Experimental and computational determination of hardened zones during laser hardening of steels

A P Savin¹, V P Biryukov, D V Panov² A N Prince³ V N Petrovsky² and D V Ushakov²

¹Mechanical Engineering Research Institute named by A.A. Blagonravov, Russian Academy of Sciences
4 Maly Kharitonovsky Pereulok, Moscow, 101000, Russia
² National Research Nuclear University MEPhI,
31, Kashirskoye highway, Moscow, 115409, Russia
³ Russian University of transport RUT (MIIT)
9, Obraztsova, Moscow, 127994, Russia

Laser-52@yandex.ru

Abstract. Experiments in defocus of beam rectangular-shaped fiber laser in the range of 30-65 mm. using a full factorial experiment, we constructed the surface to depth and width of the zone of hardening through varying the speed of the beam in the range of 15-20 m/s, power 3-4 kW. Comparative wear tests have shown that laser hardening with a rectangular spot reduces the number of tempering zones and increases the wear resistance of 40Cr steel by 25-35% compared to hardening with a round spot.

1. Introduction
Laser heat treatment of the surface of ck45 steel creates a microstructure with 91.7% needle martensite and 8.3% residual austenite [1]. At the same time, the hardness of martensite reaches up to 8600 MPa, and residual austenite 4100-5900 MPa. Wear tests were performed according to the disk – finger scheme at a load of 30N and a travel speed of 7, 9.9 and 14.9 mm / s. the hardness of the disk was 3870 MPa. The duration of each test was 10 minutes. The wear resistance of laser hardened samples is twice as high as the original steel.

Experiments on laser quenching were carried out using a fiber laser YLR-5000-S with a radiation power of up to 5000 W, with a transport fiber in the optical head of 200 microns and a focus of a collimating lens of 150 mm [2]. The samples were hardened at a radiation power of 1895 W, beam defocusing of 80 mm at a power density of 12865 W / cm². The beam velocity was 8 mm / s. Steel samples with different carbon content, % from 0.21 (AISI 4820) to 0.96 (AISI 5210) were Studied.

According to the results of metallographic studies, it was found that the microhardness of the samples corresponded to the carbon content and amounted to 5070 and 8140 MPa, respectively.

Laser hardening of carbon steel AISI 4130 was carried out using a high-power diode laser using a calculation methodology based on the response surface [3]. As input technological parameters, the scanning speed of the surface 4-7 mm/s, laser power 1200-1600 W and the position of the focal plane relative to the sample surface or defocusing 0-20 mm were considered. The size of the laser spot in the focal plane was 1.5 × 8 mm. When optimizing the laser hardening of AISI 4130 steel, it was found that...
the scanning speed \( V = 4.5 \text{ mm/s} \), the laser power \( P = 1500 \text{ W} \), the focal plane position \( F = 62 \text{ mm} \), with these parameters, the power density is \( 83 \text{ W/mm}^2 \). Under optimal treatment modes, the hardness increases to 7970 MPa, and is 3 times higher than the hardness of the base metal 2660 MPa at a depth of 1.3 mm and a width of 9.9 mm of the hardened zone. It was found that laser hardening with 50% track overlap has a more uniform hardness of the sample surface than with 30% track overlap. Laser hardening of the surface of carbon steel AISI 4130 leads to a change in the initial phases of the base metal to the martensitic phase. It was found that a lower percentage of ferrite in the phases of the microstructure increases the hardness. Changing the position of the head from the focal plane within 20 mm leads to a change in the average microhardness in the range from 7000 to 3000 MPa, which will adversely affect the processing of shaped surfaces with a significant deviation from the horizontal plane.

2. Materials and equipment
Laser hardening of 40Cr steel samples with dimensions of 15×20×70 mm using a laser complex based on fiber laser LS10, with a diameter of transport fiber 200 microns, equipped with an optical shaper, to obtain a laser spot in the focal plane of 10.8×1.2 mm. The Treatment was performed at a laser radiation power of 3000 and 4000 W, beam travel speed of 15 and 20 mm/s, beam defocusing within 30 – 65 mm. Metallographic studies were carried out using a microhardness measurements on PMT-3M at a load of 0.98 N, a digital microscope AM413ML, metallographic microscope Altami MET 1C. Wear tests were carried out on the friction machine MTU-01 according to the scheme plane (40Cr steel with laser hardening) - ring (40x steel, HRC47-53). TP 22C oil was used as a lubricant. The Specific pressure was 2 MPa, the sliding speed was 1.58 m/s.

The influence of treatment modes on the parameters of hardened tracks was determined using the full factor experiment (FFE) method [4]. The radiation power \( P, \text{ W} \) were chosen as the experimental factors, processing speed \( V, \text{ mm/s} \), and beam defocusing \( Z, \text{ mm} \) to construct mathematical models, the depth \( H \) and width \( B \) of laser quenching zones were considered as system responses. Table 1 shows the levels of experimental factors.

