 | 321.629 | -1.1071 | 1508 | -1.9605 | 434.067 | -1.4396 | 1451 | -1.9914 |

While substituting the obtained coefficients in equation (1), we herein determine the forms of the analytical dependences of the depth changes of the strengthened layer on the discharge energy values for all the sample materials.

It concerns constructing the theoretical curves on the basis of the obtained analytical dependencies.

Using MathCAD Program, we herein construct the theoretical curves h = f (Wp) depending on the labor intensity of the CEEA process for the processing periods of time of 1; 2; 3; 5; 7 and 10 minutes (Fig. 2).

From a set of theoretical curves for all the sample materials, there are selected dependences corresponding to the maximum experimental labor intensity of the process, that is 10 minutes, with the coefficients corresponding thereto in equation (1) (Table 1).

We herein determine the equation of h = f (T) function curve at the maximum experimental discharge energy Wp=6.8 J. For this purpose we find out the intersection points of the curves h = f (Wp) for various labor intensity values with a line corresponding to Wp = 6.8 J (vertical and dotted line) in Fig. 2.

We herein construct the theoretical curves for the dependence of the labor intensity values of the CEEA process on the discharge energy values for the samples made of such materials as Armco-iron; 12X18H10T; 30X13 and 40X (Fig. 3).

Assuming, in the first approximation, the form of dependence as being between the depth of the carbonized layer and the exponentially increasing discharge energy, we have:

$$h = a_2' \cdot e^{\frac{b_2}{T}}, \qquad (2)$$

As a result of the studies, we determined the coefficients "a'2'" and "b2" of the equation (2) for all the sample materials [5]. According to the obtained coefficients, we herein construct the analytical dependences of the strengthened layer depth changes on the process labor intensity at the discharge energy value Wp = 6.8 J for all the sample materials (Figure 4).

Next, we construct a spatial model of cumulative dependence of strengthened layer h depth change on discharge energy Wp for various labor intensities of T process.

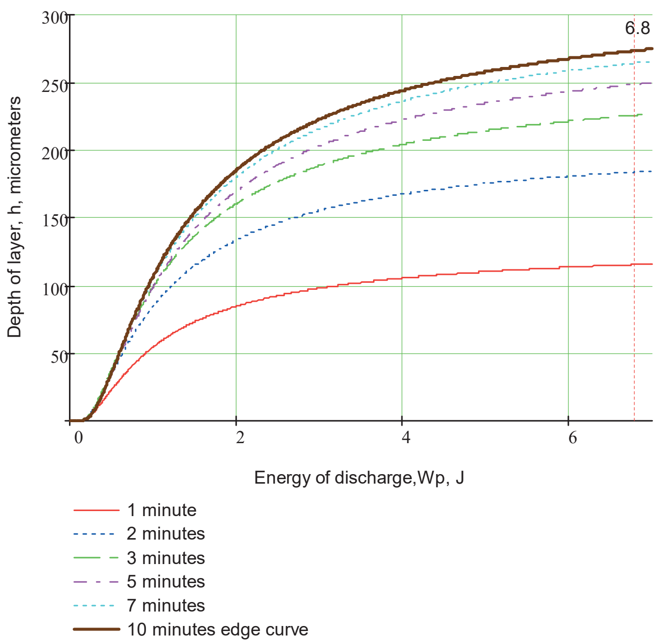



***Fig. 2. Dependence h from Wp for samples of 12X18H10T steel***

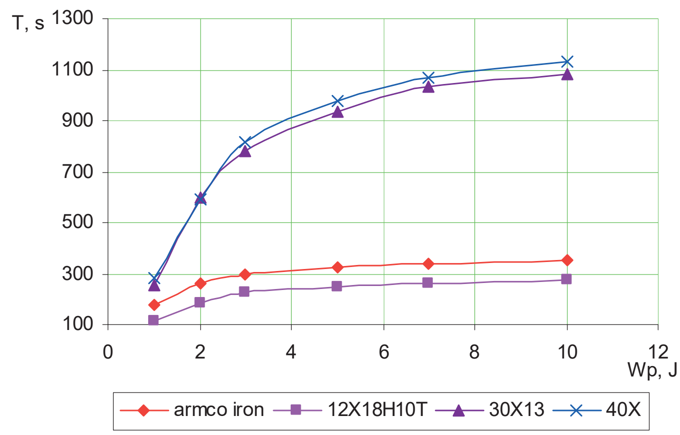



***Fig. 3. Changing a process labor intensity value due to discharge energy changes for samples made of such materials as: Armco iron, 12X18H10T, 30X13, 40X***

