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EVOLUTION OF STEEL SURFACE LAYER STRUCTURE AND PROPERTIES DURING PULSED LASER PROCESSING

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It is established that temperature gradients and thermal stresses appearing in metal zones irradiated with surface melting contribute to liquid convective mixing at a rate of 10^3 cm/sec and also to partial or complete carbide dissolution. As a result, a significant amount of textured metastable retained austenite (40–60%) is fixed, which has high dispersion of the structure (dendrite cross section is 5–9 nm). This leads to anisotropy of the main operating properties of irradiated products and increases wear resistance if the irradiated layer is under compressive stresses during operation. It is established that in the case of thermal deformation laser treatment without melting a steel surface the effects of local plastic deformation appear within irradiated zones, which leads to austenite dynamic polygonization, and after rapid cooling to formation of hereditary fine needle martensite. The physical nature and structural organization of the "white zone" formed around carbides in steel under the influence of pulsed laser radiation is studied. A "white zone" is a fine austenite-martensite structure with a martensite lath size of ~150 nm. Existence within laser-hardened steel of large amount of fine carbides (more than 40%), surrounded by "white zones", contributes to creation of a special product working surface structural state. This has high microhardness values and is indifferent to external temperature and force loading during operation. Quantitative multifractal evaluation of the structure parameters of irradiated steels is conducted. This makes it possible to designate laser processing regimes in order to obtain structures within product surface layers that are resistant to external loads or adaptable to them.

Keywords: laser processing, steel, structure, properties.

Introduction

Structural changes within pulsed laser action zones proceed under conditions of a high temperature and powerful thermal "shock". During local heating of a steel surface there is high-speed phase recrystallization and quenching of a thin outer metal layer with formation of thermal (due to nonuniform heating) and structural (as a result of phase transformations) stresses. Under action of these stresses microvolumes of a heated metal surface, surrounded by "cold" walls of unheated metal, experience local plastic deformation, and also synchronous occurrence of dynamic recovery, polygonization, and mass transfer processes whose completion is determined by heating and cooling rates. In these processes there may be a certain contribution of thermal expansion coefficient anisotropy for neighboring grains and a boundary within the volume of phase expansion in multiphase materials (for example within steel) [1–4].

As a result of a material strengthening effect during laser action not only martensitic transformation, partial or complete carbide dissolution, impregnation of a matrix by their components are achieved, but also

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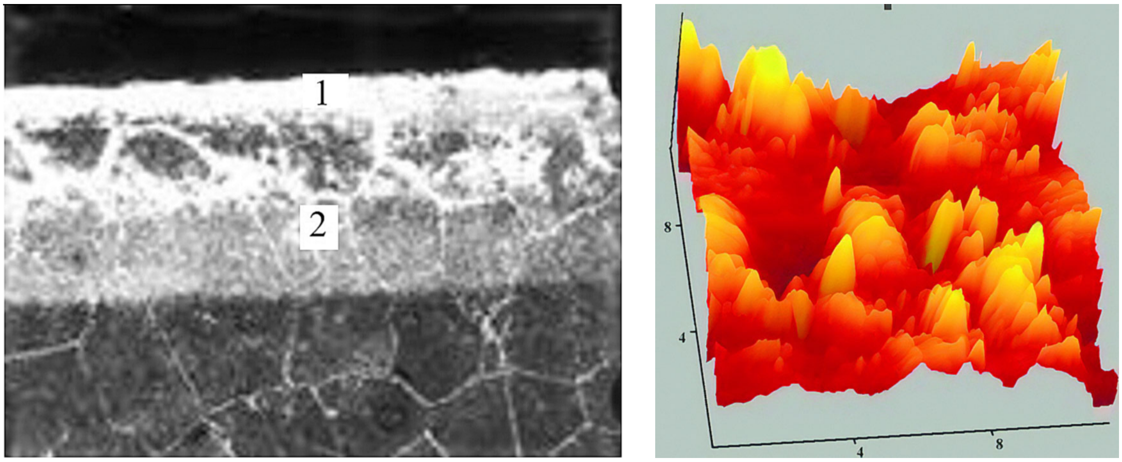


(a) (b)

Fig. 1. Microstructure of laser hardening zone from liquid (1) and solid (2) conditions on steel Kh12M (a), scanned image of surface irradiated with melting (b).

high-temperature work hardening, an increase in crystal structure defect density, plastic shear under the action of stresses, that are different in nature.

