Structure of the surface layer and the microhardness of high-carbon instrumental steel after laser treatment

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Abstract. The article presents the results of the study of the effect of laser treatment on the structure and microhardness of the surface of high-carbon steel samples. The treatment is carried out in order to obtain surface layers, parts with high properties for industries of various purposes. The samples from high-carbon steel U10 A after preliminary thermal treatment by modes of 780–800 ºC heating for 2 minutes with cooling in 10 percent water solution of sodium chloride with tempering at 270–320 ºC and cooled in the air and without the thermal treatment are treated with the Nd:YAG laser with the capacity up to 1 kW. Metallographic studies and microhardness properties illustrate the influence of laser surface processing on the increase in mechanical properties. It is shown that the laser thermal treatment of steel allows obtaining a surface microhardness of about HV 800-1000 MPa and depends on the original state of the metal and the previous thermal treatment.

1. Introduction

To improve the surface properties of metals, it is possible to use several surface hardening methods [1-4]. These may include changes in the chemical composition of the surface, such as alloying, or changes in the microstructure of the surface, such as quenching [5-9]. To enhance the durability of most machine parts that work in wear conditions [1, 5, 6], cavitation, cyclical loads, corrosion at cryogenic or high temperatures [2, 8] and working surfaces of the production instrument, including the deformed instrument, surface thermal hardening found its application [10-14]. The hardening of the surface is a process of thermal treatment in the localized heating zone [15-18] which uses concentrated sources of energy, such as laser [1, 2, 19-22], electronic beam [3], plasma arc [4,5], welding arc [5, 7]. The application of surface hardening on steel parts and combining it with a rapid tempering method, which is called martensite quenching, allow increasing fatigue durability and limit the deformation of steel parts [9-12].

The laser beam is able to quickly raise the surface temperature to a temperature above the austenization temperature (As₃) [1-4, 7, 8]. This intensive heating process converts the existing surface microstructure into austenite, and then, through rapid cooling, creates a very dispersive martensite microstructure with high hardness [19-22]. To get a homogeneous solidity profile on details with
complex geometry, one needs to adjust the parameters of laser-quenched processes, such as laser power and scanning speed [1, 2, 9-14]. This uniform hardness profile is recommended for uniform distribution of mechanical loads. This layer is formed as a uniform martensite layer on the surface of quenched parts. This homogeneous hardened layer prevents the concentration of stresses on a solid surface layer of parts and limits the spread of cracks during periodic loads, which improves resistance to fatigue of the parts [10–12].

In the case of slip joints, a homogeneous hardness profile on the teeth geometry can effectively reduce the wear and tear caused by attrition [13]. To achieve this uniform hardness profile, it is important to calibrate such parameters as laser power, scanning speed and rotation speed. The work [14] proposed an experimental approach, backed up by dispersion analysis (ANOVA), to develop a model to optimize laser processing parameters. Despite the fact that the technology of laser treatment of the surface is constantly evolving and many works consider these issues [1, 2, 9-22], however, there is also interest in further works on the influence of the complex of laser irradiation parameters on the change of surface morphology, structural changes and characteristics of the material, the evolution of microstructure over time, as well as combinations of laser treatment with other types of treatment.

The relevance of this work is substantiated by the need to increase the service life of machine parts and working surfaces of the production tool. The issues of technologies of hardening and durability enhancement, as well as their introduction into production are of particular interest to various industries.

2. Materials and methods of study

The samples of high-carbon instrumental steel U10 A GOST 1435-99 were made to study the influence of laser treatment parameters on the characteristics of the hardened layer, namely its thickness, microstructure and hardness. The chemical composition of the material is presented in Table 1.

| Element t | C     | Si     | Mn     | S      | P      |
|-----------|-------|--------|--------|--------|--------|
| Content (%) | 0.95 – 1.09 | 0.17 – 0.33 | 0.17 – 0.28 | ≤0.018 | ≤0.025 |

Laser treatment was carried out for samples without preliminary thermal treatment and samples that were quenched by 780 – 800 ºC heating for 2 minutes with cooling in 10 percent water solution of sodium chloride with tempering of 270 – 320 ºC and cooling in the air. The surface of the samples was hardened with the "Kvant-15 MSZ" laser setup in an inert argon gas environment. Equipment is included in the setup (Figure 1).

