Topological layered nanostructures with controlled functional characteristics induced by laser radiation on a solid surface

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Abstract. Models of the formation of roughnesses on the surface of materials and the movement of distributed flows in their presence are considered, which ultimately determines the functional properties of such topological materials of different compositions induced by laser radiation. The paper also presents simulation of crystallization of complex structures from a melt with an analysis of the morphology of the resulting crystalline structures, and shows examples of the occurrence of fractal dendritic formations. Different types of morphology are induced depending on the energy of the laser radiation and the duration of the heating; determining the final state of objects with the desired functional and structural characteristics. Using the methods of cellular automata, the models were obtained for both the distribution of crystallization centers and the growth of an individual cluster under the influence of diffusion mechanisms. The relationship between the resulting morphology and the modified parameters of the models used is analyzed.

Introduction

The uniqueness of laser technology is primarily determined by the synthesis of micro-nanostructured surface layers of different elements composition with a certain topology and with variable dimensional parameters under different durations of laser pulses (from continuous to femtosecond), which play a fundamental role for the needs of various applied problems, especially in aspect of the use of critical parts of mechanical engineering. Such 4D-technologies (firstly, with a spatial component, depending on the emerging laser-induced surface spatial structure, and secondly, with a temporary component – a variable time of laser irradiation to implement specific mechanisms of laser exposure to materials) have no competitive analogues for today. Here, at first glance, a paradoxical result arises when monolithic products have performance characteristics worse than the same products with laser-induced inhomogeneous/granular structures on their surface, synthesized by controlled way and in a given direction (cf. [1]).

In the paper, we will consider these very promising directions of the subject and demonstrate our achievements, which can form the basis of new technologies, taking into account laser-controlled modification of the structure and topology of the surface layers of a solid and/or thin multilayer
structures of different compositions deposited on it in order to obtain the necessary characteristics for objects of various purposes.

This is important feature of precisely laser methods for guiding such structures with controlled of their topology on the solid surface, which generally determines the physicochemical properties of the materials and thin films obtained in this technique[2], and will make it possible to implement the principle of a breakthrough jump in technology — «overtake, don’t catching up».

In a fundamental aspect, these controlled morphological characteristics, on the one hand, make it possible to solve the local problem of nanostructured dynamic surface modification in various time ranges — from continuous laser irradiation and melting in the millisecond ($10^3$ s) time scale to the femtosecond ($10^{15}$ s) time with laser ablation, and up to its onset threshold with the development of non-stationary laser-plasma complex processes with, accordingly, tearing out substances of different compositions from the surface of the sample and its subsequent deposition on the surface or restructuring of the electron-phonon states of matter. The structural phase transition as a function of the size of the nanoparticles may occur that make up the material processing in the same series of phenomena. A new state of the medium here arises for a certain size of nanoparticles and/or a characteristic scale of their spatial association in nanoclusters on the surface. But in the case of laser irradiation of the medium with such an induction of its different phase states, many new effects appear (compared with standard approaches), primarily dynamic ones with unique kinetics and elements composition.

On this path, it is possible to trace the entire chain of development of new laser technologies — from controlled structuring of the surface of the material in order to create the required functional properties in combinations of various elements composition to the use of such objects in final products with the necessary design characteristics, including in extreme operating conditions (strong vibrations, high temperatures, aggressive environment, etc.).

Thus, the conducted studies can be regarded as the initial stage for the development of laser-controlled processes of surface treatment of various materials, taking into account the inhomogeneities that arise on their surface. These heterogeneities and their stability determine the development and/or principal of trends in creating objects with the required application characteristics for use in specific products based on them (cf. [3]). The analysis of the impact of such inhomogeneities on behavior of dynamic processes during laser processing of materials is a subject of our consideration in present paper.

1. Basic principles and preliminary results

Of particular importance is the production of nanostructured materials with the required characteristics in the formation of surface micro- and nanostructures. One of the methods for exciting such granular structures is nanostructuring of the surface when the sample cools after laser heating and melting of the surface of the material during surface treatment of materials. Another possibility is the laser ablation of the sample substance, firstly by, with its deposition on the surface of another object, secondary, e.g. on a transparent substrate located directly above the irradiated sample.

Further development of these methods is associated with controlling the parameters of micro- and nanostructures formed by different mechanisms when exposed to laser radiation with different parameters both in time and space domains. This is especially important for applications in obtaining materials with certain functional characteristics based on laser technologies.

