Determination of Geometric Parameters and Tribological Properties of Laser-Surfaced Steel Coatings

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Abstract. The paper presents the results of metallographic and tribotechnical studies of composite coatings with the addition of ultrafine titanium carbide to the composition of the charge. Mathematical modeling using a full factorial experiment allowed us to determine the geometric dimensions of the deposited rollers depending on the power, processing speed and diameter of the laser beam. The regularities of the change in the coefficients of friction from the pressure and the sliding speed are obtained. The wear and tear resistance of the coatings is higher than the steel base.

1. Introduction
Laser surfacing on stainless steel is widely used, for example, in the aerospace industry and in nuclear power plants [1-4]. It is used to produce coatings with a metallurgical compound with a base [5] with minimal porosity and mixing coefficient, no cracks to produce high-performance composite surfacing layers [6]. Laser surfacing is used to eliminate material surface defects, which has also been the subject of research in recent years [7-9]. Nickel (Ni) - based powder materials can provide a sufficiently high hardness to increase the wear resistance of coatings [10]. In addition, the high resistance of coatings in various environments is provided by the addition of alloying elements and they are compatible with the corrosive environment in which stainless steel is used [11, 12]. To increase the service life on the friction surface of stainless steels, coatings based on nickel, cobalt or high-entropy alloys are deposited [13], which have a high cost due to the increased requirements for chemical purity of 99.5-99.9% of the incoming elements.

The objectives of the work are to determine the geometric dimensions of the laser surfacing zones of composite powders from the processing modes and the effect of the introduction of ultrafine TiC particles into the charge on the tribotechnical properties of coatings.

2. Materials and methods
In experimental studies, the IMASH RAS laser automated complex was used. The samples were made of 12X13 steel with dimensions of 15×20×70 mm. For the production of the powder charge, powders based on nickel (Ni-Cr-B-Si) and cobalt (Co-Cr-W-Ni-Si-B) were selected in a ratio of 3:1, respectively, with a particle size of 40-150 µm. Ultrafine TiC powder with a particle size of 1-15 microns was added to the deposited charge of 5 and 10 wt.%. The powders were mixed in a mechanical mixer until the components of the charge were evenly distributed. Powder coatings were applied with a thickness of 0.85-0.91 mm. An aqueous solution of hydroxyethylcellulose was used to bind the powder material.
particles. The radiation power $P=700\text{-}1000$ W, the processing speed $V=7\text{-}10$ mms$^{-1}$, and the beam diameter $d=2.5\text{-}3.5$ mm were selected as variable parameters. The treatment was performed with a defocused beam and with transverse beam vibrations with a frequency of $f=218$ Hz. To determine the tribotechnical characteristics, tests were performed at a sliding speed of $0.25\text{-}3.5$ mms$^{-1}$ and a pressure on the sample in the range and $1\text{-}6$ MPa. TP22C oil was used to lubricate the friction pair.

To determine the geometric dimensions of the deposited tracks, the method of planning a full factor experiment (FFE) was used. In mathematical modeling, the height $H$ and width $B$ of the deposited rollers were considered as the responses of the system. Table 1 shows the levels of the experimental factors.

| Factor | Upper level of factor $z_i^+$ | Lower level of factor $z_i^-$ | Center of the plan $z_i^0$ | Variation Interval $\lambda_i$ | Dependence of the encoded variable on the natural |
|--------|-------------------------------|-------------------------------|-----------------------------|-----------------------------|----------------------------------|
| $P$ (W) | 1000 | 700 | 850 | 150 | $x_1 = \frac{P_i - 850}{150}$ |
| $V$ (mms$^{-1}$) | 9 | 7 | 8 | 1 | $x_i = V_i - 8$ |
| $d$ (mm) | 3.5 | 2.5 | 3.0 | 1 | $x_i = d_i - 3$ |

Laser surfacing was performed on 8 samples. The sections were made according to the standard method. To obtain the mathematical expectation, the measurements of the deposited tracks were carried out three times.

The regression equation with respect to the new variables has the form:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{13}x_1x_3 + b_{123}x_1x_2x_3$$

where:
- $y$ is the system response;
- $x_i$-factor levels;
- $b$ – coefficients of the regression equation.

