Influence of laser quenching modes on tribological characteristics of 40Cr steel

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Abstract. This paper presents the results of metallographic and tribological studies of 40Cr steel samples after laser quenching with a rectangular beam. Using a full factorial experiment (FFE), the regularities of changes in the geometric parameters of the laser thermal hardening zones from the processing modes are obtained. It is shown that the jamming load is 1.5-2.1 times higher, and the coefficient of friction is 2-4 times lower than that of normalized 40Cr steel.

1. Introduction

The application of laser hardening technologies in modern mechanical engineering is an urgent task. Laser hardening of 50-70% of the friction surface area can increase the durability of friction units in power and transport engineering by 2-3 times. Samples of steel containing 1.0% carbon and 1.5% chromium with a size of 11×24×100 mm were used for laser hardening with a Laserline diode laser, a rectangular spot with a size of 3×8 mm, at a radiation power of 2000 W, and a beam travel speed of 20 mm·s⁻¹ [1]. The first batch of samples was processed by laser radiation, without preliminary heat treatment (WHT). The second batch was heated to 1000 °C and released at 650 °C (HTQ). The third batch was quenched at a temperature of 500 °C and released at a temperature of 170 °C (QHT). The fourth batch was quenched twice at 850 °C and released at 170 °C (DQHT). The depth of the laser-hardened layer of WHT, HTQ, QHT, and DQHT samples was 462.8 microns, 480.9 microns, 669.5 microns, and 663.2 microns, respectively. The depth of the laser quenching zone of HTQ and QHT samples with preheating up to 160 °C was 578.5 microns and 764.5 microns, respectively. The depth of the laser quenching zone of HTQ and QHT samples with preheating up to 160 °C was 578.5 microns and 764.5 microns, respectively. The maximum hardness of the hardened layer 1000 HV was at a depth of 0.5 mm. For WHT and DQHT samples, the maximum hardness within the hardened layer was about 900 HV, at a depth of about 0.3 mm.

In order to investigate the impact of the surface geometries on the characteristics of the heat-affected and hardened zones, laser hardening experiments were conducted at steel 38MnVS6 in the present work using a beam an IPG fiber laser with a power of 2 kW and a beam diameter of 9 mm and speed 10 mm·s⁻¹ [2]. For comparison, two types of samples are made flat, and with a groove 6.9 mm wide with a radius of 4 mm and a depth of 2 mm. The depth of the laser hardening zones is determined from optical micrographs and hardness measurements. It was 890 ± 6.5 microns and 897 ± 0.5 microns for the flat sample, and 719 ± 75 microns and 706 ± 17 microns for the shaped sample, respectively. The maximum measured hardness values were 942 HV₀.05 (flat surface) and 943 HV₀.05 (curved...
Samples of 44MnSiVS6 steel in the form of disks with a thickness of 10 mm and a diameter of 110 mm with a surface roughness Ra 0.5-1 microns were strengthened using a fiber laser system from IPG Photonics [3]. The maximum laser power was 3000 W, and the beam travel speed was 100 mm·s⁻¹. The treatment was performed with three types of laser spot. Round shape with a diameter of 4 mm, with a Gaussian distribution of radiation energy. A 4×4 mm rectangular spot with uniform energy distribution and a 4×4 mm rectangular spot with 16 radiation points, with a total power loss of 37.9% of the round spot. The depth, width, and microhardness of the steel hardening zones were 0.4×1.6 mm, 5800-8000 MPa, 0.3×1.4 mm, 4200-7300 MPa, 0.2×1.1 mm, and 3800-7200 MPa for round, rectangular, and spot spots, respectively. Treatment with a round laser beam resulted in residual compression stresses of up to 506 MPa in the quenching zone to a depth of 400 microns.

Laser surface treatment was carried out on samples of powdered carbon steel containing 1% carbon PA - FeGr with a porosity of 4%, 8% and 10%, as well as for comparison of U10 steel [4]. Powder steel samples were obtained by powder metallurgy from iron powder and colloidal graphite. The powders were mixed in a mixer with an offset axis of rotation, pressed in a mold at a pressure of 400 MPa, then annealed in a vacuum furnace at a temperature of 900°C, re-compact in a mold at a pressure of 500 or 550 MPa, and finally sintered in a vacuum at a temperature of 1150°C. Laser surface treatment was performed on samples in the form of parallelepipeds 25×25×200 mm in size using an industrial additive machine Optomec LENS 850-R with a 1 kW fiber laser in argon. The diameter of the spot of the laser beam during laser processing was assumed to be 1.5, 2, 2.5 and 4 mm. The laser radiation power was 251-502 W, and the beam travel speed was 8-12 mm·s⁻¹. In contrast to U10 steel, microstructure analysis in powder steels allowed us to divide the hardening region into 4 zones: I - melting with reduced porosity, II - melting with initial porosity, III-solidification, and IV-base. Structure in zones I and II, martensitic microhardness is high, up to 1000 HV₀.05. Porosity does not affect the microhardness of the surface layer, but it affects the depth of hardening, which is greater with a lower porosity, and for a sample of U10 steel, the depth of hardening corresponds to the depth of the heat-affected zone.

The purpose of this work is to determine the effect of laser treatment modes with a rectangular spot on changes in the jamming load from the sliding speed, friction coefficient, and wear intensity of 40Cr steel.
Using mathematical planning of the experiment, the equations [5] are obtained.