It is important that in the case of a surface laser melt of a sample and the formation of a liquid phase, various dynamic modes can be realized, and, in particular, due to the arising hydrodynamic nonlinear processes of various scales the spatially extended surface regions are created with a variable topology of granular structures depending on the specific scheme and laser exposure conditions. Obtaining such new structured materials with controlled surface topological characteristics is an urgent problem of modern materials science and nanotechnology, in which laser physics methods can play a dominant role.
However, diagnostics of high-temperature processes accompanied by a laser melt of the substance on the surface of the sample under study, directly during laser exposure in the interaction region itself, is difficult due to the presence of both the erosion plume arising directly above the irradiated surface and the natural radiation of the surface heated to a high temperature material. This fundamental problem prevents the use of direct and highly informative methods for recognizing nonlinear optical images by high-speed methods for recording video images and machine vision for the study of the real-time laser exposure zone itself. They are of most interest in the aspect of studying physical mechanisms that require regulation and are responsible for laser-excited hydrodynamic processes and instabilities in the surface melting of solids, as well as for developing methods for directly controlling the nonlinear wave processes and phenomena directly during laser irradiation. We implemented this by using a monitor of special type (cf. [4]) in a single layout of an intelligent laser technological complex, which is a prototype of a product ready for commercialization.

This two channel pump-probe system in general configuration includes a separate complex for visualization of laser-induced processes (laser monitor) with the corresponding characteristics, which provides (at a wavelength of probe Cu-laser radiation of 510 nm):

- the ability to visualize in real time the area of laser processing of the surface of the material in the presence of strong thermal radiation arising from the erosion / laser plume directly above the surface to be treated;
- spatial resolution of the recorded image – order10 microns;
- temporary resolution of the registration system – not worse than 1 ms;
- amplification/gain of the radiation reflected from the visualized surface – about $10^4$.

In addition, to measure the temperature of the processed surface, an original high-temperature micropyrometer is used that meets the following requirements [5]:

- range of controlled temperatures – from 2000 °C to 5000 °C;
- time resolution – no worse than 0.5 ms.

We made detailed measurements to control the resulting micro- and nanostructures using the example of surface modification of graphite samples / glassy carbon under laser irradiation (cf. [4-6]). The patterns obtained here can be generalized to other materials, but studies with carbon /metal-carbon compounds are the most promising for future breakthrough dual-use technologies.

The properties of the samples after laser irradiation were studied using atomic force microscopy (AFM) – an INTEGRA scanning probe microscope in contact mode with an accuracy of about 10 nm in the scanning plane. The result of sensing the material are the AFM-images of its surface.

The measurements revealed the dependence of the morphological properties of the generated nanostructures on the distance to the center of the laser irradiation region (Fig. 1). It turned out that for different distances the mechanisms of their formation have a different nature. Signs of the formation of a melt directly in the center of the laser cavity with the simultaneous deposition of matter from the gas phase beyond the boundaries of the exposure region were recorded (see Fig. 2) [7-12]. A control image of the unperturbed surface of glassy carbon is also shown in Fig. 2. In this case, a study was carried out of graphite samples after laser irradiation with an irradiation time of 1 to 10 seconds with average powers $P = 30 \div 76$ W. The most striking signs of glassy carbon melting are detected at a maximum laser power of $P = 80$ W for a laser exposure time of at least $t = 3$ s under normal conditions – a pressure of the order of 1 atm, room initial temperature. Therefore, for analysis, this conditional boundary in terms of exposure time was adopted.
Figure 1. Temperature distribution in the region of laser exposure to a glassy carbon sample. Distances from the center of the laser spot on the target surface are indicated in relative units.

Figure 2. Image of the surface of a glassy carbon sample obtained using an atomic force microscope (on the left – 2D images, on the right – 3D images: a) formation of submicron and micron defects inside the laser cavity, irradiation time $t = 2$ s, average power 60 W; b) the deposition of particles beyond the boundaries of the laser exposure region, the irradiation time $t = 5$ s, the average power 80 W; c) image of the glassy carbon surface before laser exposure.

2. Models of the formation of roughness on the surface of materials and the movement of molten streams in their presence

We used the hydrodynamic model of the motion of molten flows to determine the basic geometric characteristics of the resulting coatings in a laser experiment.

