Hardening of steel with a defocused and oscillating laser beam

V. P. Biryukov 1, D. V. Panov 2, V. N. Petrovsky 2, and D. V. Ushakov 2
1 Mechanical Engineering Research Institute named by A.A. Blagonravov, 4, Maly Khaittonyevsky Pereulok, Moscow, 101990, Russia
2 National Research Nuclear University MEPhI, 31, Kashirskoye highway, Moscow, 115409, Russia
E-mail: laser-52@yandex.ru

Abstract. The paper deals with the process of laser hardening of 40Cr steel samples using fiber laser radiation and transverse sinusoidal beam scanning with a frequency of 200 Hz. A complete factor experiment on laser quenching with changes in the distance from the focal plane, radiation power and processing speed was performed. The regularities of changes in the depth and width of the quenching zones with a defocused and oscillating beam are obtained from the regression equations.

1. Introduction

In modern mechanical engineering, laser hardening technologies are becoming increasingly important. To increase the service life of turbine shaft necks used in the production of power plants and nuclear reactors, in most cases, it is not enough to use traditional hardening technologies. Finishing technologies of laser hardening of friction surfaces allow to increase the service life of aggregates by 2-3 times. However, the regularities of the formation of laser quenching zones with simultaneous changes in the defocusing of laser radiation, power and speed of laser beam processing have not yet been established.

The maximum value of microhardness of samples of steel AISI 4130, for hardening with diode laser radiation power of 1400 watts, Costello 792 HV with a depth of 1.02 mm, and the processing of solid-state Nd:YAG laser power of 700 W - 698 HV with a depth of 0.98 mm, 1.38 and 1.22 times higher hardness after the volume of sample quenching of this steel (572 HV), respectively [1]. The amount of ferritic phase in the samples after normal quenching is greater than when hardened with diode and solid-state lasers.

Laser heat treatment of the surface of ck45 steel creates a microstructure with 91.65% needle-like martensite and 8.35% residual austenite [2]. The hardness of martensite reaches up to 850 HV, and the residual austenite 400-600 HV. 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.

Laser hardening was performed on a steel sample with dimensions of 40×60×11 mm, with a carbon content of 0.45% [3]. The treatment was performed at the radiation power of a diode laser of 720 W, the beam diameter of 4.5 mm, and the speed of its movement of 5-10 mm/s. The parameters of the hardened zones were used for calculating the temperature distribution in the ANSYS software package using the finite element method. The deviation of the calculated values of the depth of the quenching zones does not exceed 7% compared to the experimental values. The calculated width of the quenching zone is greater by 0.5 mm than the width obtained in the experiment at a processing speed of 10 mm/s, and less by 0.8 mm at a speed of 5 mm/s. The error in calculating the width of the quenching zone was 12-20% compared to the experiment. When processing with a round laser spot with a Gaussian energy distribution, the cross section of the quenching zone has the shape of a segment or well. To equalize the depth of the hardening zones and the time of exposure to the laser
beam, a pass-through optical module was developed, which allowed converting a round beam into a 5×1.5 mm laser spot with increased radiation intensity at the edges. Quenching zones with a width of 4.1 mm and an almost uniform depth of 0.36 mm were obtained at a radiation power of 480 W and a travel speed of 5 mm/s.

Laser hardening of samples with a diode laser from Rofin-Sinar, Germany was performed on samples of AISI 1045 sheet steel with dimensions of 40×60×5 mm with a carbon content of 0.42-0.50% [4]. The initial hardness of this steel was 165-255 HV. The treatment was performed at a radiation power of 470, 650 and 760 W and a beam travel speed of 5-25 mm/s. The beam was focused into a spot with a size of 3.8×1.7 mm on the surface of the sample. The temperature of the laser beam heating zone was determined using the finite element method using the ANSYS software. The depth of the quenching zone on the samples was 0.3-0.5 mm, and the width of the zone was 2.3-3.0 mm. The hardness of the samples was largely determined by the processing speed. Its maximum value is obtained when the beam travel speed is 10 mm/s 600 HV, and the minimum value is 400 HV at 25 mm/s.

