The role of local plastic deformation in the formation of structure and properties of materials under extreme heating

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Abstract. Based on the physical processes analysis in the areas of pulsed laser applied on metals, the research reveals the peculiarities in self-organization of the structure, which leads to the formation of non-trivial properties of surface layers. Structural features of the hardening process during high-speed laser processing depend on the resulting level of strains in the processing zones, that is, on the ratio of plastic deformation processes during heating under the influence of thermal and phase strains and energy dissipation by polygonization and recrystallization. As a result, the effect of material strengthening is achieved not only by martensitic transformation, microchemical heterogeneity, but also by high-temperature riveting, increasing the density of crystal structure defects, plastic shifts under the strain of different nature.

1. Introduction

The study of phenomena occurring on the surface of metal alloys when they are processed by concentrated energy flows (CEF), is technically the most promising in a number of modern scientific areas. Such processing allows to get results unattainable with traditional technology.

Under the influence of CEF, laser radiation particularly, complex structural and phase transformations occur in steel within thousands of a second. Such transformations lead to significant hardening. The mechanical properties of steels depend on many factors: the degree of martensitic transformation, the initial chemical contents, the amount and dispersion of carbide phase. Experimental studies proved the maximum hardening after laser processing on steels with more than 0.6-0.8% carbon weight [1, 2]. High-speed processes typical to laser method of hardening, increase the hardness of steel by 20-30% compared to traditional bulk hardening.

Better mechanical properties in the steel surface zones processed by CEF is due to the high speeds of heating and cooling, a significant temperature gradient in the areas, which, along with $\alpha \leftrightarrow \gamma$ recrystallization lead to the appearance of the thermal strain (due to the difference of specific volume and linear extension coefficient of coexisting phases), relaxing due to the formation, movement and interaction of dislocations.

Thus, the hardening of alloys observed under the laser pulse radiation is determined by:
- martensite transformation;
- the influence of high-temperature local plastic deformation, leading to a special dislocation structure with the increased dispersion of blocks as during the irradiation process, as in the following fixation of non-equilibrium structures;
- acceleration of the process of atom mass transfer by "drift" mechanism.
The leading role in the organization of finite structures belongs to internal strain fields, as well as to incompleteness of homogenization processes and the nature of distribution of impurities and alloying elements in the solution before cooling. In this case, the hardness of the final structures will depend not only on the level of total saturation in solid solutions, but also on the degree of preserved microchemical heterogeneity around the dissolution sources. Localization of relaxation processes as a result of the beginning and development of deformation flows along the interfacial boundaries, next to the inclusions of carbides, nonmetallic inclusions and in the adjacent areas of the steel matrix causes the formation of long-range strain fields during laser processing, accompanied by localization of the origin of dissipative structures and indicating the processes of self-organization in the irradiated material.

The practical use of laser irradiation effects is hindered by the lack of a unified concept of the nontrivial structure formation mechanism and the physical processes in the areas of laser radiation used on metals, taking into account the role of the structural heredity phenomenon, the occurrence of significant temperature gradients that lead to local plastic deformation, as well as the degree of relaxation of the riveting consequences.

2. Research methods
The studied materials are: carbon and alloy steels, as well as "model" materials – copper, nickel, steel 12X18H9T and 08X13.

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. Studies of the structure of the processed layers were carried out on the electron microscope EMMA-4 at magnifications of 15000-20000 by the foil method, which is based on the image formation by diffraction contrast.

Measurements of microhardness were carried out on PTM-3 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.

The "lines" ("steps") of shear, which occurred during plastic deformation, and their measurements were carried out using the Linnik microinterferometer MII-4M.

Identification of phase compounds in the areas of thermoinfluence was made by diffraction x-ray depth analysis, after electrolytic polishing of samples and metallographic control of the studied surface structure. The study was carried out on defractor DRON-0,5 in filtered FeKα - a radiation with registration of the intensity of scintillators. X-ray lines profiles scanning was a nonstop recording at a speed of 1 deg/min.

3. Results and discussion
Experimentally proved [3] that due to uneven distribution of energy within the laser beam cross section, the irradiated metal zones have a heterogeneous structure. The maximum amount of energy is absorbed in the center of the spot, the maximum heating temperature is reached, which decreases to the periphery of the irradiated area.

