Effect of laser hardening modes on the hardening zone geometric parameters and tribological properties of 40Cr steel

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Abstract. In the work experiments on the beam of a multichannel CO₂-laser (ALTCU-3) with a unique layout within 25-130 mm using a full factorial experiment, we constructed the surface to depth and width of the zones of hardening through varying the speed of the beam in the range of 10-20 mm/s, a power of 1-2 kW and a beam diameter of 4-14 mm. Comparative wear tests showed that with the increase in the hardening area to 50% of the surface friction, the wear resistance increases by 3.2 times in comparison with the normalized steel 40Cr. It is shown that the value of the average microhardness decreases with increasing power and reducing the processing speed by 300 MPa, and the depth of the quenching zone increases up to 2.5 times.

1. Introduction
The reliability parameters of the system general depend on the reliability of its individual elements. According to preliminary studies, it was found that the quality of the surface layer in the friction pairs of hydraulic units affects the duration and intensity of their running-in process. One of the formation directions of the surface layer during the finishing treatment is laser heat treatment, which allows the hardened surface layer with certain properties [1]. In this case, laser treatment is usually not subjected to the entire surface of friction, and its individual sections. The result is a surface of consistently alternating “soft” (the original structure of cast iron) and solid areas of the laser impact zone. It has been experimentally established [1] that laser treatment not only increases the wear resistance of piston rings (PR) by 1.5-2.4 times, but also reduces the wear of serial cylinder sleeves. The alternation of wear-resistant laser tracks having a structure of high hardness bleached cast iron of, and cast iron areas of with graphite inclusions on the PR working has a positive effect on the performance of the friction pair. Based on field tests [2] in marine conditions of diesel engines 6 CRN 36/45 found that the laser-treated PRs with an operating time of 7.5 thousand are highly completive with a chrome piston rings (“RUMO”) JSC in respect to wear-resistance and as compared to “surface analysis” (Zavod Nizhegorodskii Teplokhoz) exceeds 1.8-2.2 times.

However, the main problem of laser processing industrial application is the need to obtain the dependence of the hardened layer parameters on the processing modes for a particular type of laser. So in [3], for experimental studies, structural steels 65Mn, 30CrNiSiA, 45 were chosen. Processing was carried out on a specialized laser technological complex ALTCU-5 on the basis of a multichannel
CO₂-laser with a unique arrangement of tubes. Mode selection was carried out on the variation in optimal treatment intervals: power 1000 – 4600 W, the moving speed of the laser beam 10 to 30 mm. However, the presented results of hardening are given in tabular form are particular, and do not show the General dependence of the laser hardening zone parameters necessary as a tool for determining the laser processing modes for real production.

Effects of laser treatment with diode laser on the material structure with the conclusion of the necessary dependencies of the quenching zone parameters on the processing modes [4]. The results are obtained by processing a rectangular unfocused laser beam and by defocusing the beam by 25 mm. The hardness of the hardened layer is reduced by half, and can, not be applied to the surface of the dies of bending dies, threads and other complex shape parts.

For 40CrNi2MnA steel, the technology of laser hardening by fiber laser using IPG 2D scanners has been developed, which allows hardening zones with a width of 15-50 mm and a depth of 0.2-2.5 mm per one robot am pass at transverse vibrations up to 100 Hz [5].

A special place in the laser thermal hardening is the processing of multi-channel CO₂-laser, which has its own characteristics. At the same time, its operation involves a number of difficulties associated with the uniformity question of the rays, focusing and their arrangement. At the same time, for the industrial use of laser thermal hardening technology is relevant research on materials that have found wider application in engineering, including in hydraulics, in particular steel 40Cr. The sizes of the laser quenching zones are obtained by regression equations depending on the processing modes for the CO₂-laser and the parameters of the material surface layer for the "Kometa-M" installation [6]. However, as noted above, such studies need to be carried out for each specific type of equipment.

