Описані результати дослідження впливу режимів лазерного гартування на властивості конструкційних сталей 40, 40Х і 38Х2МЮА. Показано, що лазерне зміцнення дозволяє значно підвищити твердість. Знайдені математичні закономірності впливу швидкості переміщення лазерного променю на глибину локально зміцненого шару залежно від марки сталі. Показано, що найвищі значення твердості відповідають зоні найбільш дисперсного мартенситу

Ключові слова: сталь, лазерне гартування, глибина шару, зміцнення, твердість, гартування, поліпшення

Описаны результаты исследования влияния режимов лазерной закалки на свойства конструкционных сталей 40, 40Х и 38Х2МЮА. Показано, что лазерное упрочнение позволяет значительно повысить твердость. Найдены математические закономерности влияния скорости перемещения лазерного луча на глубину упрочненного слоя в зависимости от марки стали. Показано, что наивысшие значения твердости соответствуют зоне наиболее дисперсного мартенсита

Ключевые слова: сталь, лазерная закалка, глубина слоя, упрочнение, твердость, закалка, улучшение

UDC 621.789

DOI: 10.15587/1729-4061.2016.65455

THE STUDY OF THE INFLUENCE OF LASER HARDENING CONDITIONS ON THE CHANGE IN PROPERTIES OF STEELS

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1. Introduction

Failure of machinery is mainly associated with surface fracture, namely, wear [1]. Today, there are a variety of technologies aimed at the surface hardening of parts such as thermochemical treatment; spraying; hard facing; surface plastic deformation; electroplating; laser hardening; induction hardening etc. There is also a wide range of combined technologies [2]. All existing technologies can be divided into the following groups: coating; diffusion coating; surface hardening by changing the structure.

The latter is of greatest interest because it does not involve any additional alloying and does not affect the chemical composition of cases [3]. Therefore, the study of the influence of laser hardening on the surface properties of steels is relevant.

2. Literature review and problem statement

In laser hardening, surface heating occurs due to the impact of the high-energy radiation beam. Almost any inner surface of the part can be hardened in this way, without hardening the outer surface and thus without changing the properties of the matrix. The case depth is regulated by laser exposure duration. With this method of hardening it can vary from several microns to tens of microns and hundreds of microns [4].

Significant advantages of laser treatment [5] in comparison with conventional methods of heat treatment of materials should be noted. In conventional heat treatment, subsequent stress-relief tempering is required. However, this treatment reduces the case hardness. As a rule, the hardness is 48–52 HRC. Laser treatment does not require additional tempering operations. In this case, the hardness of the laser-beam hardened surface zone is over 58–62 HRC.

The use of fast heating [6], producing finer structure of the hardened steel, provides a better combination of strength and toughness properties. Significant increase of operational properties of parts is achieved by improving the hardening technology, namely enhancing the properties of the surface layers of parts. The heated zone is cooled immediately upon the beam travel. This is mainly due to heat transfer into the body of the massive steel part, conductive and radiative heat transfer from the surface to the atmosphere. These parameters can be varied over a wide range.

Interaction of laser radiation with the material is accompanied by heating of surface layers and, if necessary, melting. At that, a complex set of phase transformations is observed, which result in the hardened zones on the surface of products, poorly etched by conventional etching agents [7].

The effect of steel hardening [8] under laser irradiation is achieved not only by the martensite transformation, but also reaching the optimum combination of saturation of solid solutions with carbon and alloying elements with their heterogeneity arising in partial dissolution of starting carbides, an increase in the density of crystal defects and, in particular, plastic shifts occurring in conditions of powerful heat pulse.

Thus, laser irradiation of materials is a unique way to change the submicrostructure [9]. The irradiated zones on the surface of steel samples have a heterogeneous structure due to uneven energy distribution in the laser beam cross-section, irradiation conditions, chemical composition and structure of the base metal. So, the study of the structure of the treated layers is of interest, since heterogeneity may affect the wear resistance and durability of irradiated products [10].

The steels used in the designs and for the manufacture of machine parts should provide necessary parameters of strength, ductility, fatigue strength, toughness, and hardness over the entire cross-section of the part. The surface layer of such parts should have high operational properties. One of the most rational methods of local hardening is laser hardening. However, there are still a number of unresolved issues concerning the impact of process parameters on the properties of structural steels.

3. Research goal and objectives

The goal of the research is to investigate the influence of laser processing conditions on the properties of 40, 40Cr and 38Cr2MoAl steels for surface hardening.

To achieve this goal, it is necessary to solve the following tasks:

– to make a comparative analysis of hardness indicators after through-hardening, hardening and tempering, and laser hardening of steels;

– to identify the patterns of influence of the laser beam travel speed on the case depth depending on the steel grade;

– to examine the distribution of microhardness over the cross section in the zone of local laser hardening.

