Influence of laser steel quenching on the service life of friction units

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Abstract. This paper presents the results of metallographic and tribological studies of 65Mn steel samples with laser and bulk quenching. A full factorial experiment was performed that allowed calculating the depth and width of the quenching zones with an error of no more than 3.28%. It is shown that laser hardening reduces the friction coefficients by 2-3 times and increases the jamming load compared to bulk steel quenching.

1. Introduction
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 - 1µm were strengthened using a fiber laser system from IPG Photonics [1]. 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 circular laser beam resulted in residual compression stresses of up to -506 MPa in the quenching zone to a depth of 400 µm.

Laser surface treatment was carried out on samples of powdered carbon steel containing 1% carbon PA - ZhGr with a porosity of 4%, 8% and 10%, as well as for comparison of U10 steel [2]. 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-compacted 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 lower porosity, and for a sample of U10 steel, the depth of hardening corresponds to the depth of the thermal impact zone.
For laser hardening, samples of AISI 1538MV steel with a diameter of 66 mm and a thickness of 5 mm with a hardness of 23.31 ± 1.75 HRC were used [3]. Laser heat treatment was performed on a Laserline LDF 10.00-100 diode laser with a maximum radiation power of 10 kW, with a three-coordinate and angular beam control system with a diameter of 3.5 mm, with a linear speed of 168 mm·s⁻¹. The surface hardness of the samples was 51.5 ± 2.5 and 52.7 ± 1 HRC, respectively, after laser and bulk quenching. The depth of the laser hardening zone was 760 µm. Friction and wear tests were performed in accordance with ASTM G99 on a CSM tribometer, S/N 18-259 according to the disk-ball scheme (WC 5mm, 1500 HV). The following test parameters were used: load 5 N, sliding speed 0.10 m·s⁻¹, friction path 100, 200, 300 and 500 m, track radii 4, 6, 8 and 10 mm. The sample of the original steel showed a constant average sliding friction coefficient of 0.37 at a distance of 200 m, and then this value increased significantly to 0.45 at a friction path of 500 m. The laser-quenched sample showed the lowest coefficient of friction of 0.295 for sliding distances of 100 and 200 m, and then the coefficient of friction increased to 0.361 for a friction path of 300 and 500 m. The depth of the wear hole was 540, 430, and 385 µm for the initial, volume-hardened, and laser-hardened steel, respectively.

2. Materials and equipment
Laser processing of 65Mn steel samples with dimensions of 12×20×70 mm was performed at the technological complex of the IMASH RAN collective center. The radiation power $P = 700-1000$ W, the processing speed $V = 7-10$ mm·s⁻¹, and the beam diameter $d = 3.6-5.0$ mm were selected as variable parameters. As an additional factor, we considered beam scanning with a fixed frequency $f = 226$ Hz. A resonant type device with an elastic element on which a mirror is fixed was used. Metallographic studies of deposited coatings were performed on a PMT-3 microhardness meter at a load of 0.98 N, a metallographic microscope, and an AM425 digital microscope.

Tribological tests were carried out according to the scheme plane (heat – strengthened laser beam sample) - sleeve, steel 40Kh (49-52 HRC). The sliding speed and pressure on the sample varied discretely in the range of 0.5–3.5 m·s⁻¹ and 1-5 MPa, respectively. TP22C oil was used as a lubricant.

The influence of processing modes on the parameters of hardened tracks was determined using the full factor experiment (FFE) method. To construct mathematical models, the depth $H$ and width $B$ of the laser hardening zones were considered as the system responses. Table 1 shows the levels of experimental factors.

| Factor  | Upper level of factor | Lower level of factor | Center of the plan | Variation Interval | Dependence of the encoded variable on the natural |
|---------|------------------------|-----------------------|--------------------|-------------------|-----------------------------------------------|
| $P$ (W) | 1000                   | 700                   | 850                | 150               | $x_1 = \frac{P_i - 850}{150}$                  |
| $V$ (mm s⁻¹) | 10                   | 7                    | 8.5               | 1.5               | $x_i = \frac{V_i - 8.5}{1.5}$                |
| $d$ (mm) | 5.0                   | 3.6                   | 4.3               | 0.7               | $x_i = \frac{d_i - 4.3}{0.7}$                |

Since FFE $2^3$ was performed, the number of experiments was 8 for each series.