Physical models of phenomena arising within materials during laser treatment considered in this work make it possible to form within steel surface layers a required prescribed structure exhibiting the desired level of operating properties.

Research Procedure

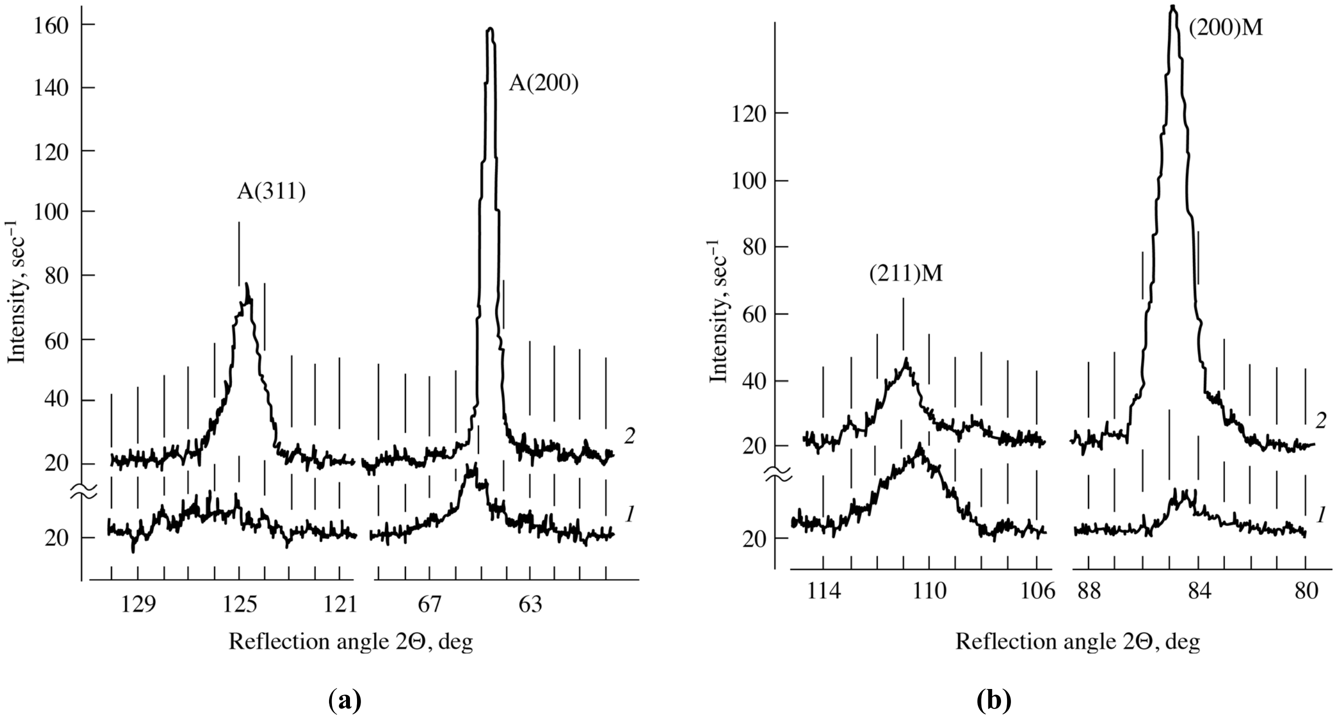
Materials for this study were: steels 45, U10, Kh12M, R6M5, and R18.

Pulsed laser radiation was conducted in a Kvant-16 production unit. Measurement of radiation energy, degree of beam defocusing (3–6 mm), radiation pulse duration $(1\text{–}6)\cdot 10^{-3}$ sec made it possible to vary radiation power density over a wide range (70–250 $\mathrm{MW/m^2}$). Phase composition identification and a study of the material structure after laser treatment was accomplished by several methods: metallographic, X-ray, a study of the fields of laser treatment using a scanning probe microscope in an atomic force microscopy regime, hardness measurement, etc.

Research Results and Discussion

Interaction of pulsed laser radiation with metals is accompanied by a complex set of structural self-organization effects. Irradiated areas have a heterogeneous structure and generally consist of zones of laser hardening from a liquid and solid (austenitic) condition, differing in formation temperature range, phase composition, degree of etching capacity, and hardness (Fig. 1a). We consider steel structure formation features within irradiated surface layers successively, starting from a melted zone.