For laser quenching and conventional heat treatment, 1538mv steel with a diameter of 66 mm and a thickness of 5 mm with an initial hardness of 23.31 ± 1.75 HRC was used. Laser heat treatment was performed using continuous radiation of a 10 kW diode laser with a spot diameter of 3.5 mm. The depth of the quenching zone was 760 microns. The hardness of the samples after furnace quenching and tempering was 52.7 ± 1 HRC, and the hardness of the laser-hardened layer was 51.5 ± 2.5 HRC. Wear tests were carried out according to the disk-ball scheme without lubricant in accordance with the US standard ASTM G99 using a CSM tribometer, S/N 18-259. Test results showed that laser treatment reduces the average coefficient of friction by 25% and the wear rate by 60% compared to conventional quenching.

The experimental study was performed on AISI 4340 steel with sample sizes of 60×6×5 mm with an initial hardness of 25-30 HRC [6]. For laser hardening, we used a solid-state laser with a radiation power of 3000 W, a six-axis robot "Fanuc M-710IC", an ILVDC scanner mounted on a laser head to perform various beam paths: linear, sinusoidal, triangular and circular. The focal spot diameter was 0.52 mm. Based on preliminary experiments, the quenching modes were selected: the radiation power of 500-800 W, and the speed of beam movement of 20 - 40 mm/s. The depth and width of the hardening zones of AISI 4340 steel were determined, which were 392-1011 microns and 778-2578 microns, respectively. The hardness for a linear beam path is 56-60 HRC, and for other beam paths it is 50-58 HRC. It is found that the sinusoidal trajectory of the beam gives the maximum width with an acceptable depth and a uniform distribution of hardness, while the linear trajectory gives the maximum depth with an insignificant width. The circular path of the beam represents a relatively good compromise between the hardened depth and width, but with an uneven distribution of the hardness and depth of the hardening zones.

The purpose of this work is to determine the mutual influence of the fiber laser beam defocusing, processing modes on the depth and width of the laser hardening zones, on the parameters of the hardened zones under high-frequency transverse vibrations of the beam.

2. Materials and methods
Laser hardening of 40Cr steel samples with dimensions of 12×20×70 mm was performed using a laser complex based on a fiber laser LS10, equipped with an optical head FLWD50L fixed on the movable flange of the robot arm KR120HA. The diameter of the transport fiber is 200 microns, the focus of the collimating lens is 160 mm, and the focusing lens is 500 mm. The processing was performed at a laser power of 4000 and 5000 W, a beam movement speed of 40 and 50 mm/s, and a beam defocusing within 25 – 200 mm. Metallographic studies were performed using a PMT-3 microhardomer with a load of 0.98 N, a digital microscope AM413ML, metallographic microscope Altami MET 1C.

At the end of the experiments, the slots were made according to the standard method and three-fold measurements of the depth and width of the hardened zones were made. The effect of processing modes on the parameters of hardened tracks was determined using the method of full factor experiment (FFE). The radiation power P, W, processing speed V, mm/s, and beam defocus Z, mm
were selected as experimental factors. To construct mathematical models, the depth \( H \) and width \( B \) of the laser quenching zones were considered as the system responses. As an additional discrete factor, we considered scanning, transverse vibrations of the beam with a fixed frequency \( f = 200 \text{ Hz} \). All possible interactions of factors were determined in the calculation. Since PFE 23 was performed, the number of experiments was 8 for each series.

The regression equation has the form [7]:

\[
y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{1,2} x_1 x_2 + b_{1,3} x_1 x_3 + b_{2,3} x_2 x_3 + b_{1,2,3} x_1 x_2 x_3
\]

(1)

where:

\( y \) – system response;

\( x \) - encoded variables

\( b \) – coefficients of the regression equation.

