Effects of laser treatment modes on the parameters of the hardening zones and the wear resistance of steel 40Cr

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Abstract. The paper presents the results of metallographic and tribological studies of laser hardening zones of steel samples. A full factorial experiment on laser hardening with a change in the distance from the focal plane, radiation power and processing speed was carried out. The regularities of changes in the depth and width of the quenching zones are obtained from the regression equations. With low-frequency transverse scanning of the laser beam up to 100 Hz, the hardening zones with a width of 20 mm and a depth of 1.4-2.0 mm in one pass were obtained. The wear resistance of the hardened zones is 3.68 times higher than the base material.

1. Introduction
Laser hardening of martensitic stainless steel AISI 416 with a carbon content of 0.167% was carried out on samples with dimensions of 55×10×7.5 mm with an initial hardness of 155 HV [1]. The Nd:YAG laser of Rofin-Sinar company with a maximum radiation power of 2.2 kW was used. The laser beam was focused to a diameter of 2 mm on the sample surface. The testing regimes of laser hardening was carried out at radiation power of 0.7 and 1 kW when the velocity of the beam of 0.5; 1; 2; and 3 m/min. The maximum depth of hardening of 0.9 mm with a hardness of 400-700 HV obtained with a radiation power of 1 kW and a speed of displacement of the beam 0.5 m/min. the wear Tests were performed according to the scheme of the disk (diameter 73 mm, hardness 63 HRC) – pin (7×7,5×10 mm). The linear velocity of the disk 8.4 m / min., the Load on the image under test 50 N. Found that the minimum wear rate amounted to 0.001 g / min for the samples treated with the speed of movement of the beam of 0.5–1 m/min and output power of 0.7–1 kW. This corresponds to the wear intensity of the reference samples of this steel after volumetric hardening.

Laser heat treatment of the Ck45 Steel surface creates a microstructure with 91.65% needle martensite and 8.35% residual austenite [2]. Martensite hardness reaches up to 850 HV, and residual austenite 400-600 HV. Wear tests were performed according to the disk – finger scheme at a load of 30 N, the speed of movement of 0.7 - 1.49 cm/s. the Hardness of the disk was 385 HV. The duration of each test was 10 minutes. The wear resistance of laser-hardened samples is twice as high as that of the original steel.

The effect of the fiber laser beam defocusing on the depth and width of the laser hardening zones, processing modes on the parameters of the hardened zones at low-frequency transverse vibrations of the beam is determined.
2. Materials and methods
For laser hardening, 40Cr steel samples with dimensions of 12×20×70 mm were performed using a laser complex based on a fiber laser LS2 equipped with an optical head FLWD50L fixed on the movable flange of the KUKA robot arm. The diameter of the transport fiber 100 µm, focus collimating lens of 160 mm, the focusing lens of 500 mm. The processing is performed with the radiation power of the laser 1000 and 1800 W, the speed of the beam 10 to 18 mm/s, the defocusing of the beam in the range of 25 – 200 mm.

Metallographic examination was performed with use of hardness testing of the PMT-3 under a load of 0.98 N, a digital microscope AM413ML, metallographic microscope Altami MET 1C.

In the second series of experiments using the method of full factorial experiment (PFE) the influence of processing modes on the parameters of hardened tracks was determined. The power of radiation P, W, processing speed V, mm/s, and defocusing of the beam Z, mm were chosen as experimental factors the depth H and width B of the laser hardening zones were considered as the responses of the system. For the construction of mathematical models. Table 1 presents the initial data. In this paper, in addition to taking into account the influence of experimental factors on the response, all possible interactions of factors with each other were taken into account. The regression equation has the form [3]:

\[ y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{1,2}x_1x_2 + b_{1,3}x_1x_3 + b_{2,3}x_2x_3 + b_{1,2,3}x_1x_2x_3 \] (1)

where:
y – system response;
\( x\) - encoded variables
b – coefficients of the regression equation.

| Table 1. Summary table of coding of FFE variables |
|-------------------------------------------------|
| Factor  | Upper level factor | Lower level factor | Centre plan | Range of variation |
|---------|-------------------|--------------------|-------------|-------------------|
| \( x_i \) | \( x_i^+ \) | \( x_i^- \) | \( x_i^0 \) | \( \Delta_i \) |
| P (W)   | 1800             | 1000              | 1400        | 400               |
| V (mm/s)| 18               | 10                | 14          | 4                 |
| Z (mm)  | 150              | 100               | 125         | 25                |

At the end of the experiments, the sections were made according to the standard procedure and triple measurements of the depth and width of the hardened zones were made. All possible interactions of factors were determined in the calculation. Since FFE 23 was performed, the number of experiments was 8 for each series.