It has been established by experiment that within an irradiated and melted surface zone metal temperature gradients and thermal stresses develop facilitating convective movement of liquid at a rate of 10^3 cm/sec, and also in spite of an extremely short laser pulse time (10^{-3} sec), partial or complete dissolution of material original structure carbides [5, 6].



(a) **(b)**

Fig. 2. Textured effects within surface layers of steels Kh12M (a) and R6M5 (b) after bulk hardening *(1)* and laser treatment with surface melting *(2)*.

As a result there is a change in melted metal chemical composition, the martensitic transformation point is lowered, and a significant amount of metastable residual austenite is recorded (40–70%).

Analysis of the laser melting zone microstructure using a scanning tunnel microscope shows (Fig. 1) that dendrite or dendrite cells of high dispersion are noted (dendrite cross section is 5–9 μm). The laser melting zone hardness is 8–9 GPa.

An important structural feature of melted spot zones recorded during X-ray structural studies is an anomalous ratio of austenite diffraction line intensity within steel Kh12M (Fig. 2a) or martensite within steel 6M5 (Fig. 2b). This points to development within surface melted layers of texturing effect (crystallization texture).

It should be noted that formation of an austenite texture is apparently connected with the preferred orientation of sub-grains with a metal surface layer, arising as a result of metal directional crystallization after the end of a laser pulse, and also with features of the material stressed state during laser treatment. The martensite texture within irradiated steel R6M5 is prescribed by a regular crystallographic bond of its lattice with an austenite lattice [7–9].

Some possibilities are determined in this work for use of texture causing property anisotropy with steel surface layers in order to improve production properties of irradiated objects. For this purpose, bend tests and impact strength tests were conducted on specimens of steels R6M5 and R18 irradiated in different regimes and by different schemes.

The strength of specimens in bending was determined using an IM-4A machine, and impact strength of specimens without a notch was tested in a KM-5T pendulum hammer. The specimens used were 4X6X55 mm in size, one side of which (6X55 mm) was subjected to laser radiation with radiation power density of 10–150 MW/m^2. It should be noted that use of specimens of standard cross section gave rise to a requirement for stiffening the degree of the effect of thin strengthened layer on measured properties.

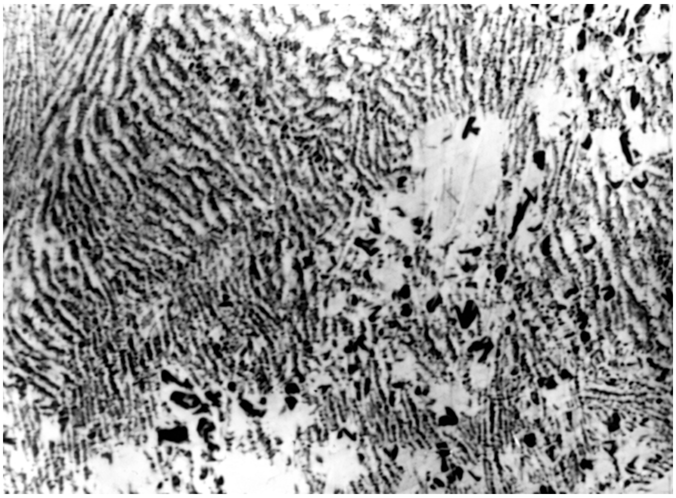


Fig. 3. Melt microstructure in steel Kh12M in hardened from liquid condition after laser cementation.

Table 1
Steel R18 Mechanical Properties before and after Laser Treatment

Treatment regime	$\sigma_{\text{ben}} \times 10$, MPa		$a \times 10^{-1}$, MJ/m^2	
	compression	tension	compression	tension
Standard heat treatment (quenching and tempering)	272 ± 7	272 ± 7	3.2 ± 0.2	3.2 ± 0.2
Laser treatment with surface melting	258 ± 7	32 ± 7	2.8 ± 0.2	0.2 ± 0.2

During testing a laser-hardened layer was under the action of compressive or tensile stresses depending upon the location with respect to the laded element.