The regression equation has the form:

$$y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{13} x_1 x_3 + b_{12} x_1 x_2 + b_{23} x_2 x_3 + b_{123} x_1 x_2 x_3$$  \hspace{1cm} (1)

Where, $y$ – system response; $x_i$ – is the levels of factors; $b$ – coefficients of the regression equation.
3. Results of experiments and calculations

Figure 1 shows the micro-sections of the laser thermal hardening zones of 65Mn steel obtained at the radiation power \( P = 1000 \) W, the beam travel speed \( V = 10 \) mm\( \cdot \)s\(^{-1} \), and the beam diameter \( d = 5.0 \) mm. With transverse beam vibrations with a frequency of 226 Hz and the same processing modes, the area of the quenching zone increases by 1.56 times (figure 1 (b)). Based on the results of metallography of all samples, regression equations for determining the parameters of laser hardening zones are obtained.

\[
H = 0.917 + 0.08775x_1 - 0.0445x_2 + 0.09375x_3 - 0.02175x_1x_2 + 0.0325x_1x_3 - 0.02025x_2x_3
\]  
(2)

Depth of hardening with transverse oscillations of the beam, \( H_s \):

\[
H_s = 0.866125 + 0.090875x_1 - 0.032125x_2 + 0.097875x_3 - 0.026875x_1x_2 + 0.027625x_1x_3 - 0.031375x_2x_3
\]  
(3)

Width of laser thermal hardening zones without scanning the beam, \( B \):

\[
B = 3.512625 + 0.122875x_1 - 0.088375x_2 + 0.330125x_3 - 0.041125x_1x_2 + 0.079375x_1x_3 - 0.022875x_2x_3
\]  
(4)

Width of quenching zones with transverse vibrations of the beam, \( B_s \):

\[
B_s = 5.97875 + 0.3265x_1 - 0.204x_2 + 0.23125x_3 - 0.02325x_1x_2 + 0.163x_1x_3 + 0.066x_2x_3
\]  
(5)

The equation for determining the depth of quenching without scanning, \( H \) has the form:

The obtained regression models of \( H (P,V) \) and \( B (P,V) \) dependences are entered into the MsExcel table editor and comparative surfaces for these functions are constructed (figure 2) for defocusing a 5.0 mm laser spot. The radiation power has a predominant influence on the geometric parameters of the quenching zones. With increasing power, the width and depth of the quenching zone increase. As the speed of movement increases, the depth and width of the hardened zones decreases. As the laser defocusing increases, the depth and width of the hardened zones increases.

![Figure 1. Micro-Sections of laser thermal hardening zones of steel 65Mn: \( P = 1000 \) W, \( V = 10 \) mm\( \cdot \)s\(^{-1} \), \( d = 5.0 \) mm: a – defocused beam, b – scanning with a frequency of 226 Hz.](image-url)
Figure 2. Dependence of the depth (a, b) and width (c, d) of the laser quenching zones of 65Mn steel on the processing speed and power at a beam diameter of 5.0 mm: (a, c) – with a defocused beam, (b, d) with a scanning beam.

The microhardness of the hardened zones varied in the range of 7780 – 9760 MPa depending on the treatment modes. With laser thermal hardening at high power and low beam speed, the microhardness of the quenching zone is reduced by 450-760 MPa. However, it significantly exceeds the microhardness of volume-hardened steel 65Mn by 1600-2800 MPa.

One of the most important characteristics of friction units is the low coefficient of friction, which affects the performance of fuel and lubricants in the operation of transport equipment. As a rule, the friction pair with a low coefficient of friction have a high load binding. The advantage of laser thermal hardening technologies in comparison with bulk quenching is shown in the absence or minimal residual deformations of parts after quenching. For example, when volumetric hardening of long parts, overhead sliding guides, residual deformations reach 3.5 mm per 1 m length. For further mechanical processing, straightening of the workpieces is required. The allowance for grinding such straightened workpieces is 0.7 - 0.8 mm per side. With laser thermal hardening, you can reduce the allowances to 0.1 mm per side and increase the productivity of subsequent machining.

Figure 3 shows the dependence of the friction coefficients on the pressure and sliding speed in the friction pair.
Curves 1 and 2 are obtained by friction of laser-quenched samples with transverse beam vibrations in steps of 5 and 4 mm, respectively. Reducing the step of superposition of laser thermal hardening zones (LHT) led to an increase in the area of the tempering zones between the tracks and, as a result, to an increase in the coefficient of friction. The value of the coefficient of friction of volume-hardened (VHT) samples was affected by the hardness, the higher it is, the lower the coefficient of friction. Regardless of the type of hardening with increasing pressure, the friction coefficients decreased in the studied load range. An increase in the sliding speed from the samples to 1.3 m·s\(^{-1}\) led to a sharp increase in the coefficient of friction. Samples with laser hardening had low friction coefficients of 0.02-0.03 and at a speed of 1.6 m·s\(^{-1}\).

