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Physical and Technological Principles of Processing Steel with UV Laser Radiation

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The main purpose of the article is to study the hardening of steel using non-standard wavelengths of laser radiation. The physical principles of the interaction of laser radiation with matter are also described. Experiments were carried out on hardening steel with a UV laser (wavelength 355 nm). The following experiments and a comparative analysis of volumetric hardening of steel with cooling in water, hardening with a YVO_4 laser beam with $\lambda = 1.06$ μm and hardening with a YVO_4 laser beam with $\lambda = 0.355$ μm. The studies were carried out on structural steel 45 and tool steels У12 and Р6М5. In the course of the research, new interesting scientific results were obtained: the study of the microstructure of U12 steel samples using an electron microscope showed that the martensite formed during quenching by UV radiation is more dispersed, as a result of which it can be concluded that such processing can lead to the production of surface nanostructures up to 100 nm in size. However, due to the low productivity and low power of UV radiation, the proposed steel hardening can be recommended for measuring and cutting tools.

Keywords: Microhardness, The Bouguer-Lambert law, Laser radiation, UV range, Microstructure, Nonlinear crystal, Laser beam.

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1. INTRODUCTION

Laser radiation is widely used in various technological processes, one of which is the surface thermal hardening of products (laser hardening) in order to improve their performance properties. Numerous experimental data indicate that, when laser radiation interacts with a substance, hardening in steels occurs much more intensively than with other known processing methods [1-3]. At the same time, it is very important for practice to establish under what irradiation conditions the properties consistently acquire the highest values.

2. ANALYSIS OF FACTORS THAT AFFECT STEEL COMPACTION EFFICIENCY BY UV LASER RADIATION

Laser industrial technologies are based mainly on the thermal effect of laser radiation on the material being processed, because of which, when certain temperatures are reached, various physical processes can develop on the surface and in the volume of the irradiated material [1-5].

When a laser beam falls on the surface of a material, part of the radiation is reflected from it, and part passes deep into the material, being absorbed in it. The Bouguer-Lambert law determines the intensity of the absorbed radiation at the depth z of the processed material. Taking into account the reflection from the surface, it is equal to

$$I(z) = I_0 A \exp(-\alpha z)\,, \tag{1}$$

where I_0 is the radiation intensity on the surface; α is the absorption coefficient; $A = 1 - R$ is the absorption capacity of the material; R is the reflection coefficient.

Schematically, the process of interaction of laser radiation with matter can be represented as follows: absorption of light; energy transfer to thermal vibrations of a solid body lattice; heating the material; melting, destruction of the material by evaporation and ejection of the melt and cooling after the end of light exposure.

For laser hardening, it is of interest to heat above the phase transformation temperature, but below the melting temperature, that is, hardening from the solid state. This will allow hardening of steel products while maintaining the geometric characteristics of the surface.

Threshold (critical) power densities Q_T for heating the surface to a certain temperature T can be calculated by the formula

$$Q_T = \frac{(T - T_0)\lambda\sqrt{\pi}}{2(1-R)\sqrt{\alpha\tau}}\,, \tag{2}$$

where T_0 is the initial temperature of the material, α is the thermal diffusivity of the material, λ is the thermal conductivity of the material, R is the reflection coefficient, and τ is the exposure duration.

The reflectivity of metals decreases with decreasing wavelength (Fig. 1), so the heating efficiency of metals increases when using a laser with a shorter wavelength. Therefore, the processing of metals using a Nd:YAG laser or Nd:YVO_4 laser with a wavelength of $\lambda = 1.06$ μm is more efficient than processing with a CO_2 laser with a wavelength of $\lambda = 10.6$ μm [4-7].

The reflection coefficient is largely affected by the roughness of the irradiated surface. Surfaces with low roughness ($R_a = 0.05$ μm) reflect laser radiation especially strongly ($R > 0.5$).