To test the capabilities of the developed algorithm, a series of calculations was performed for various values of Reynolds numbers (Re) and certain sizes of the computational domain with several cavities of the same type with different configurations (shown on the left in Fig. 3).

Calculations showed that for small Reynolds numbers the main flow captures the cavity (Fig. 3a), while moderate Re – in addition to the main flow a vortex forms in the channel (Fig. 3b, c). The motion in this vortex is carried out clockwise, i.e. in the area of contact of these currents, they are directed in the same way.

An analysis of the results of the flow in the presence of a «long cavity» shows that the vortex occupies the entire cavity, but its center shifts to the right boundary (in the direction of the main current) (Fig. 3d.)

With an increase in the Reynolds number, the vortex appears to expand, occupying the entire depression and «displacing» the main flow into the channel (Fig. 3 c).
The influence of the channel geometry is clearly noticeable in the case of a deep depression – another one is formed under the main vortex (Fig. 3e, f). The direction of motion in this vortex is opposite to the direction of motion of the first vortex.

Using the convection model, we estimate the temperature field and velocities of the system under consideration under various initial conditions (Fig.4).

**Figure 3.** The melt flow in the channel: with three triangular depressions at Re = 10 (a), Re = 100 (b), Re = 1000 (c); with one rectangular long shallow hollow Re = 100 (d); with four rectangular depressions Re = 1000 (e); with one rectangular Re = 100000 (f). The deposition region configurations are rectangular (1) and triangular (2) depressions (shown on the left).

The initial temperature was calculated as the average of the temperatures of the upper and lower boundaries of the computational domain. The Prandtl number was chosen equal to 1, the Rayleigh number equal to 2000, which corresponds to the conditions for the occurrence of convection. Figure 4 shows graphs of the temperature field and relative velocities for the case of heating the lower wall to 5000 C (Fig. 4a, b) and 3000 C (Fig. 4c, d). The calculation of the temperature field was carried out from bottom to top; the velocity field from left to right.

**Figure 4.** Graphs of the temperature field (left) and the velocity field (right) when the lower boundary is heated to 5000 C (a), (b); up to 3000 C – (c), (g).

The presence of vortices in the velocity field, which are localized in the center of the computational domain, was revealed. The central vortices are elongated vertically, and the nature of the vortices is symmetrical about the horizontal axis. In addition, two central vortices have extensions in the upper right part; in the lower part of the computational domain, there are two small vortices, which indicates the presence of instability near the heated substrate.

Thus, by analyzing the graphs of the temperature and velocity fields, it can be assumed that the deposition and formation of film islands is most likely in the depressions of the substrate (Fig. 3). In this case, the deposition zones are marked by broken lines ABCD – for a rectangular depression (Fig. 3 (1)) and EFG – for a triangular depression (Fig. 3 (2)).
They also carried out modeling of emerging islands in these regions in the diffusely limited aggregation approximation.

In Fig. 5 on the left shows the profile of the island for a shallow rectangular depression, in which the nanostructure is deposited only on the lower boundary. In the framework of the model for such a case, the lower boundary of the computational domain is chosen as the seed structure.

The profile of the island of the film was modeled on a rectangular computational domain of 100 in arbitrary units, the number of particles was set as \( N = p \times S \), where the parameter \( p \) – determined the viscosity, and \( S \) – the area of the computational domain.

The influence of the probability of adhesion (sc) and viscosity (p) on the film profile can be estimated by our approach.

![Image](image.png)

**Figure 5.** Aggregation center – line at the lower boundary of the computational domain:

- a) \( p = 0.01, \text{sc} = 0.1 \);
- b) \( p = 0.1, \text{sc} = 0.5 \);
- c) \( p = 0.5, \text{sc} = 1 \);
- d) \( p = 0.8, \text{sc} = 1 \).

With this deposition of particles, the resulting structure resembles «sticky fingers» – clusters grow from the surface of the substrate into the bulk of the colloidal system (during the laser-ablation process). The distortion of the structure is due to the fact that at the height corresponding to the area of the particle throw-in, «gaps» are formed.

With an increase in the probability of adhesion, the film profile becomes smoother and stretches in the horizontal direction, and the computational region becomes more filled in the vertical direction, which indicates an intensification of the island formation process. At low values of the probability of adhesion, the island profile is more heterogeneous, the computational domain is weakly filled, which is confirmed by the values of fractal dimension (cf. \([1,13,14]\)).