Table 1 shows the levels of experiment factors.

| Factor \( x_i \) | Upper level factor \( x_i^U \) | Lower level factor \( x_i^L \) | Centre plan \( x_i^0 \) | Range of variation \( \Delta_i \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( P \) (W)     | 5000            | 4000            | 4500            | 500             |
| \( V \) (mm/s)  | 50              | 40              | 45              | 4               |
| \( Z \) (mm)    | 100             | 50              | 75              | 25              |

3. Research results and discussion

The results of metallographic tests of hardened zones in the first series of experiments, plots of depth and width of the zones of hardening from the changes in the distance from the focal plane \( Z \) when running laser energy of 100 j/mm² Figure 1 (a, b) and 2. The depth and width of the zones of hardening varies almost linearly in the range of 50-100 mm, and therefore this plot can be described by regression equations of the first order.

Figure 1. Dependence of the depth of the quenching zone on the distance to the focal plane:

- a-unfocused beam: 1-\( P = 4000 \) W, \( V = 40 \) mm/s; 2-\( P = 5000 \) W, \( V = 50 \) mm/s;
- b-oscillating beam: 1-\( P = 4000 \) W, \( V = 40 \) mm/s; 2-\( P = 5000 \) W, \( V = 50 \) mm/s
Figure 2. Dependence of the depth of the quenching zone on the 
distance to the focal plane:
a-unfocused beam: 1- P = 4000 W, V = 40 mm/s; 2- P = 5000 W, V = 50 
mm/s;
b-oscillating beam: 1- P = 4000 W, V = 40 mm/s; 2- P = 5000 W, V = 50 
mm/s

The depth of the quenching zone defocused beam in physical variables:

\[
H = 1.00225 + 0.06375 \left( \frac{P-4500}{500} \right) - 0.0795 \left( \frac{V_{i}-45}{5} \right) - 0.02225 \left( \frac{Z_{i}-75}{25} \right) + 0.035 \left( \frac{P-4500}{500} \right) \left( \frac{V_{i}-45}{5} \right) - \\
0.00475 \left( \frac{P-4500}{500} \right) \left( \frac{Z_{i}-75}{25} \right) - 0.0105 \left( \frac{V_{i}-45}{5} \right) \left( \frac{Z_{i}-75}{25} \right)
\]  

(2)

where

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

Depth of the quenching zone with transverse beam fluctuations in natural variables:

\[
H = 0.626875 + 0.059625 \left( \frac{P-4500}{500} \right) - 0.070625 \left( \frac{V_{i}-45}{5} \right) + 0.036375 \left( \frac{Z_{i}-75}{25} \right) \\
- 0.010875 \left( \frac{P-4500}{500} \right) \left( \frac{V_{i}-45}{5} \right) - 0.015 \left( \frac{V_{i}-45}{5} \right) \left( \frac{Z_{i}-75}{25} \right) \\
- 0.010875 \left( \frac{P-4500}{500} \right) \left( \frac{V_{i}-45}{5} \right) \left( \frac{Z_{i}-75}{25} \right)
\]

(3)

Width of the defocused beam quenching zone in natural variables:

\[
B = 4.515625 + 0.370875 \left( \frac{W_{i}-4500}{500} \right) - 0.398875 \left( \frac{V_{i}-45}{5} \right) - 1.479625 \left( \frac{Z_{i}-75}{25} \right) - 0.309875 \left( \frac{W_{i}-4500}{500} \right) \left( \frac{Z_{i}-75}{25} \right) + \\
0.303375 \left( \frac{V_{i}-45}{5} \right) \left( \frac{Z_{i}-75}{25} \right) + 0.061125 \left( \frac{W_{i}-4500}{500} \right) \left( \frac{V_{i}-45}{5} \right) \left( \frac{Z_{i}-75}{25} \right)
\]

(4)