It should be noted that the reduction of laser-hardened structure can be a result of a dynamic polygonization [4-6], as a result of relaxation of thermal strains, with the formation of the smallest subgrains (nanostructural effect) with a developed surface of the boundaries having low energy.

Hardened spot zones are of different morphology. In the case of laser processing with surface melting of the sample, there are generally three zones in the spot. The central, melted zone, of 5-20 µm...
deep, has a dendritic-cellular structure and contains \(\alpha\)-, \(\gamma\)-phases and some insoluble carbides. Nevertheless, \(\gamma\)-phase reaches 30-90% depending on the chemical compound of the irradiated steel.

In the cross section, columnar crystals look like equally axed grains consisting of separate blocks within each grain in a certain way, that is, the central part of the spot has a mosaic substructure.

The research found that in the areas of laser quenching due to temperature and concentration gradients there is a high degree of non-equilibrium of the liquid phase, bifurcation instability of the melt and the transformation of laminar fluid flow to turbulent. The vortices in result provide energy dissipation, abnormal mass transfer flows and dispersion of growing crystals at different scale levels.

The peculiarity of the molten zone structure is the curved grain boundaries in the form of serration, which, apparently, is a consequence of the boundaries migration due to the significant strain and plastic deformation in the micro volumes under laser processing. It should be noted that in the case of metal surface laser melting, that is, when a layer of solidified melt appears in the center of the spot, the main source of deformation is the thermal strains during crystallization, as well as strains at the boundary of the melt zone and the solid metal during crystallization.

Thus, during laser processing with melting of the surface, after rapid absorption of the laser pulse energy follows the expansion of the heated area surrounded by a large mass of cold starting metal. Thus, with a large temperature gradient there is an uneven thermal expansion. This process with local volume changes in polymorph \(\alpha\leftrightarrow \gamma\) transformations leads to the appearance of the next (second) zone of thermal strain irradiated spot, relaxing due to the formation, motion and interaction of dislocations.

Here are some typical results of the study of local plastic deformation effects in the area surrounding laser quenching zone in liquid state.

Tracing plastic deformation during irradiation is a difficult task. Plastic deformation absolute value is, obviously, small due to the short-term light pulse. Moreover, normal deformation effects (changing the shape of grains, the formation of twins and deformation bands) on most materials are not found. However, in the study of "model" alloys with single-phase structure or a structure with a small amount of the second phase it is possible to prove the existence of the plastic deformation effect.

Copper and nickel alloys, as well as technical iron containing little carbon were chosen for the experiment in this paper. The samples had a polished surface to study the traces of slip and rotation of the grains. It is found that in copper and nickel alloys next to the melted zone (in the zone of thermal influence) there is a deformation relief and grain rotation.

These phenomena are connected with the summ of micro-displacements of a large number of dislocations in their slip planes, which leads to the formation of macro-displacements that appear on the surface of the polished samples in the form of slip lines or bands and relief grain boundaries. Moreover, it is possible to find the traces of sliding of several systems, the nature of which indicates the high-speed plastic deformation [7-9].

Thus, by selecting materials and irradiation conditions, the existence of local plastic deformation in the processing of metals by concentrated energy flows is proved. In the areas of laser irradiation of alloys, a complex strain occurs, accompanied by relaxation processes reducing localized stresses and mass transfer. Complex deformed dislocation dissipative structures are formed as a result.

![Figure 1](image-url) Sliding lines on copper after laser processing in a conventional microscope (a) and in an interference microscope (b) (×700).
Deformation is possible due to a vivid transverse slip in the grain (figure 1, a). In a large slip band (length $L=10^{2} \text{ mm}$), the number of dislocations accumulating on the ends (at the edges) is rather high about $n \approx 1000$.

Around such horizontal dislocation groups there will be a field of high strains directed against the source and caused stoppings in the neighboring sliding planes. Due to the large clusters of dislocations, it is possible to bend and rotate the slip bands, which also leads to the stops of moving dislocations and hardening.

Interference microscopy with the use of microinterferometer MII-4M was used to study the slip traces. Using the results obtained on the "model" alloys, an attempt is made to find the shear strain causing plastic deformation of the metal in the laser processing zones.

