Influence of laser treatment mode on the friction coefficient and wear of bearing steel

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Abstract. The article considers the influence of input factors of the laser processing: the radiation power, the longitudinal feed of the laser beam and the distance from the protective glass of the focusing head to the workpiece on the friction coefficient and absolute wear of steel SHH15SG. The greatest influence on the output parameters (friction coefficient and absolute wear) has the power of laser radiation, as it increases, the wear of the surface layer decreases. The obtained multi-factor models and graphical interpretation of the experiment results allow us to assign a laser treatment mode that provides the demanded wear of the treated surface layer of bearing steel. The developed method of assigning the laser processing mode reduces the auxiliary time of the technological operation and eliminates the need for additional experiments in production conditions. The results of the research are useful for manufacturing enterprises that implement laser processing processes, as well as for design organizations that develop modern laser equipment.

1. Introduction

The working surface layer of machine parts has high performance properties provided that the required geometric and physical and mechanical quality indicators are formed during processing, the main ones being dimensional accuracy, roughness, hardness, and wear resistance [1-6]. To ensure these quality indicators, finishing hardening technological operations are used, among which laser processing takes a worthy place. Currently, laser processing is used not only in the aviation [7], but also in the automotive industry [8] and medicine. To date, the mechanisms of phenomena accompanying laser processing processes, the influence of modes on the microstructure, microhardness and wear resistance, as well as other indicators of the physical and mechanical state of the hardened surface layer have been studied. One-factor models have been developed that allow controlling laser processing processes [1-3, 9-18]. But one-factor models are characterized by serious disadvantages: the significant labor intensity of experiments, the inability to use them to solve multi-criteria and multi-factor problems typical of the vast majority of industries, and etc. [19].

Friction and wear of details during the operation of machines plays a crucial role in ensuring the required operational reliability of machines, so when creating modern technical and technological systems, it is necessary to have reliable data on these important characteristics for various materials. Very important are multi-factor experimental models of the friction coefficient and wear resistance of bearing steels, which establish the relationship of the elements of the laser treatment mode with the
specified parameters. Until now, the development of multi-factor models for laser processing of materials has not been given due attention.

The aim of the research is to develop multi-factor experimental models of the friction coefficient, absolute wear of bearing steel and method for assigning laser treatment modes that provide the demanded values of parameters. Multi-factor models are relevant for manufacturing enterprises that implement laser processing and design organizations that develop technological laser equipment.

2. Materials and methods

Bearing steel SHH15SG, widely used in mechanical engineering, was chosen as the processed material. The plan of a multi-factor experiment N=2^3=8 was implemented, and independent factors of laser treatment were selected for the entry of the technological system: radiation power $W$, longitudinal feed $Spr$ of the laser beam, distance $L$ from the protective glass of the focusing head to the workpiece surface. The output parameters of the processing process are represented by the friction coefficient $f$, and absolute wear $u$ of surface layer. In each of the vertical columns of independent factors (tab. 1) the higher number corresponds to the upper level of the factor, the lower number - to the lower level.

| Code | $x_1$ | $x_2$ | $x_3$ | $f$ | $u$, μm |
|------|------|------|------|-----|---------|
| 1    | 2    | 25   | 85   | 0.70 | 56      |
| 2    | 5    | 10   | 85   | 0.68 | 44      |
| 3    | 5    | 25   | 60   | 0.70 | 67      |
| 4    | 5    | 25   | 85   | 0.70 | 75      |
| 5    | 2    | 10   | 85   | 0.60 | 10      |
| 6    | 2    | 25   | 60   | 0.67 | 50      |
| 7    | 5    | 10   | 60   | 0.89 | 90      |
| 8    | 2    | 10   | 60   | 0.83 | 82      |

The main level of the factor was defined as the arithmetic mean of the upper and lower levels. The values of the friction coefficient and absolute wear of the treated surface layer of steel SHH15SG were determined on a tribometer of CSM Instruments (Switzerland).

