Journal of Nano- and Electronic Physics
Vol. **15** No 1, 01007(7pp) (2023)

Журнал нано- та електронної фізики
Том **15** № 1, 01007(7cc) (2023)

New Technologies of Laser Hardening of Parts of Fuel Equipment

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(Received 02 January 2023; revised manuscript received 17 February 2023; published online 24 February 2023)

Laser thermal hardening of steel (laser hardening) consists in heating a section of the steel surface above the phase transition temperature by laser radiation, followed by rapid cooling due to heat removal. As a result of this treatment, martensite is formed – a saturated solid carbon solution in α-iron. For laser hardening, gas CO_2 lasers, solid-state (mainly Nd:YAG) and fiber lasers with a power of 0.5 kW or more are most often used. Optical systems for deploying and scanning the beam allow you to harden large areas of the surface with maximum efficiency. Not all products need processing of significant areas. Measuring and cutting tools, parts of fuel equipment, pump injectors are subject to significant abrasive wear of individual small areas. Less powerful lasers can be used to process them. There are no results of using low power pulsed lasers (up to 20 W) for surface hardening of steel products. The purpose of this work is to determine the modes of surface hardening of parts and tools made of carbon and alloy steels using low power pulsed solid-state YAG lasers. For laser hardening, a solid-state YAG laser with a power of 5 W (diode pumping, radiation wavelength = 1.064 μm, pulsed mode) was used. The use of a nonlinear crystal made it possible to obtain UV radiation from $\lambda = 0.355$ μm (third harmonic). Processing with single pulses and multi-pulse processing with short pulses were investigated. Thermal hardening was carried out on carbon and alloy steels of various compositions: 20, 45, У12, Р6М5, Р9, ШХ15, structural and tool steels for the purpose. The possibility of hardening by UV radiation was evaluated on steels 20, 45, У12 and ЩХ15. The efficiency of laser thermal hardening was evaluated by measuring microhardness. For surface hardening of products, where partial melting of the surface is possible, low-power pulsed lasers can be used. Laser hardening by UV radiation is a promising direction for thermal hardening of steels without surface melting. Hardening with a low-power laser is expedient for hardening parts of fuel equipment.

Keywords: Laser thermal hardening, Low-power laser, Single-pulse and multi-pulse processing, Pulse duration, Steel, Martensite, Fuel equipment parts.

DOI: 10.21272/jnep.15(1).01007

PACS numbers: 05.45.Df, 42.60.By

1. INTRODUCTION

Laser technologies have recently increasingly used in industry, because laser processing of materials allows ensuring the high quality of the products obtained, the specified productivity of the processes, environmental cleanliness, as well as the saving of human and material resources. Because of the use of a laser beam to strengthen materials, it becomes possible to make fundamental changes in the technology of manufacturing products. Thanks to the use of a laser beam to strengthen materials, it becomes possible to make fundamental changes in the technology of manufacturing products. With this method of strengthening, it is possible to change the properties of various parts of a part made of a relatively inexpensive structural material, and to obtain alloys with unique characteristics of strength, wear resistance and corrosion resistance [1, 2].

Laser thermal strengthening of steel consists in the impact of an intense flow of laser radiation on a local area of the surface, rapid heating of this area to high temperatures (above critical) and cooling at a rate above critical. In the process of heating and cooling, phase transformations occur, leading to the formation of martensite. From the point of view of using laser radiation for surface treatment with the purpose of hardening materials, the following regimes are of interest. First, laser heating of the surface layer of the material to a temperature not exceeding the melting point, holding at this temperature and subsequent cooling (Fig. 1).

Quenching from the molten state makes it possible to obtain the highest possible hardness of the hardened layer. In addition, finally, the heating of the material to a temperature exceeding its evaporation temperature, and plastic deformation due to the shock wave or heating of the surface layer by the plasma formed during the interaction of laser radiation with the material [3]. These modes of laser heating and their accompanying physical phenomena in the material are the basis of surface hardening methods.

Laser surface hardening has a number of advantages compared to other methods – it is not necessary to use any cooling media, which simplifies the technology, is characterized by a short exposure time, locality and ensures the absence of deformations of parts. This combination of parameters makes it possible to significantly simplify the technology of manufacturing engine parts in comparison with a number of energy-intensive technologies [2, 4, 5]. The thermal effect during laser heat hardening regulated within wide limits by changing the laser radiation parameters and processing modes. This ensures regulation of the heating and cooling rates of the metal, the time the metal stays at high temperatures, which allows obtaining the necessary structure of the surface area and the corresponding properties.