Depth of the quenching zone:

\[
H = 1.17725 + 0.01625 \left( \frac{P_i - 3320}{120} \right) - 0.24675 \left( \frac{V_i - 8.75}{1.25} \right),
\]

(1)

Width of the quenching zone:

\[
B = 19.521 + 0.9885 \left( \frac{P_i - 3320}{120} \right) - 0.518 \left( \frac{V_i - 8.75}{1.25} \right)
\]

(2)

For figure 2 shows the dependences of the depth (H) and width (B) of the laser-hardened layers on the processing modes.

![Figure 1. The micro-sections of the zones of hardening of steel 40Cr.](image)

![Figure 2. Dependence of the depth (a) and width (b) of the laser hardening zones of 40Cr steel.](image)

As the beam power increases and the processing speed decreases, the depth and width of the quenching zones increases. The regression equations were used for calculations 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 3.56%.

Figure 3 shows graphs of the dependence of the jamming load on the sliding speed. Laser hardening increases the jamming load in comparison with the initial samples at a sliding speed of 1 m·s⁻¹ by 1.6 – 2.1 times, depending on the microhardness of the quenching zones. At a pressure of 1.1 MPa, laser-hardened surfaces are susceptible to jamming at speeds of 2.6 – 3.1 m·s⁻¹, while untreated samples are inoperable at speeds of 1.45 m·s⁻¹.
Figure 3. Dependence of the jamming load on the sliding speed:
1-normalized steel, 1800-2040 MPa, 2- 5780-6740 MPa, 3- 6230-7130 MPa, 4- 6350-7210 MPa, 5- 6640-7840 MPa.

One of the most important characteristics of a friction pair is the coefficient of friction. Figure 4 shows the regularity of changes in the coefficients of friction from pressure. As the microhardness of the laser-hardened layer increases and the pressure increases, the coefficient of friction decreases. At a pressure of 3 MPa, the coefficient of friction is 3 to 4 times lower for hardened samples compared to the original steel. With a further increase in pressure to 5 MPa, the value of the coefficient of friction remains 2-3 times less than in normalized steel.

An equally important characteristic of the friction pair is the wear rate. Table 1 shows the results of tests for the wear rate of samples. As the microhardness of the samples increases, the wear rate decreases. Wear resistance, the reverse value of the wear intensity increases 2-2.6 times compared to the base material.

4. Discussion
The results obtained clearly show the possibility of increasing the wear resistance and friction surfaces of machine parts and aggregates during laser quenching. In our country, the most developed technologies are strengthening pulsed solid-state, gas, and fiber laser installations. The creation of a laser complex with a powerful 6 kW diode laser will expand the range of hardened parts.

One of the unsolved problems is laser hardening of gears with a module of 6-10 mm with a depth of the hardened layer of 1.2-1.45 mm in one pass. Laser hardening of the tooth surface with the imposition of tracks can lead to jamming of the engagement. This is due to the fact that when applying laser tracks, tempering zones with a width of 0.5 – 1.7 mm appear, which are the centers of setting of friction pairs, even at small specific loads. The hardening width of 15-21 mm is sufficient to increase the wear resistance by 3-5.5 times of tillage tools, cultivator paws, disc harrows and others.

The introduction of a new laser hardening technology will increase the durability of parts in the energy, aerospace and transport engineering industries.

The paper presents a narrow range of processing power and speed. Further research is needed to expand the processing modes and range of steel grades. Tribological tests will reveal the possibilities of new laser strengthening technologies.
Figure 4. Dependence of the coefficient of friction on pressure: 1-normalized steel 1800-2040 MPa, 2-5780-6740 MPa, 3-6230-7130 MPa, 4-6350-7210 MPa, 5-6640-7840 MPa.

Table 1. The wear rate of the samples.

| No. sample | Microhardness, MPa | Intensity wear | $I_1\cdot 10^{-9}$ | $I_{1m}\cdot 10^{-9}$ |
|------------|--------------------|----------------|---------------------|---------------------|
| 1.1        | 1820-1970          |                | 0.983               |                     |
| 1.2        | 1800-2020          |                | 0.969               | 1.024               |
| 1.3        | 1860-1990          |                | 1.120               |                     |
| 2.1        | 5780-6650          |                | 0.536               |                     |
| 2.2        | 5820-6710          |                | 0.525               | 0.519               |
| 2.3        | 5690-6740          |                | 0.496               |                     |
| 3.1        | 6320-7020          |                | 0.523               |                     |
| 3.2        | 6440-7067          |                | 0.489               | 0.496               |
| 3.3        | 6350-7130          |                | 0.478               |                     |
| 4.1        | 6350-7120          |                | 0.460               |                     |
| 4.2        | 6430-7090          |                | 0.475               | 0.459               |
| 4.3        | 6390-7210          |                | 0.443               |                     |
| 5.1        | 6640-7380          |                | 0.410               |                     |
| 5.2        | 6720-7690          |                | 0.397               | 0.394               |
| 5.3        | 6680-7840          |                | 0.376               |                     |

5. Conclusion
The technology of laser hardening of 40Cr steel with a layer depth of 0.9 – 1.4 mm and a quenching zone width of 18 – 20 mm with a rectangular beam has been developed. The scuff resistance of laser hardening zones is 1.5-2 times higher, and the coefficient of friction is 2-4 times lower compared to normalized 40Cr steel.

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