The width of the quenching zone with transverse fluctuations of the beam in natural variables:

\[
B = 6.845625 + 0.361125 \left( \frac{W_{i}-4500}{500} \right) - 0.348625 \left( \frac{V_{i}-45}{5} \right) - 0.748875 \left( \frac{Z_{i}-75}{25} \right) - 0.188625 \left( \frac{V_{i}-45}{5} \right) - \\
0.206875 \left( \frac{W_{i}-4500}{500} \right) \left( \frac{Z_{i}-75}{25} \right) + 0.178875 \left( \frac{V_{i}-45}{5} \right) \left( \frac{Z_{i}-75}{25} \right)
\]

(5)

Calculations were made using regression equations and compared with the results of the 
experiment. The calculated values differ from the actual values of the depth and width of 
the quenching zones by no more than 3.8%. Regression models of dependencies of type H (P, V), B (P, V) 
are entered in the MsExcel table editor and comparative surfaces for these functions are constructed.
(Fig. 3 and 4), obtained at distances from the focal plane of 50 and 100 mm.

The prevailing influence on the geometric parameters of the quenching zones is the radiation power (Fig. 3a and b). 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 at Z=50 and 100 mm (Fig. 3 and 4). With increasing defocus (diameter) of the beam, the depth of the quenching zones decreases, and the width increases. The use of transverse beam vibrations leads to a slight decrease in the depth of the hardened layer by 30-35% (Fig. 3 b and d) and to an increase in the width of the quenching zones by 2 times (Fig. 4, b) when defocusing Z=50 mm. When defocusing the beam, up to 100 mm, the width of the zone with transverse fluctuations of the beam is higher by 20-30% than when strengthening with a defocused beam. However, in some cases this can be decisive factor for the application of quenching with the scanning of the beam. This applies to technologies for hardening the working surfaces of gear and spline gears, when their width does not exceed 6 mm and can be quenched in one pass. The microhardness of the quenching zones with the unfocused and scanning beam was 6480-7860 MPa and 7190-8360 MPa, respectively.

Figure 3. Depth of the quenching zones depending on the processing power and speed:
- a-unfocused beam, Z = 50 mm; b-oscillating beam, Z= 50 mm;
- c-unfocused beam, Z = 100 mm; d-oscillating beam, Z = 100 mm
Figure 4. Width of the quenching zones depending on the processing power and speed:

a - unfocused beam, Z = 50 mm; b - oscillating beam, Z = 50 mm;
c - unfocused beam, Z = 100 mm; d - oscillating beam, Z = 100 mm.

Processing performance when scanning the beam increases by 1.3-2 times depending on the location of the focal plane, compared to quenching with a defocused beam under the same quenching modes.

4. Summary

Linear regression equations are obtained for 50-100 mm beam defocusing, which allow calculating the depth and width of the quenching zones with an error of no more than 3.8%.

Surfaces showing the regularity of changes in the parameters of hardened zones from processing modes are constructed. The performance of laser quenching with transverse beam vibrations is 1.3-2 times higher than when quenching with a defocused beam at Z=50-100 mm.

References

[1] Moradi M 2020 How the laser beam energy distribution effect on laser surface transformation hardening process; Diode and Nd:YAG lasers Optik - International Journal for Light and Electron Optics vol 204
[2] Adel K M 2014 Enhancement of Dry Sliding Wear Characteristics of CK45 Steel Alloy by Laser Surface Hardening Procedia Materials Science vol 6 p 1639 – 1643
[3] Hagino H 2010 Design of a computer-generated hologram for obtaining a uniform hardened profile by laser transformation hardening with a high-power diode laser Precision Engineering vol 34 p 446–452.

[4] Lusquinos F 2007 Theoretical and experimental analysis of high power diode laser (HPDL) hardening of AISI 1045 steel Applied Surface Science vol 254 p 948–954

[5] Carrera-Espinoza R 2020 Surface Laser Quenching as an Alternative Method for Conventional Quenching and Tempering Treatment of 1538MV Steel Advances in Materials Science and Engineering vol 2020

[6] Tarchoun B 2020 Experimental Investigation of Laser Surface Hardening of AISI 4340 Steel Using Different Laser Scanning Patterns Journal of Minerals and Materials Characterization and Engineering vol 8 p 9-26

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