Fractal parametrization in erosion process and surface investigation received by electrospark modification

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Abstract. High-energy metal surfaces processing by electrospark modification (ESM) leads to formation of the difficult structural state of work materials in non-equilibrium thermodynamic conditions by the self-organizing laws. The article deals with the fractal geometry approaches for a quantitative assessment of the erosion processes by using ESM and the surface structure states after treatment. The authors determine the synergies between fractal dimensions of the surface structures, received by ESM of steel, and their physical and mechanical properties. They point out the surface formation with the maximal gauge, microhardness and durability in the case of definite energy of a spark impulse. In this condition, the fractal dimension of structures is maximum too.

1. Introduction

Maintainability engineering products and increasing their resource become possible due to hardening their detail surface layers. The authors introduce several technologies of the surface modification with high concentrated energy flows. In the industry, the method of electrospark modification (ESM) is widely known. This method is based on the material transfer phenomenon of an alloying electrode (anode) on a processed surface (cathode) at the spark discharge. The new surface forms because of such external actions. Processes, which lead to formation of a new structural state of the material, are activated in the surface layer [1, 2].

The processes, occurring at the ESM, carry in the extremely non-equilibrium thermodynamic conditions. The material erosion of an alloying electrode and surface layers with the modifying structure are the basic processes, which influence physical and mechanical properties of materials. These processes regard to dynamic self-organizing processes. Research and quantitative assessment of the self-organizing processes in materials is based on the fractal parametrization. It is a fresh approach on the analysis, modelling and forecasting of material properties. The fractal structures are used for a geometrical assessment of self-similar and different-scale objects. They can be multipurpose tool for analysis of the self-organizing process while material investigation [3, 4].

The fractal parametrization allows getting several fractal correlation in any objects and the processes having complex multi-stage structure. In this regard, the fractal parametrization, except information
loading, reveals physics of the processes. To sum up, using the fractal formal description to the process analysis with the ESM materials is topical enough. Erosion of the particle stream and the case with complex grain and block structures are characterized by the fractal properties of the ESM. The purpose of the research is evaluation of optimum technological parameters of the ESM. They control structural state and material properties by the surface treatment in terms of the contact between these parameters with the fractal dimension of the structure.

2. Results and discussion

The central technological parameters and conditions of the ESM are electrode material, pulse energy and machine time. They determine the structure and properties of the surface layer. These parameters define quality of the surface and their characteristics such as adhesive strength with a foundation, a structure and coating thickness, and durability. The erosion mass stream composes with a burst form scattering substance of an electrode material under the ESM. Development of the erosion particle stream with the high internal energy proceeds in the non-equilibrium conditions. It comes amid further size reduction to the state wherein the total surface energy of disintegration products of the particles will completely counterbalance their internal energy. Energy conditions of such particle organization form are expressed by the equation

$$\gamma \cdot \sum F_i = \mu \cdot V,$$

where $\gamma$ is the specific surface energy; $\mu$ is the specific internal energy; $\Sigma F_i$ is the total area of all erosion stream particles; $V$ is the total volume of the particles.

Make a transformation of the equation (1) to the form

$$\frac{\mu}{\gamma} = \frac{\sum F_i}{V}.$$

From (Equation 2) follows that with increase of the internal energy, erosion substance flow will have "the developed" surface, i.e. small erosion particles. The mass erosion stream is non-homogeneous in its dimensional range and characterized by the fractal proportion

$$N = \frac{C}{\nu^D},$$

where $N$ is the total number of erosion particles; $D$ is the fractal dimension of the erosion product distribution by volume; $\nu$ is the volume of a separate erosion particle; $C$ is the constant characterizing by self-similarity of the received particles. If the system is non-equilibrium, the frequency of the particle distribution on the volume $n$, we can present it in the form of differential exponential function. As a result, we receive following expression

$$n = -\frac{dN}{d\nu} = \frac{DC}{\nu^{D+1}}.$$

The erosion particles have the sphere form. It is possible to use the correlation from geometry, such as each particle with the volume $\nu$ has the surface area proportional to $\nu^{2/3}$. Radius $r$ expresses in terms of the sphere volume formula, we can substitute it in the formula of semisphere surface area and we receive

$$S = 4\pi \left( \frac{3\cdot\nu}{4\cdot\pi} \right)^{\frac{2}{3}}.$$

The total area of all erosion particles can be defined under the formula
\[ \sum F_i = \sum \nu_i \cdot n_i = CD \int_0^\nu \frac{d\nu}{\nu^D} = \frac{CD}{\frac{2}{3} - D} \cdot \nu_i^{\frac{2}{3}}. \quad (5) \]

The total volume of the erosion particles can be defined on the expression

\[ V = \sum \nu_i n_i = CD \int_0^\nu \frac{d\nu}{\nu^D} = \frac{CD}{1 - D} \cdot \nu_i^{1 - D}. \quad (6) \]

In this case, the proportion of the total area of all erosion particles to their total volume is

\[ \frac{\sum F_i}{V} = \left( \frac{D - 1}{D - \frac{2}{3}} \right) \frac{1}{\sqrt[D]{\nu}} = \frac{C_\ast}{\sqrt[D]{\nu}}, \quad (7) \]

where \( C_\ast \) is the constant, characterised by the fractal dimension of particles.