Along the grain boundaries, v-shaped protrusions are formed on the surface associated with the need for accommodation of different deformation in neighboring grains. The development of a strong surface relief caused by sliding and discharges inside the grains is a result of structural changes in the local plastic deformation due to the impact of CEF. By measuring the displacement of interference fringes of equal thickness we can judge about the magnitude of the shear strains that cause local plastic deformation on the surface of the irradiated spot.

As can be seen in figure 1, b, the displacement of interference lines appears on the slip lines. The measurements of these displacements ($\Delta$) were made, then the height of the step ($h$) formed on the sliding line was calculated by:

$$h = \frac{\lambda \cdot \Delta}{2 \cdot l},$$

(1)

$\lambda$ - wavelength of monochromatic radiation;
$\Delta$ - displacement;
$l$ - the distance between the interference bands.

The height of the step $h$ is proportional to the number of dislocations coming from the current dislocation source $nb$ ($n$ is the amount of dislocations that came to the surface, $b$ is the Burgers vector). The probability that dislocations output was perpendicular to the observed plane is very small. Taking the angle of the output equal to $45^0$, we get

$$nb = h \sin \theta = \frac{2h}{\sqrt{2}},$$

(2)

The elastic deformation preceding the slip in the crystal is $\tau/G$, with $\tau$ - the applied strain, $G$ - the shear module. When sliding starts, the elastic deformation relaxes in the area with a diameter of $2L$, with $L$ being the length of the dislocation sliding lines [7].

Taking full conversion of total elastic deformation $(2L\tau/G)$ in plastic, equal to distribution of $n$ dislocation loops size $nb$, we get

$$nb = 2L\tau/G$$

(3)

Thus, using the expressions (2) and (3), the shear stress ($\tau$) causing plastic deformation can be calculated (with $L=10^{2} \text{ mm}$).

The results of the calculations are given in table 1. The variety of calculations is associated with a large number of measurements. Despite this, the results show that the shear strain causing local plastic deformation on the surface of the irradiated spot is much higher than the yield strength of the alloys. This difference is due to stress relaxation by plastic deformation as the yield strength of the material is reached.

The role of inclusions of different compounds of the initial structure in the formation of the structure and properties of laser-hardened layers, especially on alloyed steels, should be singled out separately. Inclusions, being strain concentrators and contributors to localization of relaxation as a result of the beginning and development of deformation flows along the interfacial boundaries and in the neighboring parts of the steel matrix, cause the formation of long-range stress fields, accompanied by the localization of dissipative structures and, thus, proving the processes of self-organization in the inclusion-matrix system.
Table 1. Calculations of shear stress in laser-irradiated layers of "model" materials.

| Material          | Shear strain \( \tau \), MPa | Yield strength \( \sigma_{0.2} \), MPa |
|-------------------|-------------------------------|-------------------------------------|
| Copper            | 320.9-423.8                   | 40-80                               |
| Nickel            | 311.7-578.4                   | 120-160                             |
| Technical iron    | 519.6-607.8                   | 120                                 |
| Steel 08X13       | 410.7-547.6                   | 205                                 |
| Steel 12X18H9T    | 386.5-485.3                   | 195-205                             |

During the metal-physical experiments, it was found that the laser beam energy was sufficient for melting refractory and melting fusible carbide inclusions in alloy steels, as well as for the development of mass transfer across the boundaries of the inclusion - matrix. The matrix zones next to the inclusions are filled with the components of inclusions, which are fixed under spontaneous cooling in solid solution. Apparently, relaxation microplastic deformation occur next to the inclusions, and during cooling process – relaxation of thermal strains.

It should be noted that the studies have revealed the occurrence in the irradiation zone of conditions for melting inclusions, some of which may harden in the form of thin amorphous films during melting and rapid cooling. This factor makes an additional contribution to the overall hardening of steel during laser processing.

Metallographic studies of steels have shown that since the temperature increases in the laser impact zone, recrystallization occur, which have a dynamic nature and are classified by the type of steel and its initial state. Here dynamical polygonization, primary, secondary and collective recrystallization are possible.

