Multifractal parameterization of metal structure dynamic evolution under high-speed surface heat treatment

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Abstract. The paper presents the results of experimental studies of the structural state peculiarities and the properties of steel surface layers after laser treatment. The study is devoted to the examination of relationship between the processes of self-organization and adaptability of structures emerging from laser radiation, and material properties using key synergistic basics and fractal theory.

1. Introduction
The current development of mechanical engineering is constantly raising the level of requirements for structural and instrumental materials, and therefore it requires their improvement or the creation of new ones, based on them, with special properties, in particular through various options for treatment by concentrated energy streams. In particular, there is a need to find a interrelation between the processes of self-organization, stability, structural adaptability formed by laser radiation, and the properties of materials, using key synergistic basics and fractal theory. Introducing quantitative measures of structures in the form of fractal dimension allows the description of various structural levels in multi-fractal analysis and the prediction of irradiated steels properties [1-3].

2. Research methods
The studied materials are: technical iron, carbon steels M1044 and W1-9/0,5.

Pulsed laser surface processing was carried out at laser equipment “Kvant-16” with a change in the radiation power density in the range of 80-150 MW/m². The degree of beam defocus (3-6 mm) and the duration of radiation (3·10⁻³ s - 6·10⁻³ s) allowed us to vary the density of radiation power within wide limits. Surface processing was applied on more than 7 samples of 10×10×15 mm for each hardening. Measuring different values, their average measures, standard deviations and trust intervals were determined at the level of reliability P=0,95 (Student's criteria was 2,447).

Microstructures demonstration were made on cross and lengthwise sections on the microscope Neophot-21. Measurements of microhardness were carried out on device with a load of 0,49 N. We stick to the standard rules of placement of prints, according to which the minimum distance between the centers of neighboring prints was 30 µm, from the center of the print to the end of the sample – 20 µm.

Multifractal parameterization of materials structure after laser treatment was performed using the freely distributed software. Digital micrographs of surface irradiated layers of steels were divided into 512x512 pix cells using the method of generation of coarse splitting measures. A scale increase of 500 times turned acceptable. The grains and interphase boundaries visible after the conversion of the images into the bitmap format in the graph editor served as the information units.
3. Results and discussion
The accuracy of the software calculation of multifractal characteristics: \( f(a) \) – spectra and \( D_q \) – spectra of the Rényi dimension was determined by the following conditions: \( D_{q1} \geq D_{q2}, q_1 \leq q_2, q > 0 \); for canonical spectrum, and \( D_{q1} \leq D_{q2}, q_1 \leq q_2, q > 0 \); for pseudo-spectrum.

As an example, figure 1 shows the characteristic areas of the micro-structure of irradiated technical iron prepared for multi-fractal analysis.

![Figure 1](image)

**Figure 1.** Splitting of the microstructure of technical iron with a mesh overlap: micrograph (a); a bit image of the structure with typical cells of 20x20 \( \mu \text{m} \) (b), 512x512 pix

(MZ - «melting zone», L/S - «liquid-solid state zone», SS - «solid state zone», SS/BM - transition zone «solid state/base metal»)

The obtained multi-fractal characteristics made it possible to estimate similarity \( (D_0) \), homogeneity \( (f_0) \), order \( (\Delta_q) \), adaptability of structures \( (\Psi^a) \), thermodynamic conditions of their formation \( (D_q) \), i.e. to track structural changes in the metal system, occurring due to external local laser exposure. On the basis of the calculated data findings steel M1044 (table 1), the distributions of multi-fractal steel structures characteristics after laser exposure to the depth of irradiated layers are constructed (figure 2).

As shown in figure 1, the irradiated layer consists of several characteristic zones: the melting zone (MZ, 1), the hardening solid state zone (SS, 3) and the transition zone (2,4).

It has been found that the maximum dimension of the self-similarity \( D_0 \) in the irradiated technical iron belongs to the dendritic structure of the melted zone, and the same structure has the maximum values of order \( \Delta_{100} \) and homogeneity \( f_{100} \), which decrease during the transition to the original metal structure.

The analysis of the structural characteristics given in table 1 and figure 2.b showed that there is degeneracy (degradation) of the structure order in transition zones 2 and 4.