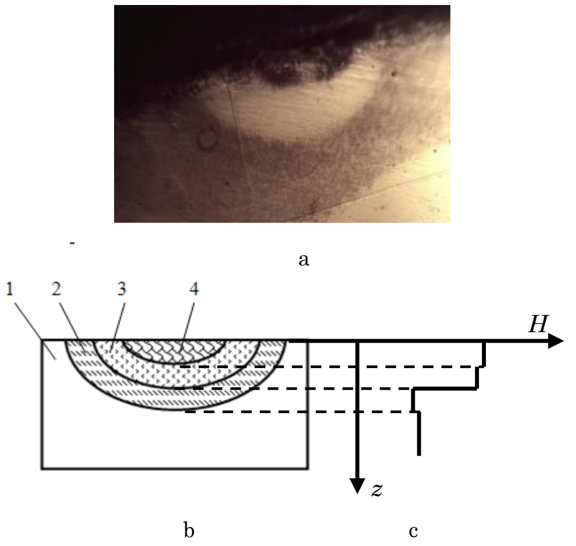

Fig. 1 – Microstructure (a), diagram of the cross section of the laser treatment zone (b) and microhardness distribution over the depth of the treatment zone (c): 1 – initial metal, 2 – tempering zone, 3 – hardening zone, 4 – hardening zone from the liquid state

Despite the existing opinion that a continuous mode is necessary for thermal treatment [6, 7], it can be assumed that the use of pulsed radiation will allow to reduce the power of laser devices. The short duration of pulses and the possibility of focusing radiation into a spot of small diameter allow creating power densities, which are sufficient to heat the treated surface to temperatures above phase transformations.

The main task of laser hardening is to increase the wear resistance of friction parts and tools. For parts of the fuel equipment of car engines, tractors, and road construction machines operating under conditions of significant friction and wear, processing of individual areas with low-power lasers can be very effective. Thus, the purpose of this work is to determine the modes of surface hardening using low-power YAG-lasers, which work in pulse mode, of parts of the fuel equipment of automobile engines.

2. ANALYSIS OF FACTORS AFFECTING THE EFFICIENCY OF LASER HARDENING

The main parameters characterizing laser radiation are power, wavelength of radiation, duration of exposure to radiation, energy and frequency of pulses, distribution of power density in the focusing spot, as well as coherence, directivity, monochromaticity and polarization of radiation.

Most laser technologies based on the thermal effect of radiation, that is, it implies the need to heat the object of influence to a predetermined temperature. Therefore, the main characteristic of the laser used in such technologies is its power. For pulsed lasers, the power in the pulse and the average power, which depends on the duration and frequency of the pulses, are considered. The wavelength of laser radiation chosen in such a way as to ensure maximum absorption of radiation by the substance. The reflectivity of metals decreases with decreasing wavelength, so the efficiency of heating metals increases when using a laser with a shorter wavelength. Therefore, the processing of metals using the Nd:YAG-laser, which has a wavelength of $\lambda = 1.06$ μm, is more effective compared to the treatment with a CO_2-laser, which has a wavelength of $\lambda = 1.06$ μm [7]. Both the roughness of the irradiated surface and the type of coating affect the absorption capacity [8-10].

The duration of radiation action determines the heating temperature of the object, the rate of heating and cooling, the magnitude of temperature gradients and the size of heated layers in the material. When using pulsed lasers, the duration of exposure is determined by the duration of the radiation pulse τ. The duration of action of lasers operating in continuous mode depends on the scanning speed VSC of the laser beam on the surface of the material. The pulse rate determines the processing performance. An important characteristic of laser radiation is the degree of its coherence, which is related to the direction of the radiation beam, its monochromaticity and polarization.

Not all of the listed parameters are equivalent in terms of the effect on the material or cannot changed when setting up the installation. The variable parameters in this work are the radiation wavelength, determined by the type of laser, the radiation power, and the duration of the laser exposure, which depends on the duration of the pulses, the frequency of their passage, and the speed of the laser beam moving along the surface of the material processed.