### 3. Modeling the formation of dendritic structures

As a model for describing the process of formation of crystallization centers, a kind of cellular automaton was chosen in the implementation of the «Life» process, as a mathematical object that is a discrete dynamic system \([15]\). Essentially, cellular automata are artificial/synthetic objects whose behavior is for the most part determined by simple locally applicable rules. In these rules, space is a uniform grid, each cell of which contains information about its state, and time is discrete. The laws of such a construction are a small number of rules, the main of which are described by a transition table, according to which the cell calculates its new state at each clock cycle (minimum time interval) based on its current state and the states of its neighbors. Each cell can be in two states – active/active or frozen/passive, i.e. empty. The state of any cell is affected by the state of neighboring cells. In time, these states are discrete in accordance with certain rules (genetic laws), consisting of 2 points.

The first one is survival or death. If a living cell has less than 2 or more than 3 neighbors in a neighborhood of 8 cells, then in the next generation it dies (modeling of real conditions – lack of resources or saturation); otherwise she survives.

The second one is birth. A living cell appears in an empty cell if the original cell has exactly 3 neighbors. The death and birth of all objects occurs simultaneously. Sometimes a colony of cells gradually dies out, but this may not happen immediately, and only after a lot of generations change.

Most often, the initial configurations either go stable and stop changing, or go forever into vibrational mode. Moreover, configurations that did not have symmetry at the beginning of the process show a
tendency to transition to symmetric forms [16]. The acquired symmetry properties in the process of evolution are not lost, and the symmetry of the configuration can only be enriched.

The task of forming dendritic structures within the framework of the approach under consideration was realized by us in the MATLAB medium according to the algorithm presented above, and the configurations of the resulting clusters were calculated. The computational domain was selected with a size of 100x100 arbitrary units, and the populated cells were filled randomly. Various configurations of the cluster system can be obtained by varying the control parameters of the population (percentage), which in our task play the role of the melt remaining in the laser exposure zone after heating by laser radiation, and are presented as a percentage of the calculated area and the number of epochs that can be compared with the time of cooling and crystallization. This description corresponds to the dendrite growth model from a supercooled melt (non-separation solidification with complete trapping of the impurity) [17].

The results of this simulation are presented in Fig. 6-8. It can be seen that with an increase in population, the number of formed simple clusters increases. In addition, with an increase in the number of epochs, the formation of stable closed structures consisting of a larger number of particles (stable crystallization centers) occurs.

![Figure 6](image1.png)

**Figure 6.** The simulation results for the following values of the control parameters: percentage = 20, epochs = 10.

![Figure 7](image2.png)

**Figure 7.** Simulation results for parameter values: percentage = 30, epochs = 100; a – view of the region in era No. 6, b – view of the region in era No. 100.

![Figure 8](image3.png)

**Figure 8.** The simulation results for parameter values: percentage = 10, epochs = 10.

To grow an individual crystal, we used a computer model of dendrite aggregation, limited by diffusion at a variable initial particle concentration (DLA method), in a two-dimensional cellular automaton using the Moore neighborhood. The model under consideration is a logical generalization,
firstly, of the Witten-Sander model, in which, however, it is impossible to vary the concentration of the initial particles, and therefore the fractal dimension of the resulting clusters always takes the value 1.71, and, secondly, the Charles Bennett model, in which the particle concentration is a variable, but the Margolus neighborhood is used [18]. Particle aggregation limited by diffusion occurs when randomly moving particles adhere to the initial nucleus represented by a fixed object and gradually increase it.

In contrast to the diffusion equation, modeling by cellular automata does not miss such important physical details as the impermeability of bodies and the final velocity of particle propagation. The advantage of such modeling is the absence of the need to use differential equations, which cannot always be solved with sufficient accuracy. The disadvantage of differential equations is also that they can only describe the change in the total concentration of particles, while modeling the motion of individual particles with their help is impossible. When using cellular automata, such difficulties do not occur.

The structure of simulated fractal clusters substantially depends on the probability of adhesion (see Fig. 9). The higher the probability of adhesion, the more branched the fractal structure is formed, which is confirmed by the values of the fractal dimension [19]. Both modeling methods can be used to analyze and simulate the problem of the formation of structures from a melt/liquid in the case of surface crystallization. This approach also describes rather well the nucleation and distribution of stable crystallization centers in the region under consideration, which is especially important in the presence of various impurities, for example, in systems with different elements composition and in composite alloys. The diffusion aggregation method takes into account the intricacies of real physical processes and is promising for the analysis of the formation of a single crystal. In addition, this method and its modifications can be used when considering the process of converting dendrite to spherulite or crystal from a melt drop.