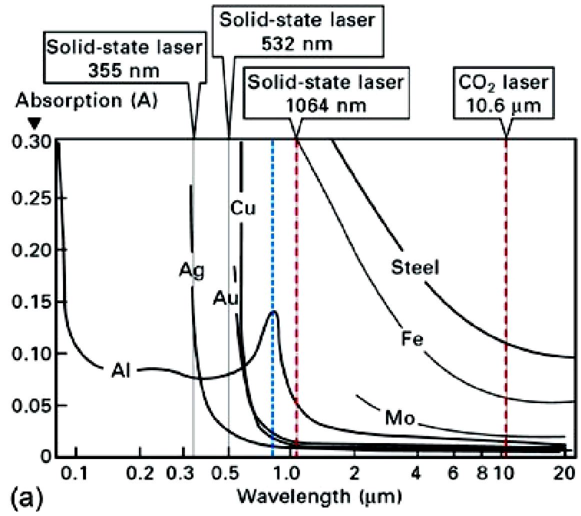


Fig. 1 – The absorption coefficient of some metals depending on the wavelength of the radiation wave [6-7]

As the surface roughness increases, the proportion of reflected radiation decreases ($R < 0.1$), therefore, the energy efficiency increases.

Laser processing is mainly carried out on finished parts with a polished surface that strongly reflects laser radiation. To reduce reflection, absorbent pastes can be applied to the treated surface. However, this method greatly complicates the technology. Thus, we again come to the need to increase the processing efficiency by reducing the radiation wavelength, and, consequently, the reflection coefficient.

The use of even shorter wavelength radiation, such as UV, is limited by the low power of UV lasers or their high cost [6-7]. As shown earlier [8-9], the use of low-power Nd:YaG lasers in a pulsed mode makes it possible to perform laser hardening of tool and structural steels. However, in the work it was not possible to carry out hardening without surface melting.

It can be assumed that it is expedient to use low-power pulsed lasers emitting in the UV range to harden polished surfaces. Despite the fact that heat treatment with a UV laser beam has been known for a long time [10], there is no unambiguous information about the effect of the energy and time parameters of laser radiation on changes in the microstructure and mechanical properties of treated steels and the formation of hardened layers. Of particular interest is the possibility of using nanosecond lasers and nonlinear crystals to generate ultraviolet radiation, which is effectively absorbed by most materials.

The optical properties of substances in the ultraviolet region of the spectrum differ significantly from their optical properties in the visible region. A characteristic feature is an increase in the absorption coefficient of most bodies that are transparent or reflective in the visible or IR region of the spectrum.

In the IR and visible regions of the optical range, metals strongly reflect incident radiation. This is due to the predominant scattering of light during its interaction with free electrons, the concentration of which in metals reaches 10^{22}-10^{23} cm^{-3}. Electrons radiate secondary waves in the process of scattering, which, when combined, form a strong reflected wave. Absorption of light quanta directly by conduction electrons is possible only in their simultaneous collisions with phonons, impurities, with each other, with the metal surface, grain boundaries and crystallites [6-7].

The reflection coefficient of all materials (including metals) decreases with decreasing radiation wavelength. In the UV and shorter wavelength ranges, the electrons of the inner shells of atoms interact with radiation, for example, in the X-ray region of the spectrum, metals no longer differ from dielectrics in optical properties.

3. RESEARCH OF THE INFLUENCE OF HEAT TREATMENT WITH UV LASER RADIATION ON THE STRUCTURE AND PROPERTIES OF STEELS

In this work, laser hardening was performed using a solid-state *YVO_4* laser with a nonlinear crystal and diode pumping with a power of 5 W and a radiation wavelength of $\lambda = 0.355$ μm, operating in a pulsed mode ($\tau = 10$ ns). The radiation frequency was 50 kHz, the diameter of the focusing spot was 75 μm and 150 μm.

The wavelength $\lambda = 0.355$ μm is provided by the generation of the third harmonic, which is implemented as a cascade process. Frequency tripling is a nonlinear frequency conversion process where the resulting optical frequency is three times the frequency of the input laser beam. A beam of light of the first harmonic with a wavelength $\lambda = 1.064$ μm is directed to a nonlinear crystal. The second harmonic is generated in the crystal in order to double the frequency of the initial radiation to a wavelength of $\lambda = 0.532$ μm (corresponding to the green region of the spectrum). This is done by including a lithium triborate in the nonlinear crystal circuit. Lithium triborate crystals are physically and chemically inert and have a high nonlinear optical efficiency. These non-linear crystals are most commonly used for frequency doubling of solid-state lasers. After the second harmonic is generated, the third harmonic is generated by adding two frequencies in the second nonlinear crystal.