At present, three types of lasers mainly used in industry: they are gas, solid-state, and fiber. Gas CO_2 lasers with a power of more than 1 kW, reliable in operation, with an automated control system of the technological complex are widely used for various technological operations, including heat treatment. However, the high cost of such systems and their low productivity limit the use of lasers. Solid state yttrium aluminum garnet lasers (Nd^{3+}:YAG lasers) have a number of advantages over gas lasers. They are more compact, have higher values of the efficiency factor. At the same time, YAG lasers have a high cost and require significant operating costs. For thermal treatment, YAG lasers with a power of 1...5 kW are used, which work both in continuous and in pulse mode [11].

To date, the most promising technological tools are fiber lasers, which have high efficiency (up to 50 %), which reduces operating costs; small sizes make it easy to integrate them into existing production systems. However, their cost still remains quite high, which also does not allow us to talk about their widespread use.

The equipment used for laser processing of materials is extremely diverse – it is the laser itself, as well as external optics devices, controlled tables, manipulators, robots for moving the product during processing, as well as software necessary for the implementation of a specific laser exposure technology.

3. RESEARCH OF THE POSSIBILITY OF THERMAL TREATMENT WITH LOW-POWER LASERS

Hardening carried out on carbon steels with different carbon contents: steel 20, steel 45, steel У12, and high-speed tool steel R6M5. The evaluation of the possibility of hardening by UV-radiation carried out on steels 20, 45, У12 and ШХ15.

Samples of steel 45 were subjected to preliminary heat treatment – quenching with cooling in water and tempering at a temperature of 600 °C (improvement, mode 1). Normalization (mode 2) subjected to samples of steel 20, 45, and У12. In order to increase the absorptive capacity, the surface of the samples was not polished after heat treatment.

The roughness of the samples was $R_z = 20$ μm, so no additional measures were taken to increase the absorption capacity of the surface [7, 8]. The study of the properties of the hardened layer was carried out in terms of microhardness.

For laser hardening, we used a solid-state YAG laser with a power of 5 W with diode pumping (radiation wavelength = 1.064 μm), which works in pulse mode. The use of a nonlinear crystal made it possible to obtain UV radiation from $\lambda = 0.355$ μm (third harmonic). The following modes were studied: processing with single pulses lasting 0.1...0.4 ms and multi-pulse processing, that is, processing with short (30...70 μs) pulses, the table movement speed was 8...2 mm/s. The energy in the pulse was determined by the photoelectric method.

The results of studying the effect of pulsed radiation from a low-power laser on the microhardness of the surface of steels with different carbon contents are shown in Fig. 2.

An analysis of the results obtained shows that the preliminary heat treatment (initial structure) has a significant effect on the properties of surface layers after laser hardening. Enhancement (Mode 1) forms a tempered sorbitol structure with spheroidized carbides evenly distributed in a ferrite matrix. The structure of steels 20 and 45 after normalization is ferrite-pearlitic (lamellar carbides), steel У12 is pearlite and cementite. Further laser hardening in a pulsed mode leads to the formation of hardening structures. For each steel, there is a certain value of the pulse duration, which makes it possible to obtain the maximum hardness (Fig. 2b).

Studies have shown that there is no relationship between the carbon content in steel and the optimal pulse duration during laser hardening (Fig. 2b). The microhardness of the surface layers hardened by laser hardening of normalized steel 45 (Fig. 2b) is significantly higher than that of improved steel (Fig. 2a), which has a more dispersed tempered sorbite structure. With an increase in the amount of carbon, the microhardness of the hardened layer increases.

These results do not agree with the results obtained in [5, 12, 13], where the maximum hardness was obtained on samples with a more dispersed initial structure (reedited). Probably, the explanation lies in the processing conditions, in particular, in the short-term temperature effect [14, 15].