### 3. Results and discussions

Figure 1 shows a general view of the micro-grinds of the deposited rollers with a composite powder material with a defocused and oscillating beam. According to the results of measuring the tracks, it was found that the surfacing area during processing with an oscillating beam increases by 1.67-2.3 times compared to surfacing with a defocused beam, which indicates a proportional increase in the surfacing performance with transverse beam vibrations.

To determine the patterns of changes in the size of the surfacing zones, depending on the power and speed of processing, graphs of surfaces with different laser beam diameters are constructed. Figure 2 shows the surface graphs constructed using the regression equations for the beam diameter of 3.5 mm. When analyzing the results obtained, it was found that the radiation power has the greatest influence on the size of the deposited tracks. With increasing power, the width and height of the deposited rollers increase. As the processing speed increases, the height and width of the tracks decreases. With increasing defocusing of the laser radiation, in the studied interval, the height and width of the rollers increases.
Figure 1. General view of the micro-section of the deposited tracks: a-defocused beam, b-oscillating beam.

Figure 2. The dependence of the height (a, b) and width (c, d) of the deposited tracks on the processing speed and power at a beam diameter of 3.5 mm: a and b – with a defocused beam, b and d with an oscillating beam.

Figure 3 shows the zones of spectral analysis of the deposited material containing 5% of ultrafine titanium carbide in the charge. The results of the element analysis are shown in table 1.

From the analysis of the elemental composition, it follows that the mixing zone of the base material with a surfaced coating of 80-160 µm contains a maximum amount of iron up to 20%, and closer to the surfacing surface it decreases to 4.5%. There is an almost uniform distribution of TiC over the surfacing cross-section.

Based on the results of tribotechnical tests, graphs of changes in the friction coefficients are constructed (Figure 4). With an increase in the specific load, the coefficient of friction for all the samples under study decreases, but at a pressure of more than 4 MPa, it increases for the base material and coating...
without titanium carbides. For friction surfaces containing TiC, the coefficient of friction decreases monotonically with increasing specific load. An increase in the speed of movement in the friction pair leads to a decrease in the friction coefficients for samples with deposited coatings in the studied range of sliding speeds.

**Figure 3.** Zones for determining the elemental composition of the roller with 5% TiC

**Table 2.** Results of the analysis of the elemental composition, wt.%

| Spectrum | C   | Si  | Ti  | Cr  | Fe  | Co  | Ni  | W   |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|
| 1        | 5.85| 2.83| 2.88| 15.96| 19.29| 12.05| 40.11| 1.03 |
| 2        | 6.17| 2.27| 3.51| 18.44| 13.76| 12.27| 40.53| 3.05 |
| 3        | 6.45| 2.81| 3.12| 19.33| 4.03 | 12.76| 48.63| 2.87 |
| 4        | 6.12| 3.52| 3.48| 19.03| 4.43 | 14   | 48.02| 1.4  |

The coefficient of friction of the base material changes in the same way as when the pressure increases. The minimum coefficients of friction are obtained at a charge content of 10 wt.% TiC.

**Figure 4.** Dependence of the friction coefficients on the pressure (a) and sliding speed (b): 1 – steel 12X13, 2 – (Ni-Cr-B-Si, Co-Cr-W-Ni-Si-B) 3- (Ni-Cr-B-Si, Co-Cr-W-Ni-Si-B) + 5 wt.% TiC, 4 - (Ni-Cr-B-Si, Co-Cr-W-Ni-Si-B) + 10 wt.% TiC.

The microhardness values in the coating with a content of 10 wt.% TiC were 8700-10800 MPa. The wear rate for composite coatings without carbides, containing 5 and 10% ultrafine TiC and the base was $6.473 \times 10^{-9}$, $4.765 \times 10^{-9}$, $3.124 \times 10^{-9}$, $16.794 \times 10^{-9}$ accordingly.

4. Conclusions
As a result of the use of powder materials based on nickel and cobalt with the addition of ultrafine titanium carbide, new properties were obtained that differ from the base material by low coefficients of friction, greater corrosion resistance compared to nickel alloys.

The wear rate of composite coatings without carbides, with 5 and 10% TiC, is 2.5, 3.9 and 5.2 times lower than the steel base, respectively.

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