The studies were carried out on structural steel 45 and tool steels У12 and Р6М5. The hardened layer was controlled by microhardness, which was measured on a PMT-3 device by indenting a standard tetrahedral diamond pyramid with a load of 100 g.

The following modes were studied: volume hardening with cooling in water (1), hardening with a YVO_4 laser beam with $\lambda = 1.06$ μm (2) and hardening with a YVO_4 laser beam with $\lambda = 0.355$ μm (3). The radiation power density was $Q = (0.8\text{-}0.9)10^4$ W/cm^2. The research results are shown in Fig. 2.

The microhardness of specimens after quenching with UV radiation is lower than that from the liquid state, but much higher than after bulk heat treatment. This indicates the effectiveness of laser hardening by UV radiation.

The study of the microstructure of samples of steel У12 using an electron microscope showed that the martensite formed during quenching by UV radiation is more dispersed (Fig. 3). It can be assumed that the improvement of the modes of such processing can lead to the production of surface nanostructures up to 100 nm in size.

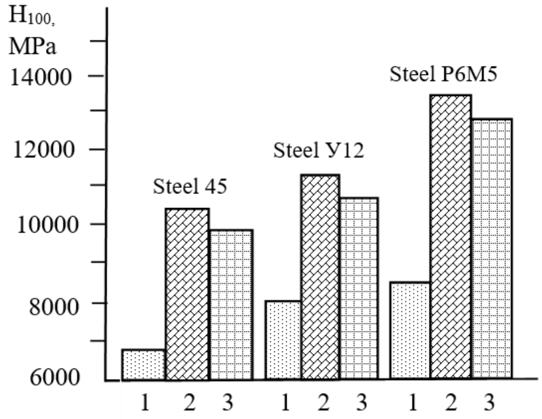
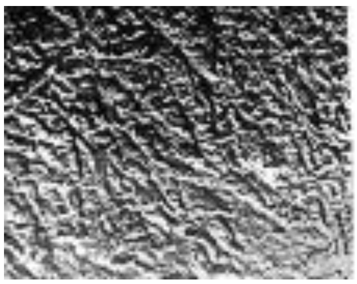
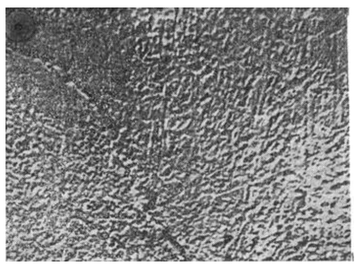


Fig. 2 – Microhardness of steels after various types of hardening: 1 – volume hardening; 2 – laser hardening with melting; 3 – laser hardening by UV radiation



a



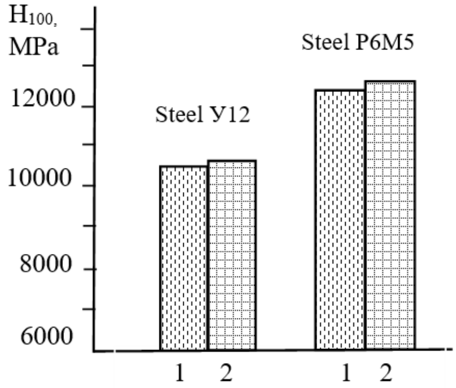
b

Fig. 3 – Microstructure of samples after laser hardening, ×10000: a – laser hardening with melting; b – laser hardening by UV radiation

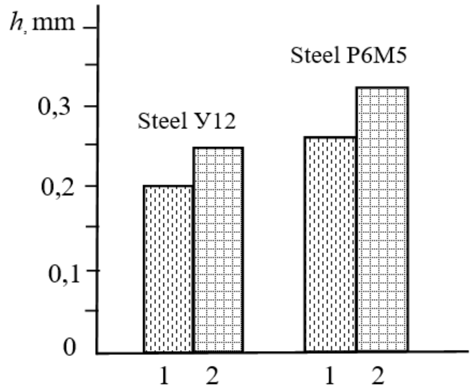
The work also carried out studies of the initial processing on the characteristics of the hardened layer. Laser hardening can be applied to pre-treated parts, strengthening individual areas. Laser processing can be used to further strengthen fully finished products. Previously, it was shown [4] that both the pulse duration and the initial structure affect the microhardness of the hardened layer. To elucidate the effect of the initial treatment, laser hardening was carried out at a constant pulse duration.