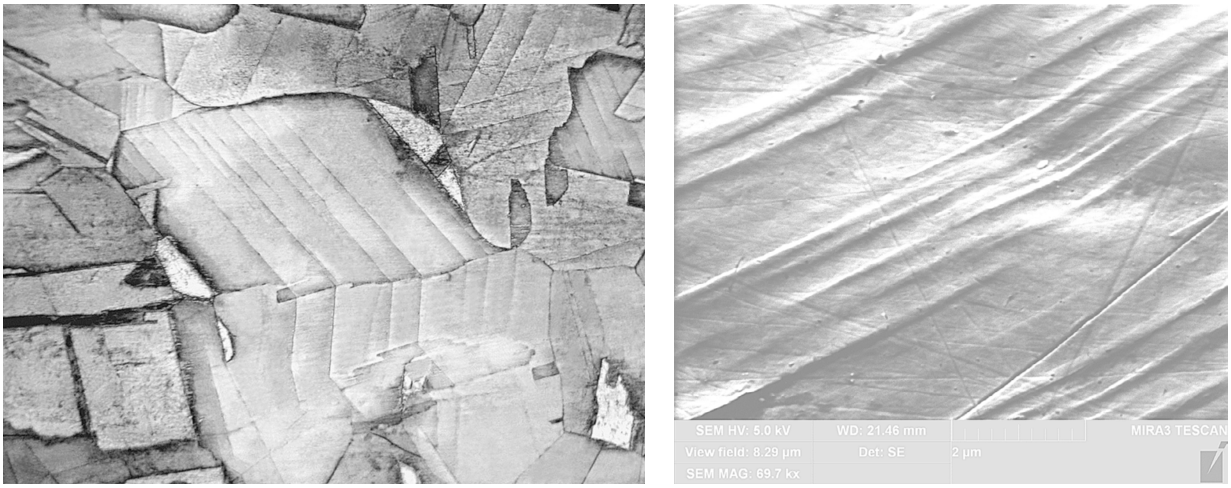
Before irradiation specimens were given standard heat treatment in order to remove internal stresses after specimen grinding to a prescribed size tempering was performed at 400°C, and also visual monitoring for absence of cracks or other defects.

As a result of tests (see Table 1) it was established that in the case of action on an irradiated layer of compressive stresses specimen strength is hardly reduced, but in the case of action of tensile stresses there was an increase in the tendency of specimens towards brittle failure.

It may be concluded that in order to improve object operating capacity it is necessary to perform radiation for those parts of a working surface that is subjected to operation of compressive load action.

A specially significant role of texture formation is played during performance of laser alloying of steel surface layers of coatings of different composition. In particular, during metal physical studies such features have been revealed of the microstructure of laser cementation zones (Fig. 3) as floating from powder coatings of fine carbon particles which are arranged within irradiated metal at grain dendrite boundaries.

In this case alongside texture effects presence of graphite platelets within irradiated zones reduces the friction coefficient at an irradiated object working surface, fulfilling the role of a solid lubricant.



(a) **(b)**

Fig. 4. Traces of local plastic deformation within copper alloy (a) (optical microscopy) and within austenitic steel (b) (STM) after laser treatment.

The factors listed in combination with high fineness of the structure in irradiated zones has a favorable effect on quality and operating properties of material surface layers, in particular they increase hardness and reduce friction coefficient in tribological contacts.

As is seen in Fig. 1a, beneath a melted zone over the depth of an irradiated region there is formation of a laser hardened zone from a solid (austenitic) state with hardness 11–11.5 GPa.

During clarification of features of metal structure formation within this zone it has been considered that the laser treatment process has fast heating and cooling rates; a lack of exposure at the heating temperature, high temperature gradients of the depth of material. This leads to development of thermoelastic stresses that are different in nature.

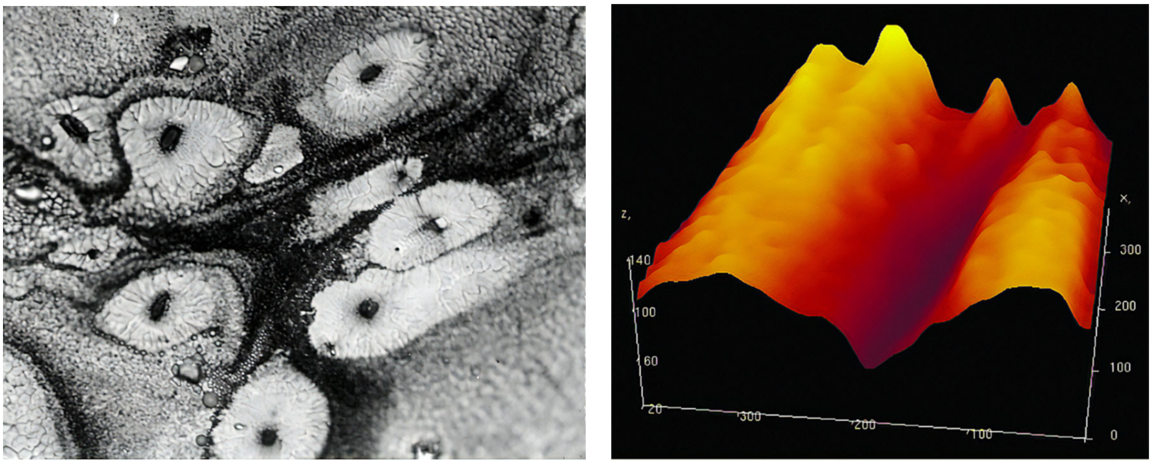
Under the action of stresses within micro-volumes of a material surface irradiated without melting local plastic deformation develops that leads to preparation of crystal structure high defect density, an independent accelerated mass transfer mechanism, and a good set of mechanical properties.