Figure 4 shows the patterns of changes in the jamming load as a function of the sample sliding speed. The increase in sliding speed leads to a decrease in load binding for all types of hardening. Samples with laser thermal hardening withstood a load of 4.7 MPa before jamming at a sliding speed of 1.7 m·s\(^{-1}\), which is almost 2 times higher than volume-hardened samples. For parts operating under high contact pressures, the jamming load is an important criterion for their durability. No less important criterion is the wear rate of friction pairs, which determines the service life of components and mechanisms of machines and aggregates. The amount of wear intensity is affected by the mechanical properties of the friction surfaces, operating loads, sliding or rolling speeds, operating conditions and lubrication of mechanisms. Traditional technologies for hardening parts are energy-intensive and do not always meet the requirements of environmental cleanliness of the process. Modern laser systems are equipped with robotic systems or multi-coordinate systems with numerical control (CNC). Technological processes for laser modification of friction surfaces are environmentally friendly. In laser thermal hardening with a round spot, the time of beam exposure in the center of the spot is determined by the ratio of the beam diameter to the speed of its movement \(d/V\), and at the edges of the spot tends to zero. In addition, the radiation power is distributed unevenly across the spot. There are one or more radiation maxima. To equalize the exposure time and power density across the spot, a cross-beam scan is applied, in which the area of the laser-hardened layer increases by 1.6-2.1 times, which means the process productivity. When quenching with a round beam, tempering zones with a width of 0.5-1.8 mm are formed along the edges of a single track. Oscillating beam hardening reduces these zones to a width of 0.1-0.18 mm. Therefore, the paper shows the effect of the quenching track step on the friction coefficients and the wear rate of samples. In table 2 shows experimental data on the wear rate of heat-strengthened laser beam samples with different steps and volume quenching of steel 65Mn to a hardness of 52-57HRC.
Figure 4. Dependence of the jamming load on the sliding speed: 1 - VHT, 48-51 HRC, 2 – VHT, 52-57 HRC, 3 – LHT step of tracks 4 mm, 4 – LHT step of tracks 5 mm.

Table 2. Wear rate of steel 65Mn.

| Type processing of steel 65Mn | Wear rate sample, $I_1$ and counter-sample, $I_2$ | Wear rate sample $I_{m1}$ and counter-sample $I_{m2}$ |
|-------------------------------|-----------------------------------------------|-----------------------------------------------|
| LHT, step - 4 mm              | $I_1 \times 10^{-9}$ | $I_2 \times 10^{-9}$ | $I_{m1} \times 10^{-9}$ | $I_{m2} \times 10^{-9}$ |
|                               | 0.328                          | 0.881                          | 0.346                          | 0.885                          |
|                               | 0.361                          | 0.862                          | 0.349                          | 0.914                          |
|                               | 0.349                          | 0.914                          | 0.293                          | 0.856                          |
| LHT, step - 5 mm              | 0.269                          | 0.925                          | 0.296                          | 0.892                          |
|                               | 0.327                          | 0.897                          | 0.412                          | 0.897                          |
| VHT 52-57 HRC                | 0.424                          | 0.832                          | 0.425                          | 0.861                          |
|                               | 0.441                          | 0.894                          |                                |                                |

The wear rate of samples with laser hardening in steps of 4 and 5 mm is 22 and 43% lower than that of samples with bulk hardening. It should be noted that the wear rate of 40Kh hardened steel counter-tiles increases up to 3.6% in the friction pair with laser-hardened samples in 5 mm increments.

4. Conclusions

The technology of laser thermal strengthening of 65Mn steel with transverse beam vibrations has been developed, which allows to increase the productivity of the process by 1.6-2.1 times, depending on the laser processing modes. The friction coefficients of samples with laser quenching are 2-3 times lower, and the jamming load at a sliding speed of 1.7 m·s$^{-1}$ is 2 times higher compared to bulk quenching. The wear rate of laser-quenched samples with different track spacing decreased by 22 and 43% compared to samples after bulk quenching.

References

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