A low-power solid-state laser makes it possible to receive pulses of very short duration with high energy density. The size of the irradiation area is very small, so super-fast cooling of the metal occurs. It can be assumed that under such conditions the processes associated with austenization and melting of steel, dissolution of carbides, hardening and subsequent $\gamma \rightarrow \alpha$-transformation do not have time to complete in full,

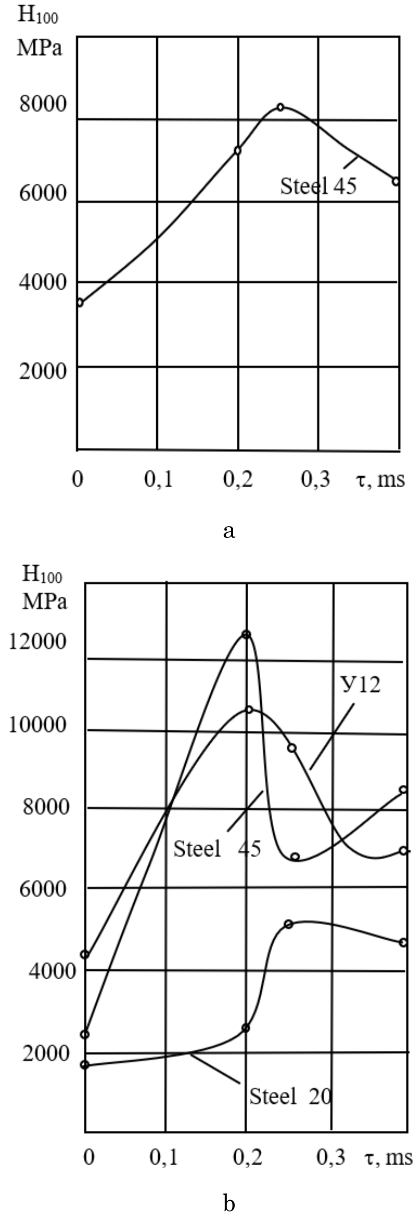

Fig. 2 – Dependence of the microhardness of carbon steels on the pulse duration: a – mode 1, b – mode 2

which leads to contradictory results that do not agree with those obtained during further processing powerful pulse lasers and continuous lasers [16, 17].

Comparison of the obtained microhardness values of control samples (bulk hardening) shows that laser hardening gives higher values, and the maximum increase in microhardness is achieved on low-carbon steel 20.

Thus, because of the studies carried out, it can be concluded that the surface hardening of steels by low-power lasers using a pulsed mode is possible. However, the productivity of such a process is low, which does not allow hardening the surfaces of large parts.

Subsequent studies included processing with single pulses lasting 0.1...0.4 ms and multipulse processing with short (30...70 μs) pulses. The research carried out on annealed steel with a ferrite-pearlite structure for 20 seconds, the surface of which irradiated with pulses of different energy densities (up to 150 J/cm²). Metallographic studies have shown that no structural changes occur during irradiation with pulses with an energy density of less than 130 J/cm^2. As the energy density increases to 150 J/cm^2, the steel structure changes.

It consists of martensite and α-phase that has undergone $\alpha \to \gamma \to \alpha$-recrystallization. A change in the number of radiation pulses leads to noticeable structural changes. After exposure to two pulses at an energy density of 150 J/cm^2 in the γ-phase, grains are crushed. The microstructure changes very significantly under the influence of five pulses – with a sufficient number of pulses, austenite homogenization occurs, because of which, upon cooling, a homogeneous structure of acicular martensite is formed.

Research was also carried out on tool steels: carbon У12 and high-speed P6M5. As the pulse duration increases, the power density values increase. These data are in good agreement with the analysis of the surface of hardened specimens. All investigated modes because heating of the treated surface above the melting temperature. However, when processing with single pulses, not only melting is observed, but also foaming of the metal, and after crystallization, microcracks form on the surface (Fig. 3).

The use of multi-pulse processing, although it leads to partial melting, which is undesirable in some cases, still provides a higher surface quality.

It can be assumed that during multipulse processing, due to the short time of laser radiation exposure to the material and the high rate of heat removal, the diffusion processes associated with the dissolution of carbides during melting do not have time to complete in full. Therefore, secondary cementite is retained, further grain refinement occurs, an increase in the density of dislocations, which leads to an increase in the level of internal stresses and, as a result, an increase in hardness.

For У12 steel, the optimal value of the pulse duration is 40 μs. For R6M5 steel, an almost monotonic increase in microhardness is observed in the considered time interval. It can be assumed, first, that studies with a longer pulse duration will make it possible to create an optimal mode of laser hardening for R6M5 steel.