With the aim of developing structural phenomena of local plastic deformation effects a series of metallographic studies was conducted on “model” materials: single-phase copper and nickel alloys, not having phase transformations, and also on austenitic steel. Irradiation was performed without melting of a previously polished specimen surface.

As is seen in Fig. 4, after laser radiation within the quenching zone from a solid state the effects detected are a sign of plastic deformation in the form of thin lines or slip bands parallel to each other, and also both one and several slip systems [10, 11].

The main local deformation parameters have been determined by calculation in [11]: shear stresses within the laser operation zone comprise 200–250 MPa, the relative deformation rate reaches values of $(3–5)\cdot 10^2$ sec^{-1}, and residual deformation is 6–9%.

It has been established that as a result of application of dynamic thermostriction effects of phase work hardening during $\alpha \rightarrow \gamma$-transformation within quenching zones from a solid state there is dynamic polygonization of austenite with formation of sub-grains with a size of 200–300 nm with a high dislocation density (10^{11} cm^{-2}). This makes shear difficult during reverse $\gamma \rightarrow \alpha$-transformation and facilitates retention within irradiated metal of a sufficiently high amount (25–40%) of residual austenite. After rapid cooling, apart from dispersed austenite,



(a) **(b)**

Fig. 5. Microstructure of laser hardening zone on steel Kh12M (a) and 3D-image of "white zone" structure (ASM) (b).

within laser hardening zones from a solid state an inherited-finely acicular martensite and carbide phase is retained, which plays an important role in forming eh irradiated metal structure and properties.

As metallographic studies of laser hardened steel have shown, around carbide inclusions there is formation of so-called "white zones" (Fig. 5a) exhibiting low etching capacity and increased hardness [12–14].

It has been shown that the physical nature and structural organization of a "white zone" is connected with development within a "carbide–steel matrix" composite boundaries of stresses caused by different thermophysical coefficients, and also stresses during shear $\alpha \rightarrow \gamma \rightarrow \alpha$-transformation, etc.

As a result of stress relaxation around carbides there is formation of a complex structural picture. Due to contact melting immediately around inclusions there is formation of a thin liquid metal shell facilitating accelerated carbon and alloying element mass transfer from inclusions into an adjacent matrix layer. After high-speed crystallization around carbides there may be formation of a high-hardness amorphous-like carcass. The main part of a "white zone" within the extreme temperature-force conditions described is, as is seen in Fig. 5b, a non-uniform austenite-martensite structure with a martensite lath size of ~150 nm. The developed surface of low-angle semi-coherent boundaries of this structure, having low energy, causes "white zone" low etching capacity [13].

Presence within laser-hardened steel of a considerable amount of fine carbides (more than 40% of the irradiated steel volume), surrounded by "white zones" facilitates creation within component working surfaces of a structural state with high hardness values.

The features of materials structural state self-organization in an irradiated zone considered are a prerequisite for improving laser-treated component operating properties.

Quantitative characteristics of the structure within laser hardening ones have been found by multifractal parametrization, which has made it possible to establish the connection of an original steel structure with that evolving during laser action on a structure [15–20].

Multifractal parametrization was accomplished by means of a *MFR Project* software.

The multifractal properties obtained have made it possible to evaluate similarity (D_0), uniformity (f_q), ordering (Δ_q), adaptation (A^{Ψ}) of the laser treatment structure towards an external temperature-force loading.