For comparison, figure 2 shows the results of a multi-fractal analysis of the structure of the exposed areas of alloys with different original structure: technical iron with ferritic structure, steel M1044 with ferritic-perlite structure and steel W1-9/0.5 with structure, consisting of perlite grains and a secondary cementite mesh.
The degree of structural order in the irradiated layer is found to decrease with the increase of carbon content in steel (figure 2.b), minimum values are found for steel W1-9/0.5. This is due to the characteristics of its original structure, the long interphase boundaries between perlite grains and the cementite mesh, which does not completely dissolve during high-speed laser heating, which results in a minimum fractal dimension of the structure of this type of steel [4, 5].

Multifractal analysis of the structure of iron-carbon alloy irradiated areas with structural parameterization $\Delta_{100}$, $\delta^\psi$, $A^\psi$ allowed to establish also the boundaries of deterministic self-organization (the chaos adaptation) corresponding to transition zones 2 and 4. In these zones, the value of order parameter is $\Delta_{100} \leq 0$ which is an indication of the structure degradation of irradiated alloys in the transition zones, and the inability of this structure to self-regeneration. In mentioned zones, the processes of hypernonequilibrium phase recrystallization of alloys are carried out under conditions of ultra-fast heating and cooling.

The adaptation properties of structure were tested under the following conditions: if 1.3 $\leq \Delta_{100} \leq 1.475$, the sparsity values are $\delta^\psi=\Delta_{100}-1.3$, and the adaptability values are $A^\psi=\delta^\psi/0.37$; if 1.67 $\leq \Delta_{100} \leq 1.89$, then $\delta^\psi=\Delta_{100}-1.475$, a $A^\psi=\delta^\psi/0.53$ [6-8]. As it is known, the structure adaptation to external exposure takes place by restructuring multifractal sets under F-symmetry conditions [9-11].

### Table 1. Multifractal characteristic distribution after laser exposure on steel M1044 with different reference state

| Reference state before laser exposure | Zone          | Multifractal characteristic |
|--------------------------------------|---------------|-----------------------------|
|                                      | $\Delta_{100}$ | $D_0$ | $D_1$ | $D_{100}$ | $f_{100}$ | $\delta^\psi$ | $A^\psi$ |
| MZ                                   | -0.046        | 0.982 | 0.980 | 1.071 | 1.063 | -0.229 | -0.620 |
| SS                                   | 0.206         | 1.864 | 1.863 | 1.456 | 0.019 | 0.156 | 0.422 |
|                                       | -0.090        | 1.797 | 1.795 | 1.531 | 2.277 | 0.231 | 0.389 |
|                                       | -0.080        | 1.800 | 1.776 | 1.379 | 2.288 | 0.079 | 0.086 |
| Base metal                           | 0.224         | 1.777 | 1.774 | 1.333 | 0.344 | 0.033 | 0.078 |
| Volumetric-tempered (Martensite)     | 0.360         | 1.941 | 1.939 | 1.351 | 0.017 | 0.051 | 0.089 |
|                                       | 0.253         | 1.793 | 1.790 | 1.363 | 0.574 | 0.063 | 0.138 |
|                                       | 0.255         | 1.748 | 1.743 | 1.341 | 0.211 | 0.041 | 0.112 |
| MZ                                   | 0.299         | 1.000 | 0.998 | 1.326 | 0.00  | 0.026 | 0.071 |
| SS                                   | -0.033        | 1.602 | 1.599 | 1.718 | 1.974 | 0.418 | 1.130 |
|                                       | 0.396         | 2.000 | 1.998 | 1.465 | 0.00  | 0.165 | 0.446 |
|                                       | -0.043        | 1.807 | 1.805 | 1.351 | 0.00  | 0.051 | 0.138 |
|                                       | 0.215         | 2.000 | 1.998 | 1.567 | 0.071 | 0.267 | 0.723 |
|                                       | 0.363         | 2.000 | 1.998 | 1.533 | 0.00  | 0.233 | 0.630 |
Figure 2. Depth distribution of the main multi-fractal characteristics of the structure for technical iron, carbon steels M1044 and W1-9/0.5 after annealing and subsequent laser hardening: fractal dimension, D0 (a); degree of order, Δ100 (b); thermodynamic conditions of structure formation, D100 (c); structure homogeneity, f100 (d)

Using the example of steel M1044, the impact of the original structure state on the alloys structure and properties after laser treatment was assessed. For this purpose, multi-fractal analysis of steel M1044 microstructures was carried out before and after laser treatment in the annealing and volumetric-tempered state. The distribution of multifractal characteristics after laser exposure on steel M1044 with different reference state can be traced from the results in table 1. The trend of increasing fractal dimension of the structure in the irradiated layer of steel with a more dispersed original structure is well noted. There is also an increase in the homogeneity and ordering of the investigated structure in the SS area for steel M1044 with the original martensite structure [12].

