Effect of laser surface modification on the hardness and wear resistance of structural bearing steel for roller screw mechanism

A.V. Zhdanov, I.V. Belyaev, V.V. Morozov
Vladimir State University, 87 Gorky str., Vladimir, 600000, Russia
zhdanov@vlsu.ru

Abstract. The article is devoted to the analysis of the effect of laser surface modification on the hardness and wear resistance of steel SHX15SG used in the manufacture of roller screw mechanisms. Experiments on laser surface modification were performed on the Russian domestic SVAROG-1-5DR laser system to get the maximum hardness value. When laser processing without melting the surface of steel SHX15SG, the laser radiation power should be in the region of 5 kW, which corresponds to the maximum power for the installation used. The speed of movement of the laser beam relative to the treated surface should be equal to 25 mm/s, and the focal length should be at least 60 mm. In the case of laser treatment with surface reflow, higher hardness values are obtained at a power of 2 kW. Increasing the power of laser radiation to 5 kW leads to a decrease in hardness. In this case, the speed value should be equal to 25 mm/s, and the focal length should be close to 85 mm. When the focal length is reduced to 60 mm, laser treatment no longer causes melting of the surface of the material under study.

1. Introduction
Structural bearing steel is intended for the manufacture of bearing elements, as well as critical roller screw mechanisms and roller gears [1-5]. The chemical composition of steel is regulated by state standard №801-78, according to which the content of the main elements in steel should be as follows (in % by weight): C = 0.95-1.05; Si = 0.40-0.65; Mn = 0.90-1.20; Cr = 1.3-1.65; Fe-base. Permissible limits of impurity content (in % by weight): S ≤ 0.02; P ≤ 0.027; N ≤ 0.3; Cu ≤ 0.25; Ni+Cu ≤ 0.5; O ≤ 0.0015; Ti ≤ 0.01. Steel is delivered to the consumer after heat treatment, including quenching from 850-860 °C in oil. In addition, steel is released at 150-160°C for 1 hour. The microstructure of steel in the delivery state is uniformly distributed fine-grained perlite [6-10].

The working conditions of steel products place high demands on their hardness and wear resistance. Therefore, any ways to increase the hardness and wear resistance of these products are relevant. One of the most promising modern ways to increase the hardness and wear resistance of products made of various materials (metals, steels and alloys) is laser modification of the surface of these products. This method is implemented using various laser systems that differ in the set and level of technical characteristics [11-12]. Processing of each specific material on any of these installations requires finding optimal modes that allow you to get the maximum (or set) values of hardness and wear resistance. It is also necessary to determine the reasons for changing these characteristics for the material being processed. Currently, there is no reliable information about the modes of laser surface treatment of steel products that allow you to adjust the hardness and wear resistance indicators in order to obtain their
optimal ratios using the Russian SVAROG-1-5DR laser system. There is also no information about changes in the microstructure of the surface layers of steel corresponding to the maximum values of hardness and wear resistance after laser treatment.

2. Materials and methods
The material for the study was bearing steel SHX15SG (the analog is 100Cr6 steel in the EU and Cr2 steel in China) according to state standard №801-78 in the form of a bar with a diameter of 50 mm. Rings 8 mm thick were cut from this bar on an electric erosion machine (figure 1). The surfaces of these rings were subjected to laser treatment at various values of the laser radiation power (W), the speed of movement of the laser beam relative to the treated surface (V), and the distance from the laser radiation source to the treated surface (focal length, F). There were different modes of laser processing without surface reflow (without SR) and with surface reflow (with SR). The results of measuring the hardness and wear resistance of the test samples before and after laser treatment are shown in table 1 (a-b).

| Sample name | Modes of l/t | Vickers hardness, HV10, N/mm² | Rockwell hardness, HRC | Hardness HB kgs/mm² |
|-------------|--------------|-------------------------------|------------------------|---------------------|
| 3.1 l/t-SR  | 1            | 636                           | 56,1                   | 580                 |
| 3.2 l/t-WSR | 2            | 281                           | 38,5                   | 357                 |
| 3.3 l/t-SR  | 3            | 718                           | 31,2                   | 295                 |
| 3.6 l/t-WSR | 4            | 324                           | 33,1                   | 320                 |
| 3.5 l/t-WSR | 5            | 607                           | 55,9                   | 576                 |
| 3.7 l/t-SR  | 6            | 441                           | 46,2                   | 311                 |
| 3.9 l/t-SR  | 7            | 478                           | 46,1                   | 434                 |
| Test        | Without l/t  | 260                           | 33,5                   | 329                 |