The study of the microhardness of the hardened layers showed that during laser hardening by UV radiation, the depth of the hardened layer strongly depends on the initial microstructure of the steel. Laser processing by UV radiation was carried out on samples of tool steels in the annealed and hardened states. In the annealed state, the microstructure of carbon tool steel У12 is a mixture of pearlite and cementite (iron carbide Fe_3C), while high-speed cutting steel is ledeburite and carbides of alloying elements. In the hardened state, these steels have a martensitic structure. After laser hardening, the microhardness and depth of the hardened layer of the annealed and hardened specimens of each steel were measured.

It has been found that the type of pre-treatment affects the hardness only in flash quenching. But the depth of the hardened layer in the case of pre-hardening is greater by 20-25 % (Fig. 4).



a



b

Fig. 4 – Influence of the initial heat treatment on the microhardness (a) and the depth of the hardened layer (b) of steel У12 and R6M5 after laser hardening by UV radiation: 1 – annealing, 2 – volume hardening

The most likely explanation is the difference in the thermal conductivity of martensite and pearlite-carbide structures. In the general case, steel hardening consists in heating it to temperatures above phase transformations, holding it at this temperature, and rapidly cooling it to suppress diffusion transformations. As a result of heating and holding, the carbides dissolve, and upon rapid cooling, a supersaturated solid solution of carbon in α-iron, martensite, is formed.

With laser hardening, there is no exposure. In this case, the characteristics of the hardened layer directly depend on the thermophysical properties of the material. Martensite has a lower heat capacity and thermal conductivity than pearlite-carbide structures of annealed steels.

This leads to the fact that, with the same energy impact for pre-hardened samples, laser radiation provides heating of deeper layers of steel. When processing a sample with an annealed structure, the radiation energy is dissipated deep into the material due to higher thermal conductivity. To obtain a deeper hardened layer, laser processing of the studied steels can be carried out on finished parts that have undergone preliminary bulk hardening. Such processing will make it possible to obtain a structure with lower thermal conductivity.

CONCLUSION

Thus, based on the studies carried out, it can be concluded that the surface hardening of steels by low-power UV lasers using a pulsed mode is possible. Due to low productivity, this process cannot be recommended for surface hardening of large parts. However, such hardening can be recommended, for example, for measuring and cutting tools.

It has been established that preliminary hardening bulk heat treatment, which provides the martensite structure, makes it possible to obtain a deeper hardened layer after laser hardening, compared with the structure after annealing, due to the difference in the thermal conductivity of the treated steels.

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Фізичні та технологічні принципи обробки сталі лазерним випромінюванням УФ-діапазону

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Основною метою статті є дослідження зміцнення сталі з використанням нестандартних довжин хвиль лазерного випромінювання. Описано також фізичні принципи взаємодії лазерного випромінювання з речовиною. Були проведені експерименти із загартування стали УФ-лазером (довжина хвилі 355 нм). Проведено експерименти та порівняльний аналіз об'ємного загартування сталі з охолодженням у воді, загартування лазерним променем YVO_4 лазера з $\lambda = 1{,}06$ мкм та загартування лазерним променем YVO_4 лазера з $\lambda = 0{,}355$ мкм. Дослідження проводилися на конструкційній сталі 45 та інструментальних сталях У12 та Р6М5. У ході досліджень були отримані нові цікаві наукові результати: вивчення мікроструктури зразків сталі У12 за допомогою електронного мікроскопа показало, що мартенсит, що утворюється при загартуванні УФ-випромінюванням, більш дисперсний, в результаті чого, можна зробити висновок, що така обробка може призвести до отримання поверхневих наноструктур розміром до 100 нм. Однак у зв'язку з малою продуктивністю і малою потужністю УФ-випромінювання пропоноване загартування сталі можна рекомендувати для вимірювального та ріжучого інструменту.

Ключові слова: Мікротвердість, Закон Бугера-Ламберта, Лазерне випромінювання, УФ-діапазон, Мікроструктура, Нелінійний кристал, Лазерний промінь.