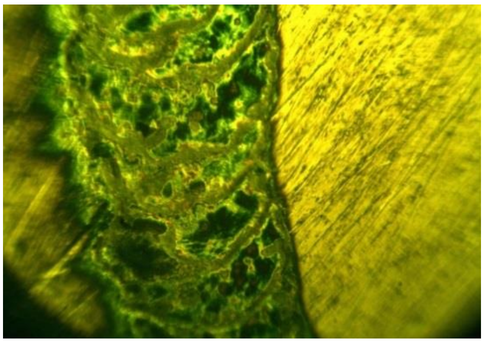

Fig. 3 – У12 steel, pulse duration 0.4 ms

An analysis of microhardness studies of specimens hardened in two modes showed that, when treated with series of short pulses, the microhardness of steel У12 is higher than when treated with single pulses (Fig. 4).

Secondly, the increase in the optimal pulse duration for R6M5 steel compared to У12 steel is associated with

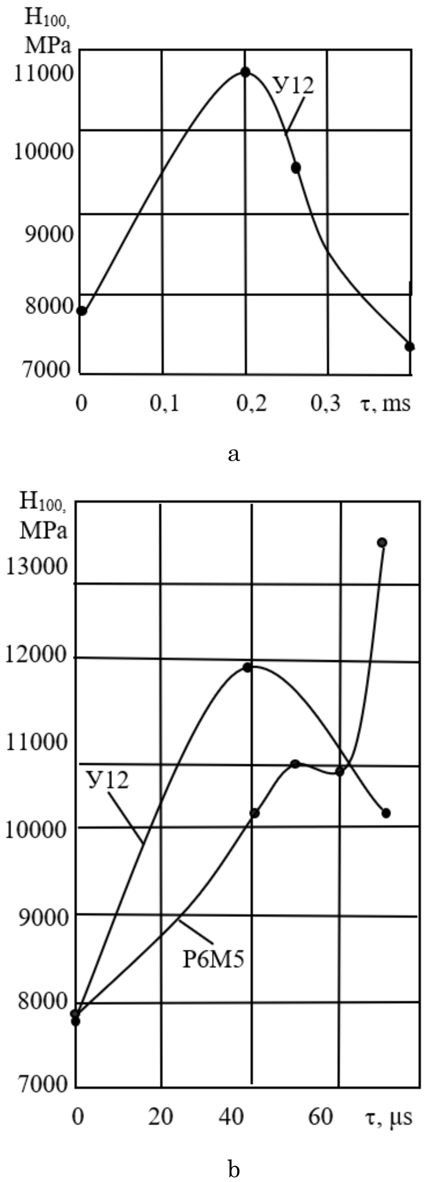

Fig. 4 – Dependence of microhardness on the pulse duration: a – processing by single pulses, b – multipulse processing

its special thermophysical properties: higher heat capacity and lower thermal conductivity compared to carbon steel.

Thus, the use of a solid-state laser with a radiation wavelength of $\lambda = 1.06$ μm allows hardening, but the heating temperature of the surface of tool steels is still too high – more than the melting temperature. After laser exposure, the surface roughness is higher than before treatment. Despite significant hardening, this treatment cannot be offered for critical parts with high surface quality.

Hardening with low-power lasers makes it possible to thermally harden steels and obtain high microhardness values of the surface layer. An increase in the power density during surface hardening was achieved by reducing the diameter of the focus spot of the laser beam and increasing the number of pulses. However, both single-pulse and multi-pulse quenching is accompanied by partial melting.

It is known [18] that the absorptive capacity of metals increases with a decrease in wavelength, therefore the hardening of steels with the help of short-wave UV-radiation, which allows obtaining a high-quality surface, is promising. Examination of the samples processed in the pulse mode at an average power of 5 W and a scanning speed of 25 mm/s showed that surface melting did not occur. The results of microhardness measurements are presented in Table 1.

Table 1 – Microhardness of various steels before and after laser hardening

Steel grade	Microhardness, MPa		
	In the original state	Hardening by IR radiation, $\lambda = 1.06$ μm	UV hardening, $\lambda = 0.355$ μm
20	2100	5770	6350
45	2700	8050	9200
У12	8150	11050	11280
ШХ15	7950	10200	10150

An analysis of the results of microhardness measurements showed the possibility of surface hardening of steels while maintaining the required surface quality by low-power UV lasers using a pulsed mode.