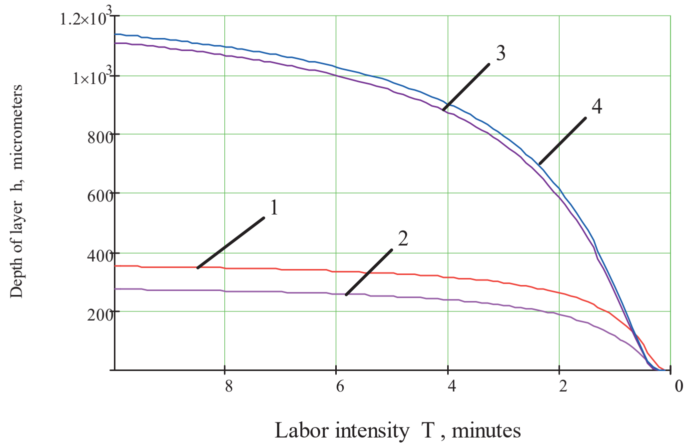



***Fig. 4. Dependence of the strengthened layer depth change on the process labor intensity for the samples: 1 - Armco iron, 2 - 12X18H10T, 3 - 30X13, 4 - 40X***

The model is constructed according to the dependence:

$$h = f(Wp, T) = k \cdot f(Wp) \cdot f(T)$$

Where k is the coefficient of coordinating the functions f (Wp) and f (T):

$$k = \frac{2}{f(Wp_{6.8}) + f(T_{10})},$$

Where f ($Wp_{6.8}$) and f ($T_{10}$) are the values of the functions f (Wp) and f (T) at the discharge energy of 6.8 J and labor intensity of 10 minutes, respectively.

We herein have:

$$h = a_1^{'} \cdot e^{\frac{b_1}{Wp}}; \quad h = a_2^{'} \cdot e^{\frac{b_2}{T}}$$

Thus, the spatial model of the cumulative dependence of the strengthened layer h depth change on the discharge energy Wp for various labor intensities of T process has the form as follows:

$$h = f(Wp, T) = k \cdot a_1^{'} \cdot e^{\frac{b_1}{Wp}} \cdot a_2^{'} \cdot e^{\frac{b_2}{T}} \qquad (3)$$

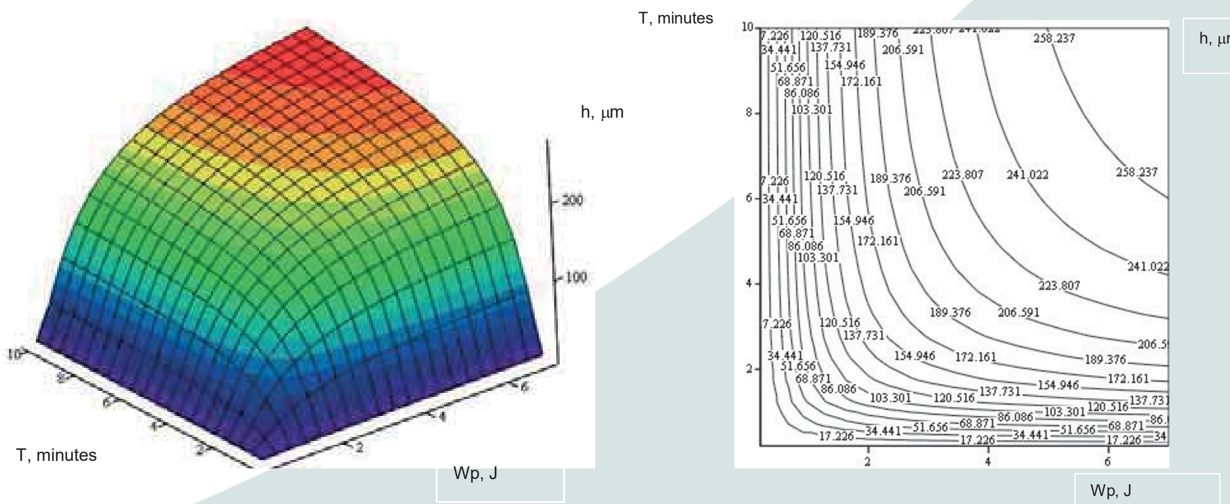
According to the obtained model, in MathCAD environment, we herein construct the curves for changing the dependence of the depth of the part strengthened surface layer (h) on the alloying condition (discharge energy (W)) and alloying period of time (T) for all the sample materials. Figure 5a illustrates the dependence for 12X18H10T steel.