The purpose of this work is to establish the influence of laser processing modes of multi-channel CO₂-laser with a unique layout on the changes in the depth and width of the quenching zones and the quenching area influence on the wear resistance of hardened samples and subsequent performance for steel 40Cr.

2. Materials and equipment

Laser hardening was performed on an automated laser technological complex [7-9], on samples of steel grade 40Cr with dimensions 10×20×80 mm. To increase the surface absorption capacity before laser treatment, the samples were phosphating. Metallographic studies were carried out using a digital microscope AM413ML and metallographic microscope Altami MET 1C, microhardness measurements on PMT-3M at a load of 0.98 N.

In the first series of experiments investigated the power density effect of laser radiation on the depth H, width B, and the microhardness HV of the hardened tracks with a radiation power of P 1000 W and 2000 W and the beam speed V 10 mm·s⁻¹ and 20 mm·s⁻¹ for the defocusing of the laser beam Z is from 25 mm to 130 mm. the Diagram of the multichannel laser treatment CO₂ - laser is presented in figure 1.

In the second series of experiments, the influence of processing modes on the parameters of hardened tracks was determined using the full factorial experiment (FFE) method [10]. Radiation power P (1000 -2000 W), processing speed V (10-20 mm·s⁻¹), and laser beam diameter d (4-6 mm) were chosen as experimental factors. The depth H and width B of the laser quenching zones were considered as the system responses for the construction of mathematical models. The sections were made according to the standard procedure and the depth and width of the hardened zones were measured three times. The calculation determined all possible interactions of factors. Since FFE 2³ was performed, the number of experiments was 8.
In the third series of experiments, the samples were strengthened with a different step of laying tracks to obtain a quenching area S 25, 50, 75, 100% and with overlapping tracks 10-30%, figure 2. Tests on wear resistance and scoring resistance was carried out on the machine friction MTU-01 according to the diagram plane (sample-ring, counter-sample, 40Cr steel, HRC 48-52) at a load of 2 MPa. As a lubricant used transmission oil Tszp-8.

3. Results of experiments and calculations

According to the measurements results of the hardened zones parameters 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 or the radiation power density are shown in Figure 3. The left and right part of the graph in Figure 1a can be represented as linear dependencies with a limit of their definition. For example, for the left part of the graph of the limit values of the laser spot diameters on the surface of part 4 to 6 mm, and for the right – 10-12 mm. Then the solution of the linear regression equations will have adequate values.
As a result of the regression analysis, a system of regression equations for the geometric parameters of the hardened zones, depending on the processing modes in physical quantities, is obtained to determine the width of the quenching zone in (1) and to determine the depth of the quenching zone in (2).

\[
H = 0.95 + 0.179 \cdot \left(\frac{P-1500}{500}\right) - 0.174 \cdot \left(\frac{V-15}{5}\right) + 0.035 \cdot (d - 5) - 0.019 \cdot \left(\frac{P-1500}{500}\right) \cdot \left(\frac{V-15}{5}\right) + 0.01 \cdot \left(\frac{P-1500}{500}\right) \cdot (d - 5) + 0.015 \cdot \left(\frac{V-15}{5}\right) \cdot (d - 5)
\]  

\[
B = 4.682 + 0.361 \cdot \left(\frac{P-1500}{500}\right) - 0.341 \cdot \left(\frac{V-15}{5}\right) + 0.445 \cdot (d - 5) + 0.0173 \cdot \left(\frac{P-1500}{500}\right) \cdot \left(\frac{V-15}{5}\right)(d - 5)
\]  

The obtained regression equations (1) and (2) were used for calculations and compared with the experimental results. 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) were introduced into the table editor of MS Excel and comparative surfaces for these functions were constructed, figure 4.

Based on the graphs (figure 4), the influence on the geometric parameters of the quenching zones has the power, speed and beam diameter. With increasing power, all other things being equal, the depth parameter of the quenching zone changes to a greater extent, as well as with a change in the processing speed. As the beam diameter increases, so does the depth and width of the quenching zones.
Figure 4. Graphs of the depth (a, b) and width (c, d) of the laser quenching zone depending on \( P \) and \( V \) processing at \( d = 4 \) and \( 6 \) mm, respectively.