Table 1. Results of measuring the hardness and wear resistance of the surface layers of steel SHX15SG before and after treatment in various modes (when designating samples, the following abbreviations were used: l/t-laser treatment; WSR - without reflow of the treated surface; SR — with reflow of the treated surface).

| The limit of tensile strength, MPa | Yield strength, MPa | Elastic modulus, Eav | Coefficient of friction, μ | The wear of the counterbody, mkm |
|-----------------------------------|---------------------|----------------------|--------------------------|--------------------------------|
| 1334                              | 1254                | 179                  | 0,14                     | 10                             |
| 821                               | 772                 | 171                  | 0,83                     | 82                             |
| 679                               | 638                 | 182                  | 0,7                      | 56                             |
| 736                               | 692                 | 182                  | 0,64                     | 50                             |
| 1325                              | 1245                | 184                  | 0,7                      | 67                             |
| 715                               | 672                 | 190                  | 0,52                     | 35                             |
| 998                               | 938                 | 200                  | 0,8                      | 60                             |
| 757                               | 711                 | 200                  | 0,6                      | 55                             |
3. Results

From table 1 it can be seen that the laser treatment modes used for steel samples SHX15SG in some cases were not accompanied by melting of the treated surface (samples 3.2, 3.4, 3.5 and 3.6), and in other cases caused melting of the treated surface (samples 3.1, 3.3, 3.7, 3.9.).

When laser processing without surface reflow, the maximum hardness value (HV10=607 N/mm² and 55.9 HRC) was obtained on sample 3.5 after processing in mode 5 (W = 5 kW, V = 25 mm/s, F = 60 mm), and the minimum (HV10 = 281 N/mm² and 38.5 HRC) — on sample 3.2 processed in mode 2 (W = 2 kW, V = 10 mm/s, F = 60 mm). The highest value of the coefficient of friction (0.83) and wear of the counterbody (82 mm) was obtained on sample 3.2, i.e. where the HV10 hardness was minimal. The lowest values of the coefficient of friction (0.64) and wear of the counterbody (44 m) were obtained on sample 3.6 (mode 4). The elastic modulus values of all measured samples correlate with the Vickers hardness values.

After laser treatment with surface reflow, the maximum value of Vickers hardness (HV10 = 718 N/mm²) had a sample 3.3 treated according to mode 3 (W = 2 kW, V = 25 mm/s, F = 85 mm), and the minimum (HV10 = 441 N/mm²) — a sample 3.7 treated according to mode 6 ((W = 5 kW, V = 10 mm/s, F = 85 mm). Maximum Rockwell hardness (HR C 56,1) had a 3.1 sample treated with regime 1 ((W = 2 kW, V = 10 mm/s, F = 85 mm) and the minimum (31,2 HRC) — sample 3.3-processed mode 3 (W = 2 kW, V = 25 mm/s, F = 85 mm), where the maximum Vickers hardness value. The lowest value of the coefficient of friction (m = 0.14) and the lowest wear of the counterbody (10 microns) had sample 3.1, which has the maximum Rockwell hardness. The highest value of the coefficient of friction (m = 0.8) and the highest value of wear of the counterbody (60 microns) had sample 3.9, processed according to mode 7 (W = 5 kW, V = 10 mm/s, F = 85 mm).

From the above, it follows that in order to obtain the maximum value of Vickers hardness during laser processing without melting the surface of steel SHX15SG, the laser radiation power (W) must be in the region of 5 kW (the maximum for the installation used). The speed of movement of the laser beam relative to the surface to be treated (V) should be equal to 25 mm / s, and the focal length (F) should be 60 mm.

In the case of laser treatment with surface reflow, higher values of Vickers hardness are obtained at W = 2 kW. Increasing the power of laser radiation to 5 kW leads to a decrease in hardness. The V value should be 25 mm/s and the F value should be 85 mm. When F is reduced to 60 mm, laser treatment no longer causes melting of the surface of steel 100Cr6.

Comparing the data in table 1 it should be noted that the best combination of high hardness and low coefficient of friction, which ensures minimal wear of the contacting mating surfaces, provides the mode 1 – W = 2 kW, V = 10 mm / s, F = 85 mm (sample 3.1) with surface reflow.

All other laser treatment modes, including those without melting the treated surface, are much less preferable because they lead to a significant increase in the coefficient of friction, and, consequently, to an increase in wear of the contacting surfaces. Figure 2 shows diffractionograms of surface layers of
samples made of steel SHX15SG after processing in modes 1-7. A diffractogram of the surface of a control sample made of the same steel that was not subjected to laser treatment is also shown here.