3. Results and discussion

The interactive influence of the radiation power $W$ and the longitudinal feed $Spr$ of the laser beam on the friction coefficient is described by formula:

$$f = 0.7388 + 0.0142*W - 0.0038*Spr. \tag{1}$$

The graphical interpretation of (1) is represented by a 3M-XYZ surface-graph (Fig. 1).
Figure 1. 3M-XYZ surface-graph of interactive influence of factors $W$ and $Spr$ on the friction coefficient.

3M-XYZ contour-graph of the influence of factors $W$ and $Spr$ on the friction coefficient is shown in Fig. 2.

Figure 2. 3M-XYZ contour-graph of interactive influence of factors $W$ and $Spr$ on the friction coefficient.

The interactive effect of the radiation power $W$ and the distance $L$ of the protective glass to the workpiece on the friction coefficient is described by formula:

$$f = 0.9689 + 0.0142 \times W - 0.0041 \times L.$$  

The graphical interpretation (2) is represented by a 3M-XYZ surface-graph (Fig. 3), which shows that the friction coefficient varies depending on the laser treatment mode.
Figure 3. 3M-XYZ surface-graph of interactive influence of radiation power W and distance L on the friction coefficient.

3M-XYZ contour-graph of the interactive influence of radiation power W and distance L of the protective glass to the workpiece on the friction coefficient of steel SHH15SG is shown in Fig. 4.

Figure 4. 3M-XYZ contour-graph of influence of the factors W and L on the friction coefficient.

The multi-factor model of the friction coefficient in the code designation of independent factors $x_1 - x_3$ of the laser processing has the form:

$$Y = 0.72125 + 0.02125x_1 - 0.02875x_2 - 0.05125x_3.$$  \hspace{1cm} (3)

The multi-factor model of the friction coefficient in the natural designation of the independent factors has the form:

$$f = 0.4072 + 0.0142*W - 0.0038* Spr - 0.0041*L.$$  \hspace{1cm} (4)

The wear of the treated surface layer of steel SHH15SG presented in the far right column of Table 1. The regression equation of interactive effects of the radiation power W, and longitudinal feed Spr of laser beam on wear $u$ has the form:

$$u = 74.4 - 3.3(3)*W - 0.5* Spr.$$  \hspace{1cm} (5)

A graphical interpretation of (5) is shown in Fig. 5.
Figure 5. 3M-XYZ surface-graph of the interactive effect of the radiation power $W$ and the longitudinal feed $Spr$ of the laser beam on the wear.

3M-XYZ contour-graph of the interactive influence of factors $W$ and $Spr$ on the wear of the surface layer is shown in Fig. 6.

The regression equation of the interactive influence of the radiation power $W$ and the distance $L$ from the protective glass to the workpiece on the wear $u$ of the treated surface layer has the form:

$$u = 43.9 - 3.3(3)W + 0.3L$$

A graphical interpretation of (6) is shown in Fig. 7 as a 3M-XYZ surface-graph of the interactive influence of the radiation power $W$ and the distance $L$. 

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**Figure 6.** 3M-XYZ contour-graph of the interactive effect of the factors $W$ and $Spr$ on the wear.
Figure 7. 3M-XYZ surface-graph of the interactive influence of factors W and L on the wear of steel SHH15SG.

3M-XYZ contour-graph of the interactive influence of factors Spr and L on the wear of the surface layer is shown in Fig. 8.

Figure 8. 3M-XYZ contour-graph of the interactive influence of factors Spr and L on the wear.

Thus, the mode of laser treatment of bearing steel SHH15SG significantly affects the wear of the surface layer processed, which is associated with the absorption of a significant amount of heat, its rapid removal to the underlying cold layers of the metal. As a result, the hardness of the treated surface layer increases [20].

4. Discussion
It follows from (1) that the friction coefficient \( f \) of the treated surface increases with increasing radiation power \( W \) and decreases with increasing longitudinal feed \( Spr \) of the laser beam. An increase in the independent factors \( Spr \) and \( L \) leads to a decrease in the friction coefficient \( f \), and with an increase in \( W \), \( f \) increases. It follows from (5) that with increasing radiation power, the absolute wear \( u \) of the surface layer decreases, which is associated with an increase in the hardness of the treated surface layer [20]. The greatest influence on the wear of the surface layer is the power of radiation, then follow the longitudinal feed \( Spr \) of the laser beam and the distance \( L \) from the protective glass of the focusing head to the workpiece surface being processed.