In particular, a connection has been determined for mechanical properties (hardness) and adaptation capacity for different zones of irradiated structural steel 45 and tool steel U10 with a different structure before irradiation

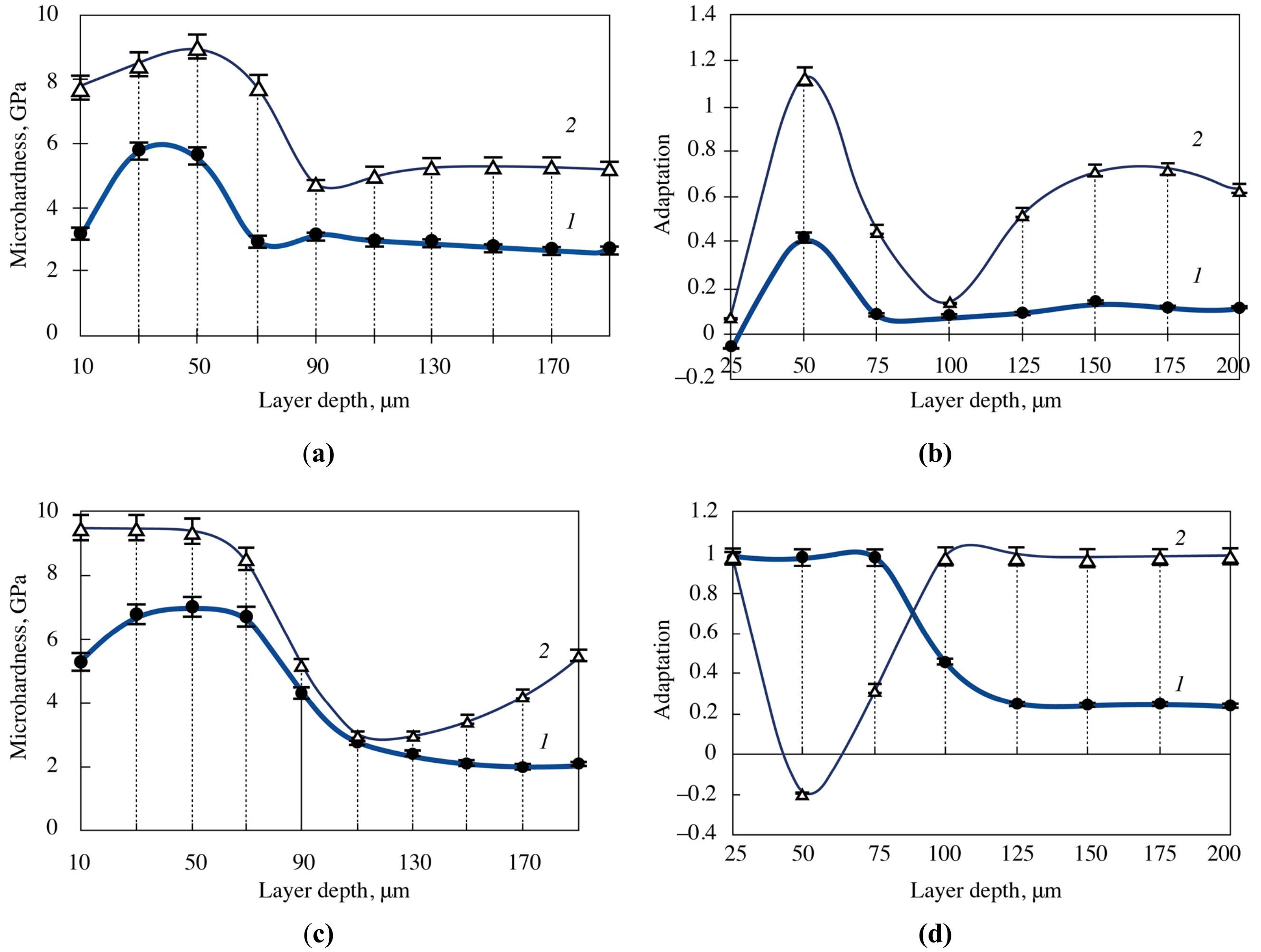


Fig. 6. Microhardness (a, c) and structure adaptation (b, d) of steel 45 (a, b) and U10 (c, d) over depth of irradiated layer after different original bulk heat treatment.

(ferrite-pearlite or granular pearlite after annealing and martensite after bulk hardening). Comparative curves for the microstructure and adaptation capacity for these heat treatment versions are provided in Fig. 6.