In the third series of experiments, broadband laser quenching was performed at transverse oscillations of the beam relative to the velocity vector of the beam using a galvanoscanner with a mirror oscillation frequency of up to 100 Hz. Wear resistance tests were performed on the friction machine MTU-01 according to the scheme plane (sample) - ring (counter-tile, steel 40X, HRC 48-52) at a load of 2 MPa. As the lubricant used oil TP 22S.

3. Research results and discussion
According to the results of metallographic studies of hardened zones in the first series of experiments, graphs of the depth and width of the quenching zones on the change in the distance to the focal plane Z at a linear beam energy of 100 j/mm are presented in Figure 1 (a, b). The depth and width of the quenching zone varies almost linearly in the range of 100-150 mm and therefore this area can be described by first-order regression equations [4].
Figure 1. Dependence of the depth (top) and width (bottom) of the laser hardening zone of steel 40Cr from the beam defocus: 1 – V = 10 mm/s, P = 1000 W, 2 - V = 18 mm/s, P = 1800 W.

In the second series of experiments the regression equations in the defocusing of a beam of 100 – 150 mm. Depth of the hardening zone:

\[
H = 1.25 + 0.196 \frac{P-1400}{400} - 0.172 \frac{V-14}{4} + 0.05 \frac{Z-125}{25} - 0.001 \frac{P-1400}{400} \frac{V-14}{4} - 0.043 \frac{V-14}{4} \frac{Z-125}{25} + 0.049 \frac{P-1400}{400} \frac{Z-125}{25} + 0.0072 \frac{P-1400}{400} \frac{V-14}{4} \frac{Z-125}{25}
\]

(2)

where

- P – laser radiation power, W;
- V – beam speed, mm/s;
- Z – distance to the focal plane, mm.

The width of the hardening zone:

\[
B = 4.701 + 0.37 \frac{P-1400}{400} - 0.275 \frac{V-14}{4} - 0.514 \frac{Z-125}{25} + 0.102 \frac{P-1400}{400} \frac{V-14}{4} + 0.134 \frac{V-14}{4} \frac{Z-125}{25} + 0.250 \frac{P-1400}{400} \frac{Z-125}{25}
\]

(3)

The regression equations were calculated and the results were compared with experimental data. The calculated values differ from the actual depth and width of the quenching zones by no more than 5%. Regression models of dependencies of type H (P,V), B (P,V) are introduced into the MSExcel...
table editor and comparative surfaces for these functions are constructed (figure 2). The prevailing influence on the geometric parameters of the quenching zones is the radiation power (figure 2). With increasing power, the width and depth of the quenching zone grow. As the travel speed increases, the depth and width of the hardened zones decreases. However, at \( Z = 100 \) mm at lower speeds, the width varies slightly (figure 2 b), which is due to the energy consumption for melting the surface of the sample material. As the beam defocus (diameter) increases, the depth of the quenching zones decreases and the width increases.

![Figure 2](image)

**Figure 2.** Influence of processing modes on the depth \( N \) and the width of the quenching zone at defocusing of the beam \( Z \): and \( Z = 100 \) mm and big \( Z = 150 \) mm.

Figure 3 shows the micro-sections of the hardened steel 40X with the width and thickness of the hardening zone of 20 mm and 1.4-2.0 mm, respectively, obtained when the defocusing of the beam \( Z = 150 \) mm, radiation power \( P = 1800 \) W at various speeds of processing with the use of transverse vibrations of a beam up to 100 Hz. The microhardness of the laser hardening zones varied within 7240 – 7900 MPa.

The results of comparative wear tests are shown in figure 4. The first column shows the wear intensity \( J = 1.98 \times 10^{-9} \) of the substrate normalized steel 40KH. The second column of the wear intensity \( J = 0.532 \times 10^{-9} \) quenched samples with the width of the zone of 20 mm.
4. Summary

Linear regression equations for beam defocusing of 100-150 mm are obtained to calculate the depth and width of the quenching zones with an error of not more than 4%. The constructed surfaces show the regularity of changing the depth and width of the hardened zones from the processing modes. The technology of laser hardening with a width of 20 mm with a layer depth of 1.5-2.0 mm in one pass at transverse vibrations of the beam up to 100 Hz has been worked out. The wear resistance of the friction surfaces with a broadband laser hardening is increased 3.68 times compared with the normalized steel 40KH.

References

[1] Al-Sayed S R 2017 Characterization of a Laser Surface-Treated Martensitic Stainless Steel *Materials* **10**
[2] Adel K M 2014 Enhancement of Dry Sliding Wear Characteristics of CK45 Steel Alloy by Laser Surface Hardening Procedia Materials Science 6 1639 – 1643

[3] Evdokimov Yu A, Kolesnikov V I, Teterin A I 1980 Planning and analysis of experiments in solving friction and wear problems. Moscow. Science.

[4] Biryukov V P 2017 Experimental determination of parameters of hardened zones during laser hardening of cast irons and steels Journal Photonics 2 22-32