4. FEATURES OF LASER HARDENING OF PARTS OF FUEL EQUIPMENT

The decisive influence on the operation of engines is exerted by the condition of the fuel equipment and especially its precision parts, namely the parts of the spray [19]. The life of the fuel equipment is largely limited by the wear resistance of the spray needle. For making a sprayer are required impact-resistant, wear-proof, heat-proof, strong, hard and corrosion-resistant materials. Reasons of wearing of fuel injection equipment: fuel is polluted by parts' wear debris, by fuel combustion products, corrosion from fuel components. During operation spray needles mainly have abrasive wear, followed by galling. Wearing of the needle causes the reduction of hydraulic density, leak-tightness, performance deterioration of fuel supply equipment. The aim of further research is to increase the wear resistance of the fuel system spray needle by laser surface hardening.

The best materials for spray needles are steel P18 and steel P9 [20]. At this work it was offered to use a needle made of steel P9. The chemical composition was determined on a portable laser analyzer Laser Z200 C+. The phase composition was investigated by X-ray diffraction analysis. For laser hardening it was used a 5 W solid state YAG laser.

It is recommended to replace the standard three-dimensional heat treatment of the P18 steel spray needle by hardening, cold treatment and one tempering, which reduces the duration of heat treatment. The resulting steel structure is high-alloy martensite, special carbides and residual austenite.

For local surface hardening of areas of the needle that are subject to intensive wear, we used low-power laser hardening.

In this research it was detected the influence of pulse duration of laser radiation on micro-hardness H_{100} of hardened layer. The maximum of microhardness corresponds to pulse duration of $\tau = 3$ ms (Fig. 5a). Pulse duration of 3 ms provides the density of radiation energy, that is energy in pulse which is required for heating to close to solidus temperature (T_c), at which happens phase transition of steel P9.

Metallographic examination failed to find the difference of the steel structure after laser hardening with different pulse duration. But the difference was detected by X-ray structural analysis. At $\tau_i = 3.0$ ms there is minimal amount of retained austenite in steel, after laser hardening by pulses of 1.5 and 8.0 ms it was detected about ~ 15 % of retained austenite.

Secondary carbides are present at the structure of the steel at all values of τ_i after laser hardening starting with temperature of T_c, their quantity also depends on pulse duration. The maximum amount of carbides was detected when $\tau = 3$ ms (Fig. 5b).

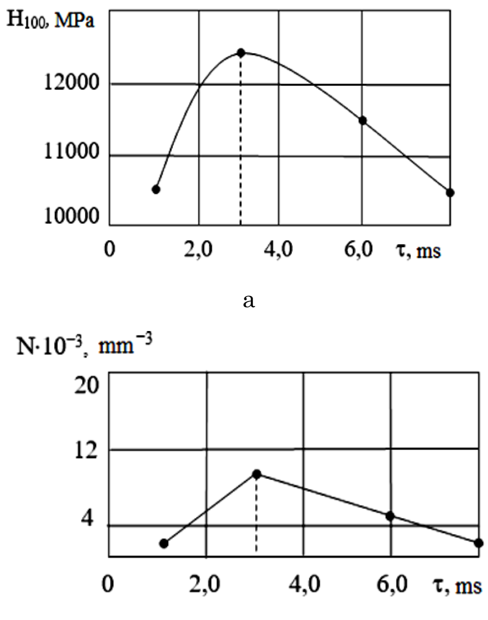

Fig. 5 – The dependence of hardness (a) of hardened layer and amount of carbides (b) on pulse duration

After pulse duration is increased (and energy density) it was noticed the reduction of hardness, which is explained by surface fusion and creating less hard structure components, increasing of amount of retained austenite.

In Fig. 6, it is shown the distribution of hardness on the depth of hardened layer. The depth of hardened layer after laser treatment at the optimal mode is 0.1-0.2 mm.

The wide use of pulse hardening is conditional upon forming of specific metastable structures which have high friction wear resistance.

At the optimal pulse duration of 3 ms the maximal surface layer hardness of steel P9 could gain 11000-12800 MPa.

Breaking laser treatment mode (increase of pulse duration) causes surface fusion. Treatment with surface fusion causes not only reduction of hardness but also quality degradation – increase of roughness, geometry perturbation, which is unwelcome for precise parts of fuel equipment.