![Table 1. Levels of experiment factors](image)

| Factor | Upper level of factor | Lower level of factor | Center of the plan | Variation Interval | Dependence of the encoded variable on the natural |
|--------|-----------------------|-----------------------|--------------------|-------------------|-------------------------------------------------|
| \( z_i \) | \( z^+_i \) | \( z^-_i \) | \( z^0_i \) | \( \lambda_i \) | \( x_i = \frac{P_i - 3500}{500} \) |
| \( P (\text{W}) \) | 4000 | 3000 | 3500 | 500 | 2 |
| \( V (\text{mm/s}) \) | 20 | 15 | 17,5 | 2,5 | 2 |
| \( Z (\text{mm}) \) | 65 | 50 | 57,5 | 7,5 | 2 |

At the end of the experiments, the plates were made according to the standard method and three-fold measurements of the depth and width of the hardened zones were made. 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 [4]:

\[
y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{13} x_1 x_3 + b_{12} x_1 x_2 + b_{23} x_2 x_3 + b_{123} x_1 x_2 x_3 \quad (1)
\]

where:
\( y \) - system response;
\( x_i \) - levels of factors;
\( b \) - coefficients of the regression equation.
3. Results of experiments and calculations

Laser surfacing of samples was performed with a defocused beam and transverse oscillations of the beam normal to the laser processing velocity vector. For figure 1 (a and b) are micro-plates of deposited tracks with dimensions of 0.75×2.1 mm, hardness (181-208HV), and 0.68×3.38 mm-(204-224HV), obtained by a defocused beam and a scanning beam with a frequency of 217 Hz, respectively. The penetration zone of the substrate during processing with a defocused beam and a scanning beam was 380 and 150 microns, respectively. The cross-sectional area of a single deposited layer is 1.5 times larger when scanning the beam than when surfacing with a defocused beam.

![Figure 1](image1)

Figure 1. The dependence of the depth (a) and width (b) of the laser hardening zone of 40x steel on the beam defocus: 1-V = 15 m/s, P = 3000 W; 2 - V = 20 m/s, P = 4000 W

According to the results of metallography in the second series of experiments, regression equations for beam defocusing of 50 – 65 mm were obtained. The depth of the hardening zone:

\[
H = 0.901125 + 0.134625x_1 - 0.084875x_2 - 0.048125x_3 - 0.064625x_1x_2 - 0.064625x_1x_3 + 0.028375x_2x_3 - 0.028125x_1x_2x_3
\]

(2)

The width of the hardening zone:

\[
B = 12.06425 + 0.43x_1 - 0.31125x_2 - 0.3095x_3 - 0.087x_1x_2 - 0.10875x_1x_3 + 0.0885x_2x_3 + 0.13375x_1x_2x_3
\]

(3)

The regression equations (2) and (3) are used for calculations, which are compared with the results of the experiment. The calculated values differ from the actual values of the depth and width of the hardening zones by no more than 4.2%.

The obtained 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) when defocusing the laser spot of rectangular shape 50 and 65 mm.
Figure 2. Dependence of depth \((a, b)\) and width \((b,d)\) of laser hardening zones on beam defocusing, speed and processing power: \(a\) and \(b\) - \(Z = 50 \text{ mm}\), \(b\) and \(d\) - \(Z = 65 \text{ mm}\)

The predominant influence on the geometric parameters of the quenching zones is the radiation power (Figure 2). With increasing power, the width and depth of the hardening zone grow. As the travel speed increases, the depth and width of the hardened zones decreases. With increasing defocusing of laser radiation, the depth and width of the hardened zones increases.

For Figure 3 the microstructures of laser hardening zones of steel 40Cr obtained under different treatment modes are presented: \(a\) - \(P = 3000 \text{ W}, \ V = 15 \text{ mm/c}, \ Z = 65 \text{ mm}\), \(b\) - \(P = 4000 \text{ W}, \ V = 20 \text{ mm/s}, \ Z = 50 \text{ mm}\), \(c\) - \(P = 4000 \text{ W}, \ V = 15 \text{ mm/s}, \ Z = 50 \text{ mm}\).

The microhardness of the hardened zones varied within 6780-8560 MPa depending on the treatment modes. Comparative tests on the wear resistance of the samples showed that the samples hardened with a rectangular spot have one tempering zone on friction surfaces, at the same time hardened by a defocused beam two tempering zones and their wear resistance is higher by 25-35% depending on the treatment modes.

The developed laser hardening technology with a layer depth of up to 1.2 mm and a width of 12 - 13.5 mm can be used in the processing of a number of parts in one pass. These include gears with a module of 3 - 5 mm, splined and keyed connections, the dimensions of the friction surfaces of which do not exceed 12 mm. In addition, this technology allows to process the working surfaces of bodies, shafts, axles, flat and shaped surfaces with greater productivity compared to laser hardening with a round defocused beam in the same modes.
Figure 3. The micro-sections of the zones of hardening of steel 40Cr: a - P = 3000W, V = 15mm/c, Z = 65mm, b - P = 4000W, V = 20mm / s, Z = 50mm, c - P = 4000W, V = 15mm/s, Z = 50 mm

4. Conclusion

Linear regression equations for defocusing the beam of 50-65 mm are obtained, which allow to calculate the depth and width of the hardening zones with an error of not more than 4.2%.

The response surfaces of the system showing the regularity of changes in the parameters of the hardened zones from the treatment modes are constructed.

The wear resistance of samples hardened with rectangular laser spot is 25-35% higher than the wear resistance of samples hardened with circular defocused beam depending on the treatment modes.

References

[1] Adel K M 2014 Enhancement of Dry Sliding Wear Characteristics of CK45 Steel Alloy by Laser Surface Hardening Processing Procedia Materials Science (vol 6) pp 1639 – 1643 doi: 10.1016/j.mspro.2014.07.148

[2] Qiu F, Uusitalo J and Kujanpa V 2013 Laser transformation hardening of carbon steel: microhardness analysis on microstructural phases Surface Engineering (vol 29 issue 1) pp 34-40 doi 10.1179/1743294412Y.0000000049
[3] Moradi M and Karami Moghadam M 2019 High power diode laser surface hardening of AISI 4130; statistical modelling and optimization *Optics and Laser Technology* (vol 111) pp 554–570 doi: 10.1016/j.optlastec.2018.10.043

[4] Evdokimov Yu A, Kolesnikov V I and Teterin P I 1980 *Planning and analysis of experiments in solving problems of friction and wear* (Moscow: Nauka) in Russian