Figure 2 shows that the diffraction profile of a control sample not exposed to laser treatment, different from the profile of diffraction patterns of the samples subjected to laser treatment. The laser treatment is also changing the profile of diffraction patterns. This indicates a change in the phase composition of the alloy due to laser treatment. Decoding of diffractograms revealed the presence of residual austenite and complex oxides in the composition of the surface layers of steel in addition to the main phase components, the amount of which varied depending on the laser treatment mode.

4. Discussion
The microstructure of the surface layer of the sample 3.5 (mode 5) after laser treatment without melting the surface, on which the maximum value of Vickers hardness is obtained, is martensite with a significant amount of residual austenite with the release of carbides of the type (Cr, Fe, Si) C. In addition, iron oxides, as well as chromium, silicon, and manganese oxides are present in the near-surface zone of the sample. The total amount of oxides is approximately 9% by weight. The thickness of the surface layer with a modified microstructure compared to the control sample is 1.5-1.8 mm, so the Rockwell hardness measurement data correlate with the Vickers data and also show a high (maximum for this type of processing) hardness (55.9 HRC). The presence of residual austenite and oxides in the microstructure of the surface layer leads to an increase in the coefficient of friction. The wear of the counter-body also increases in comparison with the control sample. The latter indicates, on the one hand, an increase in the wear resistance of this surface layer compared to the control sample, on the other hand, that when working in contact with a mated surface made of the same steel, this mated surface will be subjected to increased wear.

The surface layer of sample 3.2 (mode 2), which has a minimum Vickers hardness, contains perlite in the microstructure and a small amount of residual austenite (approximately 3.3% by weight). In addition, iron, chromium, silicon and manganese oxides are present in the microstructure in an amount of up to 16% by weight. The thickness of the layer with the modified microstructure reached 1.5 mm. In this regard, the average Rockwell surface layer hardness (38.5) correlates with the Vickers hardness value (281 N/mm2). The maximum values of the coefficient of friction and wear of the counterbody of the sample 3.2 are associated with the presence of coarse plate carbides and complex oxides in the microstructure of the surface layer. The microstructure of the near-surface layer of the sample 3.2. is shown in Figure 3a.
Sample 3.6 (mode 4) after laser treatment has an intermediate Vickers hardness value (324 N/mm²). The microstructure of the surface layer contains sorbitol-like perlite and approximately 7.6% by weight of residual austenite. In this regard, the value of the coefficient of friction is close to the control sample, and the wear of the counterbody is even lower than that of the control sample. The thickness of the surface layer with a modified microstructure compared to the control sample is significantly thinner than that of samples 3.5 (mode 5) and 3.2 (mode 2) due to the high speed of the laser beam relative to the treated surface (V) and is approximately 0.5 mm. As a result, when measuring the Rockwell hardness, this layer was pushed through by an indenter and the hardness readings corresponded to the values characteristic of the control (not laser-treated) sample.

The microstructure of the surface layer of sample 3.3 (mode 3) after laser treatment with melting of the surface, which has the highest value of Vickers hardness (718 N/mm²), is a mixture of troostite with martensite and with the release of carbides along the grain boundaries. As a result, the coefficient of friction and wear of the counterbody of the surface layer slightly increase in comparison with the control sample. The average thickness of the surface layer with a modified microstructure is approximately 0.5 mm. In this regard, due to the penetration of this thin layer, the Rockwell hardness values approximately corresponded to the hardness of the control sample (33.1 HRC). The microstructure of the near-surface layer of the sample 3.3 is shown in figure 3b.

Fig. 3. Microstructure of the surface layer of steel SHX15SG after laser treatment according to mode 2.

The microstructure of sample 3.7 (mode 6), with the lowest Vickers hardness value for samples with surface melting, is a fine sorbitol, similar in appearance to troostite, as well as iron, chromium, silicon, and manganese oxides. The coefficient of friction (0.52) and wear of the counterbody (35 mm) with this microstructure is less than that of the control sample (0.6 and 55 mm, respectively). At the same time, the latter does not indicate a decrease in the wear resistance of steel, but rather more favorable working conditions of the mated rubbing surfaces due to a decrease in the coefficient of friction. The thickness of the surface layer with the microstructure changed after laser treatment is more than 1.5 mm, so when measuring the Rockwell hardness, this surface layer is not pushed through and the hardness value is 46.2 HRC.