To provide visualization, the model h = f (Wp, T) is more convenient to represent in the form of level lines (nomograms). According to the obtained dependences, it is possible to construct a nomogram for each sample material. Figure 5b shows a nomogram for the sample made of 12X18H10T steel.

According to the nomograms, each level line corresponds to the depth of the strengthened layer achieved at performing the CEEA process.

Thus, having known the information about the desired depth of the strengthened layer, it is necessary to find the corresponding level line on the nomogram, and with the help of this line, it is possible to determine the technological condition and the labor intensity of the process. In addition, when plotting a vertical line of a given technological condition on the diagram, one can see a strengthened layer depth achieved with increasing the period of time for the alloying process. The disadvantage of such a nomogram consists in the fact that with increasing prediction accuracy, the number of level lines sharply increases. The solution of this problem is to determine a level line equation.

Using equation (3), we herein solve the equation of changing the strengthened layer depth h relative to the labor intensity T. As a result we obtain a dependence of the




(a) (b)

***Fig. 5. 3-D Model (a) and nomogram (b) of dependence of strengthened layer depth h change on discharge energy Wp at various process labor intensities T for the samples made of 12X18H10T steel***

following form

$$T = f(Wp,h) = \frac{b_2}{Ln(h) - (Ln(k \cdot a_1 \cdot a_2) + \frac{b_1}{Wp})} = \frac{b_2}{Ln(\frac{h}{k \cdot a_1 \cdot a_2}) - \frac{b_1}{Wp}} \quad (4)$$

**Research results**

With the use of the results of modeling in compliance with equations (3) and (4), it is possible to solve both direct and inverse problems of searching for rational parameters of integrated technologies, in order to improve the quality of part working surfaces.

The direct problem consists in search for the labor intensity of the CEEA process under the control parameter, that is, the discharge energy, and the given parameter, that is, the depth of the strengthened layer of the part. The procedure for finding out of the rational value of labor intensity is shown in Fig. 6, a, b.

According to the value of the required depth of the strengthened layer, we herein find the level line corresponding thereto in the spatial model (Fig. 6, a). Having the value of the discharge energy (the Passport mode of the applied technological equipment), we can determine the due labor intensity value of the process (Fig. 6, b).

The solution of the inverse problem (Fig. 7, a, b) consists in searching for the depth of the strengthened layer of the part being strengthened at the availability of the control parameter, namely the discharge energy value, and the given parameter, namely the labor intensity of the CEEA process.

According to the specified restrictions on the labor intensity for performing the operation and the discharge energy, we herein find the point of intersection in the plane (Wp, T) (Fig. 7, a). In the spatial model, the corresponding level line can be determined using the obtained coordinates. On plotting the height of the level line, we can determine the depth of the strengthened layer (Fig. 7, b).

**Conclusions:**

There is defined a form of analytical dependency that allows determining influence of integrated technologies on quality parameters of strengthened part working surfaces.