4. Research material, process conditions of laser hardening and research techniques

4. 1. Research material

The research material in this paper is 40, 40Cr and 38Cr2MoAl steels. Chemical composition of steels and critical point temperatures are shown in Tables 1 and 2, respectively.

Table 2

Critical point temperature

Steel grade	Critical point temperature, °C				
	A_{c1}	$A_{c3}(A_{см})$	$A_{r3}(A_{rсм})$	A_{r1}	$M_н$
40	730	790	780	690	340
40Cr	743	782	730	693	325
38Cr2MoAl	800	865	740	665	330

4. 2. Process conditions of laser hardening

The samples underwent standard through heat treatment – hardening and tempering.

Laser hardening was conducted on the Latus-3 setup. The power of the laser radiation was 0,9–1,1 kW, spot diameter – 5 mm. The laser beam travel speed varied in the range of 0,5–1,5 m/min.

4. 3. Methods of the study of the structure and properties of hardened cases on steels

The microstructure and depth of hardened cases were examined by optical microscopy on the MIM-8 microscope by a standard technique at different magnifications.

The microhardness variation range from the surface values to the core hardness was taken as the case depth.

The Rockwell hardness test of samples after hardening and tempering was carried out by a standard technique in which the diamond cone with an apex angle of 120° (in hardness test of very hard materials) is pressed into the test body. The cone is pressed by applying two successive loads: preload (P=10 kgf) and main load. The total load for the C scale is 150 kgf. Rockwell hardness is set in units. The value corresponding to the axial displacement of the indenter by 0,002 mm was taken as the hardness unit.

The microhardness of the samples was measured on the PMT-3 device with a load of 50, 100 g and holding for 7–15 s by a standard technique (GOST 9450–76).

5. Experimental data processing and discussion of results

5. 1. Initial heat treatment

Hardening temperature of 40 and 40KH steels according to their critical points (Table 2) was 850 °C. Holding at a hardening temperature lasted 15 minutes on the basis of dimensions of the samples. Cooling was performed in water on the basis of ill (time temperature transformation) diagrams of the given steels.

The hardening temperature of the 38Cr2MoAl steel was 940 °C with oil cooling. The cooling medium was selected on the basis of the isothermal transformation of austenite, which allows both water and oil hardening of the steel to produce the hardened martensite structure. To reduce internal stresses (structural and thermal), alloy steel should be cooled from the oil hardening temperature.

Table 1

Chemical composition of steels

Steel grade	Chemical composition of steels									
	C	Cr	Si	Mn	Ni	Cu	S	P	Mo	Al
40	0,37–0,45	to 0,25	0,17–0,37	0,50–0,80	to 0,25	to 0,25	to 0,04	to 0,035	–	–
40Cr	0,36–0,44	0,8–1,1	0,17–0,37	0,5–0,8	to 0,3	to 0,3	to 0,035	to 0,035	–	–
38Cr2MoAl	0,35–0,42	1,35–1,65	0,20–0,45	0,30–0,60	0,3	0,3	0,025	0,025	0,15–0,25	0,70–1,10

After hardening, steel samples were subjected to high-temperature tempering. Tempering temperature of the 40 steel was 550 °C, 40Cr steel – 580 °C, 38Cr2MoAl – 600 °C. The holding time at high-temperature tempering was 1.5 hours. This time is enough for complete phase transformation of hardened martensite into secondary sorbite. Still air cooling of 40 and 38Cr2MoAl steels was carried out and steel 40Cr was cooled in water to prevent tempered martensite embrittlement.

In the carbon structural steel 40, after hardening and tempering, the structure is formed of the ferrite-cementite mechanical mixture in which the granular cementite has a dispersed rounded shape due to coagulation and spheroidizing at a temperature of 550 °C. In the 40Cr steel, the presence of the chromium alloying element results in the formation of granular alloyed cementite and chromium carbides. Dispersion of chromium carbides is slightly above the rejected cementite. In 38Cr2MoAl alloy structural steel, the most dispersed secondary sorbite structure compared to 40 and 40Cr steels is formed due to the influence of alloying elements that inhibit the hardened martensite transformation and coagulation and spheroidizing of carbide particles. In the 38Cr2MoAl steel, in addition to granular alloyed cementite and chromium carbides, molybdenum carbides are formed.

Thermal treatment conditions, the resulting structure and hardness values of the examined steels are presented in Table 3.