Figure 3. Steel M1044 microhardness (a) and adaptability of structure (b) by depth of irradiated layer
Based on the obtained multifractal characteristic values for steel M1044 with different reference structure, the curves of change of microhardness (H) and adaptability ($A^\alpha$) of the material by irradiated zones depth are constructed (figure 3), characterizing the evolution of the adaptive and mechanical properties of the structure during the laser exposure, depending on the original structure state of steel and the structural elements size in the exposed areas.

It can be seen that the irradiated steel M1044 layer has the highest adaptive properties and hardness if the original, prior to the laser treatment, structure was a volumetric-tempered martensite structure. A similar trend in the distribution of multifractal characteristics after laser treatment can also be observed for steel W1-9/0,5 (figure 4), with the best adaptive characteristics, similar to steel M1044, of volumetric-tempered structure [13].

Figure 4. Steel W1-9/0,5 microhardness (a) and adaptability of structure (b) by depth of irradiated layer

Comparing the results of the analysis given in figures 3 and 4, it should be noted that the adaptability curves of the structure on steels with different carbon content after volumetric and surface laser tempering, are different. Thus, the hardening solid state zone of steel M1044 has both high hardness and high adaptability (flexibility) to external heat and force exposure, and steel W1-9/0,5 irradiated layer of high hardness has a low adaptability of the structure, that it, is able to maintain its properties under external loading for a sufficiently long time [14].

Figure 5. Fractal maps of adaptation for steels according to the state of the reference structure before laser treatment: steel M1044 (a), steel W1-9/0,5 (b)

Thus, on the basis of the found values of the adaptability and properties of metal, it becomes possible to select a steel type and some technological mode of laser treatment of product surface, ensuring either resistance to external heat and force loading (minimum adaptability) or adaptability to it through structural and phase transformations (maximum adaptability). The selection is determined by the
operating conditions of the irradiated products. In particular, a high structural stability during loading is desirable for a metal-processing tool, and the adaptability of structure to heat and force loads is desirable for parts operating under friction through moderate loads [15-18].

Evidence is provided by constructed fractal adaptation maps of the irradiated metal according to its structural state (figure 5).

Thus, the analysis carried out in this investigation revealed the relationship of the reference structure to a dynamic and laser-acting structure and showed the possibility of introducing its quantitative characteristic as a fractal dimension. This makes it possible to predict the degree of homogeneity, adaptation or resistance of the irradiated structure to external heat and force exposure under different operating conditions [19, 20].

4. Conclusion
The degree of order ($\Delta_{100}$) is a term used to estimate the relative order of the data elements (grains, subgrains, etc.) in the structure under study; it has maximum values in the melting zone of the surface of steels with the original martensite structure. The lowest values of $\Delta_{100}$ are observed in the SS zone of steel W1-9/0,5 if it has been subjected to laser exposure in the annealed state.

The homogeneity ($f_{100}$) of the melting zone structure is maximal in technical iron and has high values in steel with the original martensite structure. The homogeneity of the SS zone of the irradiated layer has the highest values for steel that has been found in the volumetric-tempered state before laser treatment.

Stability threshold values ($D_{100}$), or thermodynamic conditions of structure formation, are maximum in the SS zone for steels that had a martensite structure prior to the laser treatment.

The adaptability ($A^w$) of the irradiated metal, i.e., the resistance of the structures to external effects, depends on the original state and the coal content of the steel. Adaptability is high if the steel has undergone volumetric tempering prior to laser treatment. Furthermore, the adaptability of the SS zone is higher than the MZ in steel M1044, and, in steel W1-9/0,5, the adaptability is higher in the MZ.

Thus, the quantitative and structural analysis of the irradiated steels enables us to make a sound choice of steel type, and to prescribe pre-volumetric and laser tempering regimes in order to obtain the desired surface layers properties of products of different functional purposes: resistant to, or adaptable to loads.

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