![Figure 9. Model images of fractal structures of the cluster with the probability of adhesion: a – 0.01, b – 0.05, c – 0.5, d – 0.98.](image)

All these models are of fundamental importance when it is necessary to connect the surface structural features of a material with its functional and structural properties during controlled laser processing of products.

In the next paragraph, we consider the process of propagation of such characteristics in the framework of the diffusion model, which is adequately applicable to the phenomena of surface propagation of the specific feature/melting.

4. Mathematical modeling of diffusion of surface state/feature propagation processes under laser-induced melting effects and local inhomogeneities in multi-beam schemes
The driving force of the process of diffusion of any sign / state is the relationship of various spatial localized structures in time. Each new fragment of such a structure becomes a source of state transfer for its next/neighborhood potential fragment perceiving this state. Thus, the more connected fragments
arise, the more information they exchange and the higher the probability of the spread of this state becomes. The process is gradually replaced by the opposite tendency, which is caused by a decrease in the remaining free space on the surface (saturation process). Its homogeneity, as well as special conditions (impurities, defects), can adversely affect the diffusion rate of the feature, creating barriers in both cases when a new state propagates.

To study such processes, we will focus on the approaches of the epidemiological model [20]. This SIR (Susceptible Infected Removed) model describes the interaction of various fragments / clusters of particles (agents) in different states. When describing this process, the model takes into account 3 possible modes: «Vulnerable» – S (t) – Susceptible, ready to accept the sign; «Immune» – R (t) – Removed, will not perceive the sign; «Infected» – I (t) – Infected, the fragment has already successfully changed its state and is ready to distribute it. Within the framework of this approach, two parameters are also used that characterize the model process – the rate of propagation of the trait (β) and the rate of «Immunization» (γ), which can be interpreted as the rate of blocking the trait.

The SIR model under consideration, without taking into account the appearance of new signs and their disappearance in the case of a fixed number of source of the sign N, such that \( S(t) + I(t) + R(t) = \text{const} = N \), is the Cauchy problem for a system of ordinary differential equations.

Without details of the calculation of this problem with the corresponding equations, we present below only the final demo images for the process under consideration.

As already mentioned, a cellular automaton is presented as a dynamic system consisting of homogeneous cells forming a settlement network. The state of each cell is determined by the cells located around it, which form a neighborhood of the finite state machine. In this case, we use the Moore neighborhood of order 1 of the nearest 8 neighbors (see Fig. 10).

**Figure 10.** The neighborhood of Moore is about 1 for the 8 closest neighbors (marked with a different color / background).

The model conversion function meets the following rules.

1. An agent/cluster of particles corresponds to one cell, which can take three states: 0 – ready to accept a symptom/state, 1 – symptom/state accepted, 2 – symptom/state not pleasant.
2. An automaton makes a decision on the acceptance of a symptom/state, focusing on the state of its neighbors. At the same time, we denote this decision as 1 if the current cell is in the «ready to accept symptom/state» and the nearest cell is in the state when the symptom/state is already accepted; then the probability of accepting the attribute p is generated. If \( p < \beta \), where \( \beta \) is a fixed threshold value (trait propagation speed), then the cell goes into state 1, and the agent takes this state. We denote the value 2 for the cell when in state 1 the probability is generated not to accept this state – the probability q. If \( q < \gamma \), where \( \gamma \) is the «immunization» rate, then the cell goes into state 2.
3. The process ends if the estimated time is reached or the attribute can no longer propagate.

The proposed model allows you to set the following parameters: the area of the calculation area, which is the number of agents (N), the quantities \( \beta \) and \( \gamma \) are the probabilities of accepting or not accepting the attribute, respectively. It is also possible to specify various initial states of the model, which is realized through determining the initial point of the source and / or boundaries for the propagation of the feature.

Images of the distribution of the trait, according to the implemented method of the cellular automaton, are shown in Fig. 11-15.
In Figures 10, 11 the cells in state 0 are marked in red, green in state 1, and blue in state 2.

![Image](image_url)

**Figure 11.** Solution of the trait propagation model by the cellular automaton method for $\beta = 0.029$, $\gamma = 0.01$, $T = 100$ arbitrary units: a) $N = 100$, $S(0) = 1$; b) $N = 10000$, $S(0) = 10$.