Table 3

Thermal treatment conditions, structure and hardness values of the examined steels

Steel grade	Hardening temperature, °C/cooling medium	Hardness, HRC	Tempering temperature, °C/cooling medium	Structure after hardening and tempering	Hardness, HRC
40	850/water	58–56	550/air	α-Fe+Fe_3C	32–30
40Cr	850/water	60–58	580/water	α-Fe+Fe_3C+$(Fe,Cr)_3C$	39–38
38Cr2MoAl	940/oil	55–53	600/air	α-Fe+Fe_3C+$(Fe,Cr)_3C$+ +$(Fe,Mo)_3C$+$(Fe,Cr,Mo)_3C$+ +MoC+Mo_2C	44–43

5. 2. Laser hardening

Local surface hardening of steels was carried out on the technological complex on the basis of a powerful CO_2 laser Latus-31, a general view of which is shown in Fig. 1.

Fig. 1. General view of the laser technological complex on the basis of CO_2 laser Latus-31

The radiator with longitudinal fast pumping and convective cooling of the working mixture is equipped with a powerful high-voltage DC source. The radiation power was continuously monitored by a special throughput meter, operating at the branch of the part of radiation (10 %) of the primary beam (measuring accuracy 2 %).

Laser-beam focusing was carried out using the lens objective. Planoconvex spherical lenses with a focal length of 300 mm were used as focusing elements. The focal spot size was varied by adjusting the distance from the focusing element to the surface in the range of d0=2.0–7.0 with an accuracy of ± 0.05 mm.

The focal spot diameter was measured along the curve of radiation intensity distribution in the cross-section that is at a distance of I_{max}/e^2 from the main plane. The intensity distribution in the cross section of the focused beam was performed by scanning with a special pyroelectric analyzer.

After treatment, three layers were distinguished visually and by the change in the micro-hardness values in the zone of laser irradiation of steels.

The first layer is the melt zone, which has a columnar structure. The main structural component is martensite. This zone was not observed in all samples. The presence of the melt zone is not always appropriate for further operation of parts.

The second layer is the solid-phase hardened zone. The lower boundary of the second zone is determined by the temperature of heating up to Ac_1. Nearer to the surface, there is martensite and retained austenite, deeper along with martensite, there is ferrite.

The third layer is the transition zone, in which metal is heated below Ac_1. In this zone, typical tempered structures – troostite and sorbite were observed for all investigated steels.

The microstructure of the 40Cr steel after local laser hardening is shown in Fig. 2. As expected, the basic matrix is secondary sorbite, and in the zone of laser irradiation, there is highly-dispersed martensite structure with increasing dispersion to the sample surface. Due to the formation of this structure, surface hardening occurs, which increases operational properties of parts.

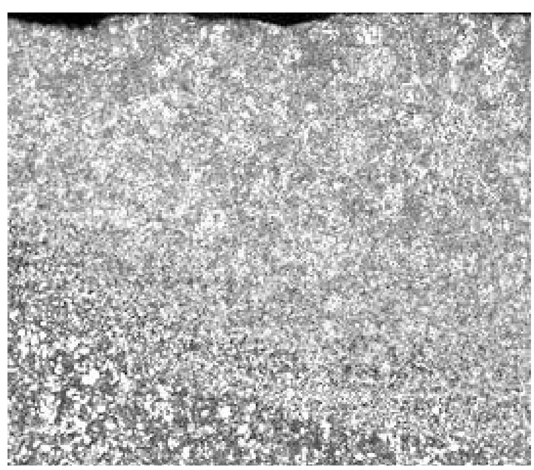

Fig. 2. The microstructure of the 40Cr steel after local laser hardening, x350

Changes in steel hardness values depending on the treatment method are shown in Fig. 3. Histograms show that the highest hardness values correspond to laser hardening, and high-temperature tempering reduces the hardness values. Thus, the use of laser hardening after hardening and tempering of steels significantly increases the surface hardness with preservation of a viscous core.

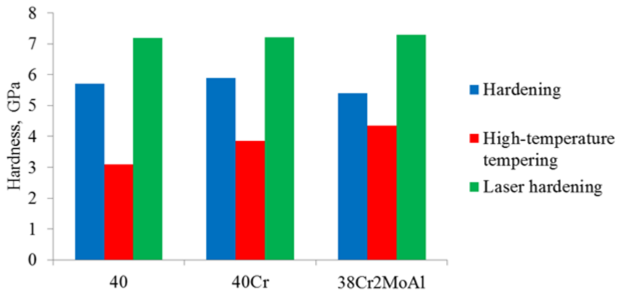

Fig. 3. Changes in steel hardness values depending on the treatment method

The values of the case depth for 40, 40Cr and 38Cr2MoAl steels are shown in Fig. 4. With the increased laser beam travel speed, the case depth reduces for all investigated steels. Quadratic and cubic polynomial approximation of the data obtained showed that the reduction takes place on the second-third degree polynomial equations. Thus, the patterns of the changes in the case depth depending on the changes in the laser beam travel speed for 40, 40Cr and 38Cr2MoAl steels are obtained (equations are shown in Fig. 4 near the curves for each steel, approximation values reliabilities are also specified). These patterns allow predicting the case depth values depending on the laser beam travel speed. With the increased content of alloying elements in steels, the hardened case increases.