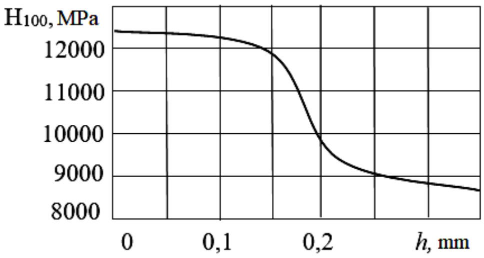

Fig. 6 – The change of microhardness from depth of laser influence

That way, on the ground of research taken it was found that micro-hardness of P9 steel, which was laser hardened, depends on pulse duration. There is a good correlation between the dependences of microhardness, the amount of residual austenite and the number of secondary carbides on the pulse length. It was detected the optimal laser pulse duration for obtaining the maximal surface layer hardness of 12800 MPa.

5. CONCLUSIONS

Thus, the paper shows that it is possible to use low-power pulsed lasers for surface hardening. For steels with different carbon contents during laser hardening, the optimal pulse durations were determined. It has established that steels with a lamellar perlite structure are most strongly strengthened. Research have shown that laser hardening gives higher values of microhardness than bulk hardness, and the maximum increase in microhardness is achieved on low-carbon steel 20. With multi-pulse machining of steels, when the pulse length is shorter than with single pulse, the intensity of hardening is higher, and the quality of the machined surface is better. However, such processing can be recommended only for those products where high surface quality is not required.

Single-pulse and multi-pulse processing are accompanied by partial melting of the surface of steel products. A promising direction of using low-power lasers for thermal hardening of steels is to increase the absorptive capacity of the surface by reducing the radiation wavelength – hardening of steels with UV radiation (wavelength = 0.355 μm) at low power (5-10 W) in a pulsed mode.

It has been found that the microhardness of the R9 steel that has undergone laser hardening depends on the pulse duration. There is a good correlation between the dependences of microhardness, the amount of retained austenite and the amount of secondary carbides on the pulse duration. The optimal duration of the laser pulse was determined to obtain the maximum hardness of the surface layer of 12800 MPa.

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Нові технології лазерного зміцнення деталей паливної апаратури

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Лазерне термічне зміцнення сталі (лазерне гартування) полягає у нагріванні вище температури фазових переходів ділянки поверхні сталі лазерним випромінюванням з подальшим швидким охолодженням за рахунок Для лазерного гартування найбільш доцільно використовують газові CO_2-лазери, твердотільні (в основному Nd:YAG) та волоконні лазери потужністю від 0,5 кВт. Оптичні системи розгортання та сканування променю дозволяють з максимальною ефективністю зміцнювати великі ділянки поверхні. Вимірювальний та різальний інструмент, деталі паливної апаратури, форсунки насосів зазнають значного абразивного зношування окремих невеликих ділянок. Для їхньої обробки можна використовувати менш потужні лазери. Немає результатів використання імпульсних лазерів малої потужності (до 20 Вт) для поверхневого зміцнення сталевих виробів. Метою даної роботи є визначення режимів поверхневого зміцнення деталей та інструментів із вуглецевих та легованих сталей з використанням малопотужних твердотільних імпульсних YAG-лазерів.Для лазерного загартування використовувався твердотільний YAG-лазер потужністю 5 Вт (діодне накачування, довжина хвилі випромінювання = 1,064 мкм, імпульсний режим). Використання нелінійного кристала дозволило отримати УФ-випромінювання з $\lambda = 0{,}355$ мкм (третя гармоніка). Були досліджені обробка за допомогою одиночних імпульсів та багатоімпульсна обробка короткими імпульсами. Термічне зміцнення проводилося на вуглецевих та легованих сталях різного складу: 20, 45, У12, Р6М5, Р9, ШХ15, конструкційних та інструментальних за призначенням. Можливість зміцнення УФ-випромінюванням була оцінена на сталях 20, 45, У12 та ШХ15. Ефективність лазерного зміцнення оцінювали за вимірюванням мікротвердості. Для поверхневого зміцнення виробів, де можливе часткове плавлення поверхні можуть використовуватися лазери малої потужності в імпульсному режимі. Лазерне загартування ультрафіолетовим випромінюванням є перспективним напрямом для термічного зміцнення сталей без плавлення поверхні. Гартування лазером малої потужності доцільне для зміцнення деталей паливної апаратури.

Ключові слова: Лазерне термічне зміцнення, Лазер малої потужності, Одноімпульсна та багатоімпульсна обробка, Тривалість імпульсу, Сталь, Мартенсит, Деталі паливної апаратури.