The microhardness of the hardened zones varied 6180–7160 MPa depending on the processing modes. The regression analysis is conducted out and the equations system of average microhardness regression of the hardened zones depending on the processing modes in natural quantities is obtained (3).

\[
HV(P, V, d) = -0.2208 \cdot P + 12.9219 \cdot V + 0.1237 \cdot d + 6262.0182
\] (3)

Comparative surfaces of this function were constructed using the regression model of type \( HV \) (\( P, V \)) (figure 5). Based on the graphs, the value of the average microhardness decreases with increasing power and reducing the processing speed by 300 MPa, which occurs due to the increase in the depth of the quenching zone up to 2.5 times.

Figure 5. Graphs of the average microhardness \( HV \) zone of laser hardening depending on \( P \) and \( V \) processing at \( d = 4 \) mm (a) and \( d = 6 \) mm (b).

At the same time, the study revealed the optimal radiation parameters (\( P = 2 \) kW, \( V = 20 \) mm\( \cdot \)s\(^{-1} \), \( d = 10 \) mm) at which the values of width \( B = 7.12 \) mm, depth \( H = 0.81 \) mm, and the average microhardness 6700 MPa.

The maximum wear resistance is obtained at 100% of the laser quenching area (see figure 6). It exceeds the wear resistance of the sample base material by 3.5 times. However, for parts operating under sliding friction conditions with a load not exceeding 3 MPa and under satisfactory lubrication conditions, it is advisable to use a technology with laser hardening of 50-60% of the friction surface. In this case, the wear resistance is increased by 3.2 times compared to the non-hardened sample, and the cost of laser treatment is two times lower.

From the presented research results it follows that the smallest losses of laser radiation energy are
achieved when the beam is defocused up to 60 mm. Further increase in the beam diameter leads to a significant loss of energy along the hardening path edges sometimes more than 50%, but in some cases this is permissible when hardening without melting, for example, when processing the surface of the punches.

![Figure 6](image_url)

**Figure 6.** Wear intensity diagram depending on the area of the hardened surface

4. Conclusion

The dependences of the depth and width of the hardened zones on the beam defocus of 25-130 mm for the speed and power of the laser beam of 10-20 mm·s⁻¹ and 1000-2000 W, respectively, are obtained. With the help of regression analysis, the surfaces demonstrating the dependence of the hardening zones parameters on the power and velocity of the laser beam are constructed. Wear resistance of samples at 50% of the hardened layer area is 3.2 times higher than the base material, normalized steel 40Cr.

References

[1] Kazakov S S and Goyim V V 2015 *Journal Karelian scientific* 11 120-3
[2] Kazakov S S and Matveev Y I 2011 *Bulletin of NGIEI* 2 55-60
[3] Arakelyan S M, Estonin G A, Skryabin I O, Abrahan S I and Novikov O A 2016 *Journal Modern high technologies* 5 9-13
[4] Moradi M and Karami Moghadam M 2019 *Journal Optics and Laser Technology* 111 554-70
[5] Biryukov V P, Fishkov A A, Tatarkin D Yu and Hreptovich E. V. 2017 *Journal Photonics* 3 28-34
[6] Biryukov V P 2017 *Journal Photonics* 2 22-32
[7] Yegorov A P, Gavrilova V S and Voronov S A 2015 *Eighth all-Russian conf. of young scientists and specialists "Future of machine-building in Russia"*: collection of reports of the Russian machine-builders Moscow MGUTU N E Bauman pp 449-51
[8] Klevetov V D, Starostin D A and Egorov A P 2018 *Technology. Security. Management: materials of VIII all-Russian scientific and technical conference* FGBOU VO "KGTU named after V A Degtyarev" (Kovrov, Russia) pp 21-30
[9] Yugov V I 2012 *Journal Photonics* 4 12-20
[10] 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