In Figure 11b, the propagation of the feature begins from the center of the computational domain, which sets the growth center of the feature (in our case, this is the area of laser exposure); moreover, the radius $r$ corresponding to the initial number of particle clusters interacting with the agent and taking the sign is equal to 10 cells. This option corresponds to the case of the propagation of a feature from the center of laser irradiation of the surface of the substrate to its peripheral regions.

Figure 14 shows the options when the propagation of a sign begins from the angles of the computational domain, which corresponds to irradiation at the edges of the sample and/or at contacts with other regions of the substrate where this symptom has already arisen. In this case, a small rate of propagation of the state is observed.

![Image](image_url)

**Figure 12.** Solution of the state propagation model by the cellular automaton method for $\beta = 0.029$, $\gamma = 0.01$, $N = 10000$: a) $T = 100$ in arbitrary units, the lower right corner; b) $T = 500$, lower right corner; c) $T = 100$, the upper left corner; d) $T = 500$, the upper left corner.

Figure 13 shows the options when the propagation of a characteristic begins from one of the boundaries of the computational domain, which corresponds to contact with the external boundary with this attribute. In this case, the greatest propagation rate of the state over the surface of the sample is observed.
Analyzing various options for calculating the propagation of a feature starting from the angles and boundaries of the computational domain, we can assume that they correspond to cases of penetration of the feature from the outside, for example, the influx of energy from neighboring areas when using multi-beam laser radiation to irradiate the sample.

From Figure 13, the effect of the initial conditions can be estimated. Here, these initial conditions are the radius \( r \), i.e. initial amount of interacting fragments / local inhomogeneities on the surface of the sample that have taken the state (under the influence of laser radiation). This approach allows us to estimate the number of initial fragments on the surface of the sample with this feature. Thus, due to the selected initial conditions (experimental conditions), the resulting distribution of the feature has more indented boundaries, which requires analysis taking into account the size of the fractal dimension [20].

**Figure 13.** Solution of the statepropagation model by the cellular automaton method for \( \beta = 0.029 \), \( \gamma = 0.01 \), \( N = 10000 \): a) \( T = 100 \) arbitrary units, the upper boundary of the computational domain; b) \( T = 500 \), lower bound; c) \( T = 100 \), the left boundary; d) \( T = 100 \), the right border.

By comparing the areas of the figures defining the initial conditions and the corresponding calculation results, it becomes possible to assess the growth of the state/development process (Fig. 15).
From the above figures, the dependence of the change in the nature of the diffusion pattern for the development of the state/process on the size of the studied areas of laser irradiation and the initial conditions of influence on them is obvious. For example, the highest rate of propagation of a state is observed when a feature is introduced into the system from outside with high intensity. The proposed approach allows, to a first approximation, to qualitatively evaluate and illustrate the nature of diffusion, for example, during surface melting processes under the influence of laser radiation in different geometries and experimental designs.

Based on the proposed models, it becomes possible to evaluate the relative growth rates, for example, various hydrodynamic processes / melting on the surface of the sample.

Thus, based on these results, an algorithm is proposed for predicting the development of new technological conditions on the surface of products under the influence of laser radiation with an appropriate choice of key control parameters for the corresponding processes.

**Conclusion**

Modification of the surface of solids by the action of laser radiation has long occupied an important place in fundamental science and in the development of new technologies. This method is highly versatile, since the laser beam can be controlled in time and space, as well as accurately dose and regulate the radiation energy. The use of lasers with different wavelengths and durations of radiation determines a wide range of materials under investigation and modifiable, as well as various techniques for changing characteristics for a specific material. By this approach, we can analyze the experimental data on the formation of fractal clusters of various types as a result of crystallization from a stainless steel melt after exposure to pulsed laser radiation. These experiments were examined using various mathematical models, including those based on cellular automata.

In conclusion, we emphasize that the noted features of the manifestation of fundamental effects and their applications in nanostructured thin-film solid-state systems allow us to speak of the formation of a new direction – topological photonics and optoelectronics, which have an undoubted practical perspective, in particular, in the direction of femtosecond nanoelectronics [1,14]. The fundamental problem here is the comparison of laser-induced topological parameters of such structures with their functional physical properties. In full, this task is hardly solvable, but even finding dominant trends is of considerable interest.
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