Particularly, it was found that in the areas of laser irradiation on samples of technical iron (low-carbon steel) there is a significant increase in hardness (2800-3200 MPa) compared to the original structure with a hardness of 1000 MPa. In this case, the metal structure near the melted zone is characterized by fineness – the average grain diameter of 3-20 \( \mu \)m (in the original structure – 80-100 \( \mu \)m) [9]. This effect is comparable with deformation hardening with high degrees of compression. Grain refinement and increase in hardness of irradiated technical iron is due to the phase riveting at \( \alpha \leftrightarrow \gamma \) recrystallization, plastic deformation under the heat strains and further recrystallization [10].

Studies of the surface layers of steel 45 after CEF processing showed that the microhardness of martensite areas on the former pearlite grains is 8200-8500 MPa, and the former ferrite grains are 3200-3500 MPa at an initial hardness of 1000 MPa. This increase in the hardness of ferrite is explained by its riveting during phase recrystallization and deformation of ferrite grains due to volumetric changes in neighboring grains that have undergone martensitic transformation.

Of considerable interest are the results of a series of experiments to study the causes of achieving abnormally high hardness of steel 45 after double hardening. To do this, the samples were first subjected to ordinary quenching (volumetric heating in the furnace to the optimum temperature and cooling at a rate above critical), then local laser treatment. The results of measuring the surface hardness of the samples showed values up to 11 GPa. At high-speed laser heating of quenching martensite or low tempering martensite, the reverse martensite transformation occurs (M\( \rightarrow \)A). Thus, in steel there are 3 martensitic transformations – 2 direct and 1 reverse. And along with the local plastic deformation, the flowing phase riveting leads to immediate increase in the density of dislocations and other defects of crystal lattices, which pre-determines the increase in the hardness and wear resistance of steel.

4. Summary

As a result of the research, this paper presents a new approach to the study of the mechanism of structure formation in metal materials under hyper speed heating by laser radiation.
It is shown by metal-physical methods that complex structural changes occur during laser surface processing in milliseconds, which are imposed by plastic deformation caused by the appearance of internal strains during polymorphic transformation and thermal strains due to the huge temperature gradient between the heated and cold metal zone. A special role of these strains is to increase the free energy of the phases, to gain the driving force of the phase transitions, which is possible by increasing the rate of transformations and getting a special structural state of the metal, unattainable with bulk heating.

As a result, the effect of hardening of materials under the laser impact is achieved not only by martensitic transformation, dissolution of carbides, filling of matrix with their components, micro-chemical heterogeneity, but also by high temperature riveting, increasing density of defects of crystal structure, the plastic changes under the influence of strains of different nature.

Structural features of the hardening process during high-speed laser processing depend on the resulting level of strains in the processing zones, that is, on the ratio of plastic deformation processes during heating under the influence of thermal and phase strains and energy dissipation by polygonization and recrystallization.

References
[1] Mirkin L I 1975 Physical Bases of Materials by Laser Beams Processing (Moscow: Moscow State University)
[2] Grigoryants A G and Safonov A N 1987 Methods of Surface Laser Processing (Moscow: Higher school)
[3] Vedenov A A and Gladush G G 1985 Physical Processes in Laser Processing of Materials (Moscow: Enegroatomizdat)
[4] Tushinsky L I 1986 Study of the Structure and Physical and Mechanical Properties of Coatings (Moscow: Mashinostroenie)
[5] Brover A V 2005 Structural features of the process of surface hardening of steel with concentrated energy flows Materialovedenie 9 18
[6] Bernstein M. L and Pustovoit V N 1987 Heat Processing of Steel Products in a Magnetic Field (Moscow: Mashinostroenie)
[7] Velikikh V S, Voronov I N and Goncharenko V P 1982 Radiographic study of residual stresses arising after pulse laser hardening of steels Phys. and Chem. of Materials 6 138
[8] Lomaev G V and Kharanzhevsky E V 2002 Hardening surface treatment by high-speed laser recrystallization Metal Sci. and Thermal Processing of Metals 3 27
[9] Brover A V 2006 The appeared effects of local plastic deformation in the surface layers of steel in the treatment of concentrated energy flows Hardening Technol. and Coat. 7 27
[10] Brover A V and Dyachenko L D 2007 Self-organization of surface layers of metal materials in the processing of concentrated energy streams Hardening Technol. and Coat. 3 8