Distribution of micro-hardness values for steels is shown in Fig. 5. The curves for different steels are general in nature, but with the increased content of alloying elements in steels, the case hardness and depth increase.

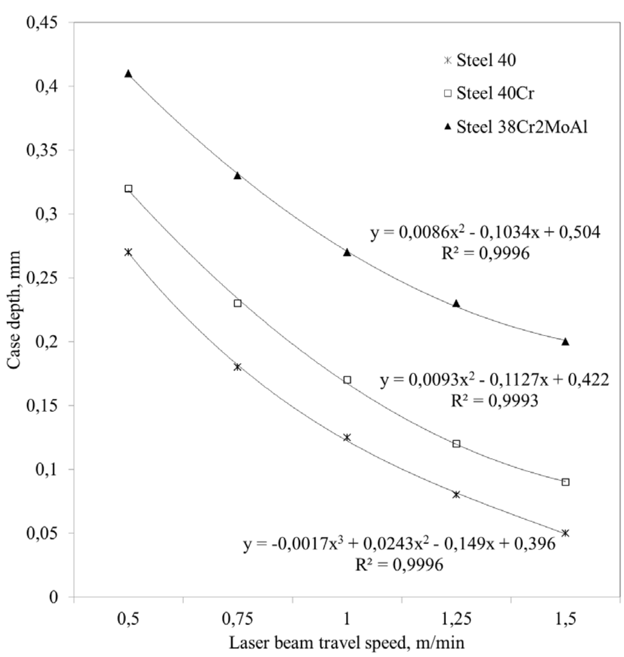

Fig.4. Changes in the case depth values depending on the laser beam travel speed

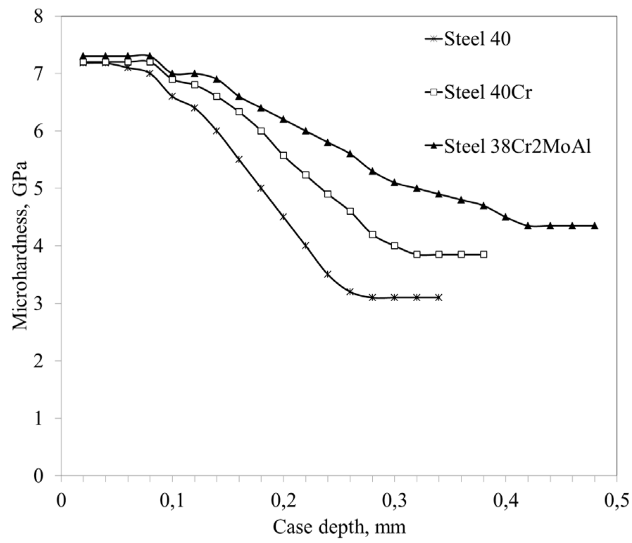

Fig. 5. Distribution of microhardness values in the cross section from the surface deep into the sample at the laser beam travel speed of 0.5 m/min

The highest hardness values for steels correspond to the zone of the most dispersed martensite, further increase in grain dispersion reduces the hardness parameters (Fig. 5).

Due to the local surface hardening of 40, 40Cr and 38Cr2MoAl steel parts by laser hardening, operational properties of parts in further operation can be improved. This method is suitable for hardening difficult-to-access areas of parts, local contact areas. The hard case is formed through laser hardening, the matrix of the part remains viscous and softer. This combination of properties enhances the durability of parts.

7. Conclusions

1. Comparative analysis of hardness parameters after the through hardening, hardening and tempering, and laser hardening of steels showed that laser hardening improves the hardness by 1.3–1.35 times compared to the through hardening and by 1.7–2.32 times compared to the hardness of steels after hardening and tempering.

2. Mathematical patterns of the influence of the laser beam travel speed on the case depth depending on the steel grade in the form of quadratic and cubic polynomials were found. These patterns allow predicting the case depth values.

3. Microhardness distribution over the cross section in the zone of local laser hardening showed that the highest hardness values for steels correspond to the zone of the most dispersed martensite, further increase in grain dispersion reduces the hardness parameters.

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