As the longitudinal feed \( Spr \) of the laser beam increases, the absolute wear \( u \) also decreases, but to a much lesser extent, compared to the power of the laser radiation.
Thus, the dominant influence on the friction coefficient and absolute wear of the surface layer of steel SHH15SG has the power of laser radiation. The obtained research results allowed us to develop a method for assigning laser treatment modes for steel SHH15SG.

4.1. Method of assigning the mode of laser treatment

We will describe the method of assigning the mode of laser processing of steel SHH15SG using the developed models and their graphical representations. Suppose that after laser treatment, the permissible wear of the surface layer should be \( u < 58 \mu m \). In accordance with the permissible wear in Fig. 6, for example, we find a yellowish-green rectangle corresponding to wear \( u < 58 \mu m \).

To reduce the processing time, it is necessary to assign the maximum possible longitudinal feed, which corresponds to the power \( W = 2.8 \text{ kW} \).

Moving up parallel to the ordinate axis from point 1 with the coordinate \( W = 2.8 \text{ kW} \) to the intersection with the yellowish-green stripe, we get points 2 and 3. Move the segment 2-3 to the ordinate axis and get the segment 4-5 with the interval of longitudinal feed \( Spr = (19-24) \text{ mm/s} \).

To determine the distance \( L \) of the safety glass to the workpiece, use the contour graph (Fig. 8). Moving up from point 6 at the value \( Spr = 19 \text{ mm/s} \) to the intersection with the strip of the same color, we get points 7 and 8. Move the segment 7-8 to the ordinate axis we get the segment 9-10 with the value \( L \approx (81.5-84.0) \text{ mm} \). As a result of the calculation, wear values of 55.6 and 33.0 \( \mu m \), respectively, are obtained, which satisfy the values of demanded wear \( u \) < 58 \( \mu m \).

Therefore, at laser processing mode: \( W = 2.8 \text{ kW}, Spr = 19 \text{ mm/s} \) and \( L = 83 \text{ mm} \) provides the formation of a surface layer that meets the condition \( u < 58 \mu m \). Similarly, we assign a laser treatment mode that provides the demand friction coefficient, while the values \( W, Spr \) and \( L \) will differ from the values that provide demand wear of the surface layer.

From the obtained values of the factors \( W, Spr \) and \( L \), limit values are selected that simultaneously meet the requirements for the friction coefficient and permissible wear of steel SHH15SG.

Thus, the presented research results allow us to quickly assign technological and design factors that provide the required performance characteristics of the surface layer to be processed and can be used in the development of technological operations of laser processing and design of laser equipment.

5. Conclusions

1. Developed multi-factor experimental models of friction coefficient and the absolute wear of the surface layer SHH15SG bearing steel subjected to laser treatment, and 3M-XYZ surface-graphs, 3M-XYZ contour-graphs, based on which the relationship between the independent factors of the laser processing and output parameters that determine the performance properties of the treated surface layer.

2. To increase the wear resistance of the surface layer of steel SHH15SG, it is necessary to increase the radiation power and the longitudinal feed of the laser beam, and the distance from the protective glass of the focusing head to the workpiece surface should be reduced. The established graphical interpretation of multi-factor models of the coefficient of friction and wear significantly simplifies the assignment of the laser treatment mode and reduces the time for performing this procedure.

3. Based on the use of 3M-XYZ contour graphs and obtained experimental multi-factor models, a method for assigning modes of laser treatment of steel SHH15SG has been developed, which ensures simultaneous compliance with the requirements for the permissible values of the friction coefficient and wear of the surface layer. This method significantly reduces the time for designing the technological operation, eliminates additional experiments in production conditions and reduces the technological cost of products.

4. Established multi-factor models and their graphical interpretation can be used not only in the construction of laser treatment technology, but also in the design of laser complexes and installations.
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