**Figure 1.** Setup for laser treatment of metals "Kvant-15 MSZ": 1 – pulse power source of solid-state laser P138; 2 – control unit of the coordinate table and treatment process; 3 – solid-state laser with optical system; 4 – television surveillance system; 5 – video control device; 6 – coordinate table.
The samples were treated with a pulse Nd:YAG laser. Radiation wavelength is 1,064 microns. Frequency of radiation pulses is up to 1-50 Hz. Pulse duration, adjustable within 0.1-6.0 ms. Spot size in the treatment area, 0.3-1.3 mm. The average capacity is 1,658 88W. The most important parameter that is characteristic of the thermal influences of radiation on the material, is the density of radiation power of the laser \( q_l \) (V/m\(^2\)), which is associated with other parameters of radiation by the following dependence:
\[
q_l = \frac{R_l}{S} = \frac{E_l}{\tau}; \quad S, \quad \tau
\]
where the \( R_l \) is the full radiation power, W; \( S \) is the area of radiation material, m\(^2\); \( \tau \) is the duration of exposure to radiation, s; \( E_l \) is the radiation energy, J.

To conduct the experiment, the selection of permanent and variable factors of the experiment is based on the analysis of literature data on laser thermal treatment of metals, as well as on the main purpose of the study – the search for optimal laser hardening modes that allow achieving the highest hardness of the metal surface. Taking into account the technical capabilities of the "Kvant-15 MSZ" laser setup in the inert argon gas environment and the requirements for maximum performance at the maximum possible width of the laser impact zone (LIZ) the following factors were accepted as permanent: the maximum diameter of the laser beam spot is 1.3 mm, the maximum duration of the pulse is 5 ms.

The energy density of radiation that determines the effect and result of laser impact on the metal surface, in this case depends only on the energy of the pulse of radiation, which, in turn, is the function of voltage of pumping capacitors of the setup "Kvant-15 MSZ" in the environment of the inert gas argon. This voltage is accepted as the main variable factor. The power of the radiation was regulated by changes in the voltage of the pumping capacitors. The first series of experiments was conducted when the laser impact spot was located without overlap when the voltage of the capacitors within the range of 450...508V changed, as well as with a heating spot overlap factor of 0.50 and 0.75. The required thermal treatment modes to harden the surface of the selected samples were determined by the calculation methods [9, 10] and presented in table 2.

Processing was carried out on five, experimentally selected modes (see table 1), varying the energy of radiation by the voltage of pumping capacitors while other parameters are constant: frequency \( f \) – 3.7 Hz, pulse duration \( \tau \) – 1.63 ms, focus – 1.6 mm. After laser thermal treatment, microslices were prepared, the microstructure of the samples was examined on the MET-3 microscope in a bright field with an increase of 50...1000 times, microhardness was determined by the results of measurements of the PMT-3 device.

### Table 2. Parameters of the laser treatment mode

| Pass mode | I    | II   | III  | IV   | V    |
|-----------|------|------|------|------|------|
| Pumping capacitors voltage, U, V | 452  | 483  | 520  | 531  | 580  |

### 3. Results and discussion

The microstructure of samples unhardened by volume thermal treatment after laser treatment (mode 1) is presented in Figure 1. In the photo of the microstructure (Figure 1) there is a non-etchable white surface layer (1, a), its depth is on average 630 cm. It is adjacent to the transitional layer and the main metal, the structural components of which, coarsely plastic perlite and cementite particles, are located in the form of a distinct mesh (Figure 1, b). On average, the microhardness of the non-etchable white layer is 946 HV that of the main metal is 264 HV, the transition zone between the main metal and the white (non-etchable layer) is on average 657 HV.

In general, it should be noted that the quenching zone from the solid phase consists of two areas: at the top, this is an area with a homogeneous structure and at the bottom, this is an area with a heterogeneous structure. In the area with a homogeneous structure, a fine-dispersed martensite with a microhardness of 720...850 HV is formed. In place of perlite grains, martensite is formed (microhardness is 557-644 HV) with a small amount of residual austenite. In the area with a heterogeneous structure, as it has already been described in the works, as long as the depth increases, there is an increase in the structure heterogeneity: first the martensite-troostite is formed, then the
martensite and troostite mesh that goes into the troostite-ferrite, and at the boundary with the original structure - to the ferritic structure. Figure 2 shows the microstructure of the main metal and the surface treated layer on mode II. With an increase in the energy of the laser radiation, the thickness of the hardened layer decreased (to 15 microns), much of the material evaporated. Further energy increase causes local heating to high temperatures exceeding the melting point of the material, which leads to a change in the geometry of the sample plane, the material evaporates intensely.

![Microstructure](image)

**Figure 2.** Microstructure of the main metal and the surface treated layer (mode I).

The photos of microslices of samples that were given a preliminary volume thermal treatment (quenching+tempering) followed by surface hardening by pulse laser are shown in Figure 3.