The microstructure of sample 3.1 (mode 1), which has the lowest values of the coefficient of friction (0.14) and wear of the counterbody (10 mm), as well as a very high hardness for both Vickers (636 N/mm²) and Rockwell (56.1 HRC), is a mixture of martensite and troostite with a small amount of residual austenite (2.85% by weight). The microstructure also contains a significant amount of iron, manganese, silicon and chromium oxides. Such a low coefficient of friction and wear of the counterbody
are explained by the very good sanding of the structural components of the surface layer of steel SHX15SG after this type of laser treatment. The thickness of the surface layer with the modified microstructure in this sample is 1.5-1.8 mm. The microstructure of the surface layer of the sample 3.1. is shown in Figure 4.

![Microstructure of the surface layer of SHX15SG steel after laser treatment according to mode 1.](image)

**Fig. 4.** Microstructure of the surface layer of SHX15SG steel after laser treatment according to mode 1.

5. **Conclusion**

Thus, laser treatment with reflow of the surface of products made of steel SHX15SG allows you to achieve higher values of hardness and lower values of the coefficient of friction than laser treatment without reflow of the surface. This makes it more wear-resistant when working in conditions of rubbing mating surfaces. Mode 5 (sample 3.5) provides the highest hardness of the surface layer during laser processing without melting the surface, and mode 2 (sample 3.2) provides the lowest hardness. Mode 4 (sample 3.6) provides the most favorable values of counterbody wear (wear resistance), and mode 2 (sample 3.2) provides the least favorable values. The highest hardness of the surface layer during laser treatment with surface reflow is provided by mode 3 (sample 3.3), the lowest — by mode 6 (sample 3.7). Mode 1 (sample 3.1) provides the most favorable combination of friction coefficient, wear resistance (counterbody wear) and hardness.

The main reason for the change in the hardness, coefficient of friction and wear of the counterbody (wear resistance) of SHX15SG steel after laser treatment is the change in the phase composition of the surface layers of this steel during laser treatment. The higher the speed of the laser beam relative to the treated surface (V), the smaller the thickness of the surface layer with the modified microstructure.

A simultaneous increase in W, V, and F will lead to a particularly strong and difficult-to-predict change in the microstructure of the surface layer of the processed alloy, as well as a strong decrease in the thickness of this surface layer with the modified microstructure. The results obtained can be used to solve the mathematical problem of optimizing the modes of laser treatment of the surface of steel SHX15SG in order to obtain the maximum values of hardness and wear resistance.

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**References**
[1] State standard №801-78. Ball-bearing steel. Technical conditions. - M.: publishing house of standards, 2004.
[2] Metallography of iron. Volume 1. "Fundamentals of metallography" (with Atlas of micrographs) / Translated from English. Edited by Akad. F. N. Tavadze. - M.: metallurgy, 1972, 240s.

[3] M. E. Bernstein. Metal science and heat treatment of steel. - M.: metallurgy, 1991. - 472s.

[4] V.V. Morozov, A.B. Kosterin, A.V. Zhdanov Efficiency of Roller–Screw Mechanisms // Russian Engineering Research V.38, Issue 4, 1 April 2018, 263-267 pp.

[5] V.V. Morozov, A.V. Zhdanov A New Aspects of the Planetary Roller-screw Mechanism Classification [Text]/ International conference on automation, mechanical and electrical engineering (AMEE 2015) JUL 26-27, 2015 Phuket, THAILAND, pp: 875-881, Destech Publicat Inc, ISBN: 978-1-60595-237-6.

[6] Zhukov I. O., Ivanchenko A. B., Zhdanov A. V. 2014 Singularities of 3D modelling of Roller Screw Mechanisms (Scientific and Technical Bulletin of the Volga Region №4) pp 100-103.

[7] Morozov V. V. 2005 RSM: Kinematic characteristics, monograph (Vladimir, Vladimir State University) 78 p.

[8] Morozov, V. V, Zhdanov A. V. 2015 RSM: Reliability and durability (Moscow, monograph) 152 p.

[9] Kononov D. M, Zhdanov A. V, Korolev A. N. 2011 Study of the properties of nanostructured PVD coatings based on carbon (Modern problems of science and education №6) p 130.

[10] Bukarev I. M., Zhdanov A. V. 2011 Experimental researches of the physicomechanical properties of multilayer nanostructured coatings (Kazan, Scientific and Technical Bulletin of the Volga Region №6) p 116-119.

[11] N. A. Smirnova, A. I. Misyurov. Features of structure formation during laser processing. / Bulletin of Bauman Moscow state technical University, series "mechanical engineering", 2012, pp. 115-129.

[12] O. N. Voitovich, I. O. Sokolov. Investigation of the influence of laser heat treatment parameters on the properties of hardened surface layers. / Bulletin of the Belarusian-Russian University, 2013, no. 2 (39), p. 6.