By analyzing curves in Fig. 6 it may be concluded that an irradiated layer on structural medium-carbon steel 45 exhibits high hardness and good adaptation capacity (adaptability) towards temperature-force action both within a laser hardening zone from liquid, and also from a solid condition. For tool steel U10 irradiated with a melted layer adaptation properties are lost with transfer to a hardened zone from a solid state. It may be concluded that a strengthened layer of steel 10 with high hardness has low adaptation capacity for the structure, and that it may retain its own properties under an external load for quite a long time.

On the basis of these experiments and calculations within the work fractal maps have been plotted with adaptation of laser-hardened metal in relation to the structural state of irradiated steel (Fig. 7), which has made it possible to determine fractal characteristics of irradiated steel zones indifferent to the action of a thermal deformation loading or adapted to it without structure degradation.

This makes it possible to predict mechanical, production, and operating properties of irradiated objects taking account of intentional use of structural adaptation phenomena for irradiated components for different functional purposes under operating conditions.

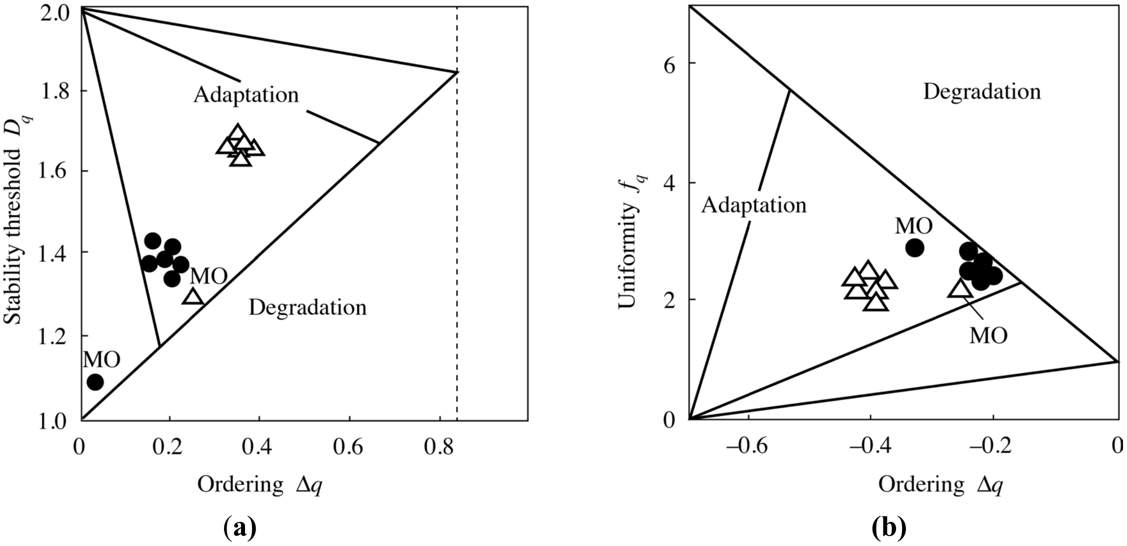


Fig. 7. Fractal maps of adaptation for irradiated steels with different structural states: (a) steel 45; (b) steel U10; (●) annealed structure; (Δ) bulk-hardened structure; MO is melted zone.

Results of multi-fractal analysis have been confirmed during practical use of irradiated structural and tool steel objects.

CONCLUSIONS

1. It has been established that under thermal deformation conditions of pulsed laser treatment the efficiency of self-organization, degree of strengthening, and steel final structure is due to superposition of the level stresses arising within irradiated metal and energy dissipation processes as a result of local plastic deformation, dynamic polygonization, and recrystallization.

2. It has been demonstrated that temperature gradients and thermal stresses developing within metal surface areas irradiated with melting are capable of connective displacement of liquid, and also dispersion of the structure and formation of textural effects, which lead to property anisotropy, in particular to a significant reduction on friction coefficient under tribological contacts.

3. It has been established that under thermal deformation conditions of the action of pulsed laser radiation during steel treatment without surface melting within structure and property formation the main role is played by local plastic deformation processes, both as a consequence of thermostriction stress relaxation, and stresses at phase boundaries within the “carbide–steel matrix” system.

4. Performance of fractal analysis of the structures of irradiated steels makes it possible to predict mechanical, production, and operating properties of irradiated objects taking account of the intentional use of the structural phenomenon of structural adaptability of objects for various functional purposes to operating conditions.

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