![Microstructure](image)

**Figure 3.** Microstructure of the main metal and the surface treated layer (mode II x200).

For all processing modes in steel after annealing or normalization, the heat-affected zone is very small, there is a sharp change in mechanical properties in the surface layers of the metal [1, 2]. It is known [9-22] that during laser hardening of steels that have previously undergone volume quenching and tempering, after laser hardening, a tempering zone is revealed at the boundary with the original structure. The entire hardening zone from the solid phase is an area of homogeneous martensite with a microhardness of 700... 850 HV, which is higher than the hardness of the martensite obtained by the oven hardening.

There is a transition zone on the border with the original structure. In this case, this tempering area with a troostite structure, this has a microhardness of 300-400 HV. In our experiments, Mode III provides maximum depth of hardening without changing the geometry of the product surface. With laser hardening of steels that were previously quenched and tempered, after laser hardening there is an increase in the microhardness values by 25-30%. In modes IV and V there are significant changes in geometry, the surface of the metal is melted. At the same time, the melting area of the heat-affected
zone has a needle-shaped martensite structure, which is transformed into the structure of the hardened layer formed as a result of phase transformations (Figure 3).

At the same time [1, 2, 9, 19-22] it is necessary to notice that a feature of laser processing with the fusion of eutectoid and hypereutectoid carbon steels is the known fact of the presence of residual austenite in the melted zone, the amount of which, according to various authors, can be up to 39% for U8 steel and up to 45% in U10 steel. Meanwhile, it is important to clarify that in the melting zone of these steels, there is no non-dissolved cementite. It is obvious that the structure of the formed martensite is overly saturated with carbon, as well as the phase of residual austenite. This fact indicates a growth in microhardness with an increase in the carbon content in the structure of martensite in the formed surface-hardened layer.

However, the presence of residual austenite in the melted zone reduces microhardness compared to hardening without melting. Based on the results of the first series of experiments, histograms (Figure 4) of the dependence of the hardness (HV) of the zones of laser impact on the voltage (U) of the pump capacitors (radiation pulse energy) were obtained in order to determine the optimal level of this parameter. We can see that each hardening mode has the maximum depth of the hardened layer. For example, mode I has a maximum depth of 110 microns, mode II -160 microns, mode III -180 microns, mode IV -260 microns, mode V - 240 microns. The decrease in the latter case is due to intense evaporation and splashing in the zone of melted metal. Comparative histograms are based on the results of comparison of microhardness values at different modes of voltage of pumping capacitors. At the same time, the comparison was conducted for all at the same distance from the surface (according to the depth of the hardened layer).

Figure 4. Microstructure of the main metal and the surface-treated layer (mode IV, x100)

Figure 5. Diagram of the dependence of hardness values on hardening modes
The analysis showed that as the energy of laser radiation increases in the beginning (at U 452-520 V) the values of microhardness generally increase. Later on, the growth of laser radiation energy at first within the range (U 520-580 V) does not significantly increase the microhardness value and even shows some decrease (the reasons we have considered above), but it increases the overall depth of the surface hardened layer. At the same time, if we take the values of microhardness by the depth of the layer, all the modes are characterized by a reduction of microhardness from the surface to the depth of the main metal. For technological purposes, when optimizing the hardening process, it is important to establish the pulse spots overlap coefficient.

Traditionally, the ratio of maximum depth and uniform distribution of hardness is considered optimal. In our case it can be seen that, depending on the laser pulse energy, which we control by the voltage of the pumping capacitors, there are structural features in depth, which are clearly manifested in modes with surface melting. The analysis of the results obtained showed that with the investigated overlap coefficients, the depth of the zones is practically equal to and is 150-180 microns, and the boundaries of these zones are quite clear (the transition zone in depth does not exceed 10-15 microns). Thus, when using the "Kvant-15 MSZ" laser setup in the inert argon gas environment in the conditions of real production to obtain a hardened layer that is sufficiently deep and structurally uniform in width on tool carbon steel (after preliminary thermal treatment by quenching and tempering), the following mode of laser thermal treatment can be recommended: the diameter of the laser exposure zone D = 1.6 mm; the charge voltage of the pumping capacitors U = 520 V; the overlap coefficient Kp = 0.5, the pulse duration τ = 3.7 ms; with a frequency f = 1.63Hz.

4. Conclusion
1. High efficiency of laser thermal treatment has been confirmed. The resulting hardened layer at a depth of 110-260 microns has a homogeneous structure and properties. The structure of the hardened layer is a freshly quenched martensite with microhardness HV = 1000 with clear boundaries in depth and transition zones of insignificant length (less than 10 microns). Average hardness HV – 880 (HRC 63-64).
2. The obtained depth of the hardened layer (150-260 microns) is sufficient for 3-5 regrinds of a worn-out tool blade (with gentle sharpening modes). During the regrinds within certain limits, their width will change slightly.
3. The research results allow recommending the use of the developed mode of laser heat treatment to harden the cutting edges of the tool.

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