In figure 1, percentile curve of microwells diameters are presented. They are formed after interaction of the erosion particles with a processed surface and represented ordinary scaling dependence. The dependence data are resulted from measurement of hundred microwells.

The fractal dimension are counted off the diameters erosion microwells using the program Image Pro Plus 5.1. [4]. It is defined under the formula

\[ D = \frac{\Delta(\ln \sum P)}{\Delta(\ln d)}, \]

where \( \Delta(\ln \sum P) \) is the logarithm increment of cumulative frequency, \( \Delta(\ln d) \) is the logarithm increment of the microwell diameters.

**Figure 1.** Integral distribution of the microwell diameters under the steel ESM with various pulse energies: \( E_1 = 0.022 \text{ J} \); \( E_2 = 0.09 \text{ J} \); \( E_3 = 0.25 \text{ J} \); \( E_4 = 0.73 \text{ J} \); \( E_5 = 0.86 \text{ J} \).
There are the fractal dimensions of self-similarity \((D_o)\), coating thickness \((\delta)\), microhardness of a surface layer \((HV)\) and ratio distortion of interplanar distance of a crystal lattice \((\Delta d/d)\) depending on energy of the singular spark discharge \((E)\) in the table 1.

Table 1. Research results of the steel surface after the ESM treatment by the electrode of BK6M mark.

| Pulse energy, \(E, \text{J}\) | \(D_o\) | \(HV, \text{MPa}\) | \(\delta, \mu \text{m}\) | \((\Delta d/d) \times 10^{-3}\) |
|-------------------------------|-------|-----------------|----------------|-------------------|
| 0,022                         | 2,130 | 8450            | 20             | 1,5               |
| 0,09                          | 2,571 | 11450           | 25             | 1,5               |
| 0,25                          | 2,453 | 13820           | 35             | 2,5               |
| 0,73                          | 2,605 | 16400           | 55             | 3,5               |
| 1,15                          | 2,444 | 14610           | 40             | 2,7               |

The tendency of the nonmonotone fractal dimension change \(D_o\) becomes apparent with energy increment of the singular spark discharge. Value of the fractal dimensions \(D_o > 2\) verifies by high maturity (activation) of the surface. Microhardness, coating thickness and ratio distortion of a crystal lattice depend on the pulse energy and they are nonmonotone by experimental results. The range of the maximum values arrangement for investigated properties reside in the same area of the electrospark impulse energy. The microhardness and the crystal lattice degree of distortion grow with increase in energy of the electric discharge. The specified physical and mechanical properties depend on defect concentration of a crystal structure [5, 6].

When we increase the defect concentration of the crystal lattice adhesion and diffusion processes become more active and the surface adhesive strength with a base enhances. Stability, bigger gauge and wear resistance increase of the surface layer characterize the changed surface.

Figure 2 presents the connection of steel plate wearing value, which is strengthened of ESM by steel 50 turning.

**Figure 2.** Dependences of steel plate wearing by steel 50 turning: 1 – after quenching; 2 – \(E = 0,022 \text{J}\); 3 – \(E = 0,25 \text{J}\); 4 – \(E = 0,73 \text{J}\); 5 – \(E = 1,15 \text{J}\).

The initial steel surface after heat treatment and strengthened with the spark discharge energy \(E = 0,022 \text{J}\) are characterised by the short period of the stationary wear and abrupt junction in the area of
“pest” degradation. There are wearing distinctive features of the modify sample with higher values in the pulse energy. These features are small wearing value at the stage of running-in ($h = 0.15 \ldots 0.175$ mm) and smooth transition in the area of the catastrophic wearing. Steel plate hardness enhances with the pulse energy increasing, has a maximum at $E = 0.73$ J and then starts to decrease.

We have analyzed the received linear connections of wearing and the sequels of the table. As a result, the biggest coating thickness and the high density of the crystal structure defects support the maximum hardness of the steel surface reinforcement at $E = 0.73$ J. Besides, the fractal dimension of the received structure $D_o$ is maximum at this value of the pulse energy. It verifies workability of the fractal dimension as a criterion for an optimum choice of technological modes and conditions of the ESM.

3. Conclusion

1. Scaling invariance of the fractal structure parameters means the correlation with it physical and mechanical properties, including durability. The connection between the fractal dimension of the hardened surface and its durability is appeared in identical change of these characteristics with increase of the singular discharge energy. Extreme points are situated in the same range of energies.

2. The fractal dimension can be considered as the topological characterization of the area. Internal state energy enhances with the fractal dimension increase. Connection between the fractal dimension and structural energetic properties are verified with the fractal size rising with increase of the crystal structure defect concentration. The comparative analysis of the change Do and $\Delta d/d$ confirms the conformity for purposes of the surfaces strengthened by the electrospark high-energy influence.

3. The analysis shows the presence of the fractal correlation of the surface characteristics with the spark discharge energy. It is possible to use the fractal dimension of the material structural state as a criterion for a choice of the optimum technological modes of the ESM and formation of the case.

References

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