There is proposed a mathematical model describing influence of a discharge energy value on a strengthened layer depth at performing a CEEA process.

There is developed a procedure providing for determining of constants for the equation predicting the depth of a strengthened layer (the activation energy of diffusion E and the maximum depth of the strengthened layer hmax).

There is developed an algorithm to search for rational variants of integrated technologies improving quality of working surfaces of parts, which algorithm provides predicting the energy parameters of the CEEA process for forming a strengthened layer of the required depth.

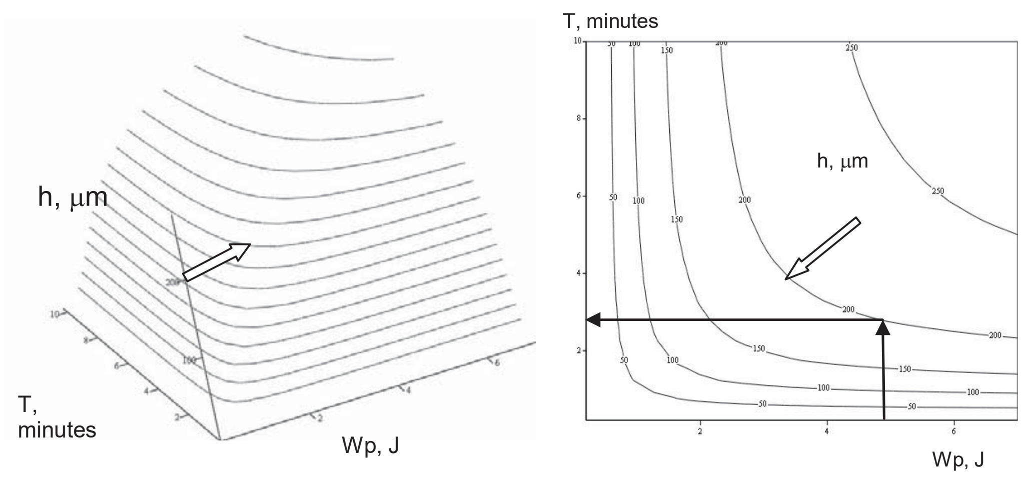



***Fig. 6. The procedure for solving a direct problem***

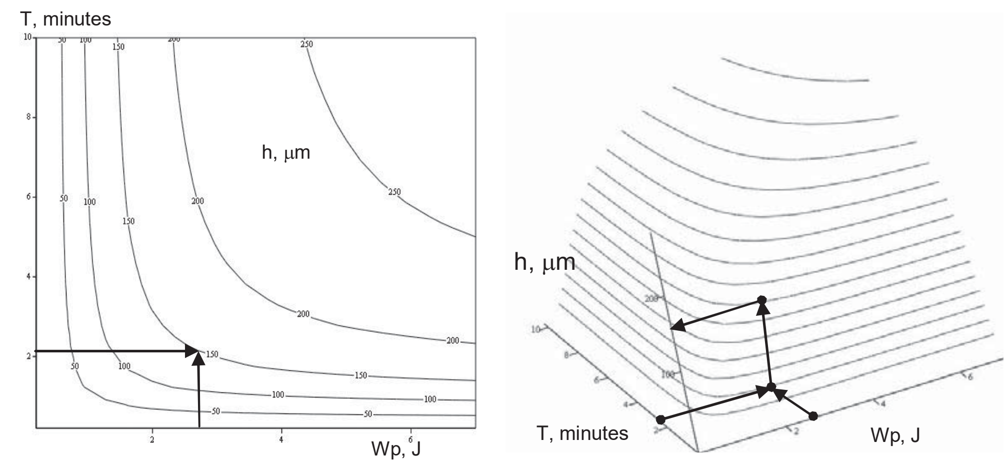



***Fig. 7. The solution of the inverse problem***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ЭФФЕКТИВНАЯ КОМПРЕССОРНАЯ ТЕХНИКА ДЛЯ ВСЕХ ОТРАСЛЕЙ НАРОДНОГО ХОЗЯЙСТВА.
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