THE STUDY OF CHARACTERISTICS OF ELASTICITY AND RESIDUAL STRESSES IN COATINGS APPLIED BY PLASMA METHODS

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Abstract:
At present, a strategically important task of technological independence of Russian industries is restoration of worn-out parts of machines and equipment by plasma methods based on the use of coatings of different functional purpose. The purpose of this study is to solve the actual problem of choosing the rational modes of plasma coating in the process of restoration of worn parts, subjected to intensive wear in the operation process. To solve this problem, the experimental studies of the elasticity characteristics in the plasma-deposited coatings were carried out. The study results allowed determining the most optimal range of rational modes of plasma coating deposition in terms of obtaining high elastic properties of plasma coatings as the key stage of resource-saving technology for restoration of worn parts of machinery and equipment.

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Plasma surfacing, Plasmatron, Fatigue resistance, Deformation curve, Fusion zone

1. INTRODUCTION

One of the main tasks in the design of technological processes for the restoration of worn items is to determine the rational parameters at which the output parameter would have an optimal value. In practice it is most often required to estimate the parameters, i.e. to build its mathematical model and determine the numerical values of the parameters of this model. In our case it is a technological process of plasma surfacing of wear-resistant coatings. It is known that the bulk of failed parts has wear not exceeding 0.2-0.3 mm. An effective way to restore such items is the plasma surfacing of thin coatings with powder carbide alloys of increased wear resistance [1-7]. At the same time, it is important to select a plasma surfacing mode that would allow applying wear-resistant coatings with minimal resistance to metal fatigue. In this case, the coating retains its original physical and mechanical properties. In order to determine the effect of plasma surfacing modes and surfacing materials on the fatigue resistance of restored parts, it is necessary to establish the elasticity characteristics arising in the coatings applied by plasma methods, as well as the residual stresses in the fusion zone [8-15].

2. MATERIALS AND METHODS

To conduct experimental studies, samples were made, which were the rings of steel grade 40G with...
an outer diameter of 55 mm, inner - 35 mm and a width of 10 mm. Plasma surfacing was performed along the outer diameter of the sample with the powdered material composition [16]. In this case, the constant parameters during plasma surfacing were:
- plasmatron vibration amplitude - \( A = 18 \text{ mm} \);
- plasmatron oscillation frequency - \( v = 80 \text{ min}^{-1} \);
- plasma gas flow rate - \( g_1 = 1.5-1.8 \text{ l/min} \);
- conveying gas flow rate - \( g_2 = 10-12 \text{ l/min} \).

The hardness of coated samples was determined by non-destructive expressive measurement using a universal programmable electronic portable hardness tester TEMP-4 (ТЭМП-4). The hardness tester allows to work in any standardized scale: Brinell (HB), Rockwell (HRC), Shore (NSD), Vickers (HV), since the values obtained by the different methods are connected with certain dependencies. Before measurements, the hardness tester was calibrated using standard hardness measures tested on state hardness standards according to Brinell, Vickers, Rockwell and Shore scales, which ensured high accuracy of measurements [17, 18]. The ranges of hardness measurements on the scales are given in Table 1.

The compact portable hardness tester TEMP-4 (ТЭМП-4) provides rapid hardness testing of almost any surface and in any direction. The procedure for hardness testing with the TEMP-4 portable hardness tester is shown in Fig.1.

To optimize the plasma deposition parameters, the method of complete factor experiment was applied [19-21]. The Young’s modulus was adopted as the optimization criterion [22-24]. Taking into account the information about the influence of individual factors in plasma surfacing on the optimization criterion, the levels and intervals of variation of the main factors that have the most significant influence on the physical and mechanical properties of the applied coatings were selected. The matrix of variation of plasma surfacing modes is presented in Table 3.

### Table 1. Hardness measurement ranges according to scales

<table>
<thead>
<tr>
<th>Scale</th>
<th>Indicator</th>
<th>Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rockwell</td>
<td>22-68</td>
<td>HRCe</td>
</tr>
<tr>
<td>Brinell</td>
<td>100-450</td>
<td>HB</td>
</tr>
<tr>
<td>Shore</td>
<td>22-99</td>
<td>HSD</td>
</tr>
<tr>
<td>Vickers</td>
<td>100-950</td>
<td>HV</td>
</tr>
</tbody>
</table>

### Table 2. Modes of plasma surfacing of samples

<table>
<thead>
<tr>
<th>Samples</th>
<th>Plasmatron arc current ( I, A )</th>
<th>Plasmatron arc voltage ( U, B )</th>
<th>Plasmatron travel speed ( V, \text{ m/min} )</th>
<th>( Al, % )</th>
<th>Hardness, ( HV )</th>
<th>Coating thickness ( h, \text{ mm} )</th>
<th>Shrinkage, ( \text{ mm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>53</td>
<td>0.34</td>
<td>8</td>
<td>583</td>
<td>1.10-1.20</td>
<td>0.15</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>53</td>
<td>0.14</td>
<td>8</td>
<td>580</td>
<td>1.20-1.40</td>
<td>0.36</td>
</tr>
<tr>
<td>3</td>
<td>140</td>
<td>48</td>
<td>0.34</td>
<td>8</td>
<td>565</td>
<td>1.10-1.15</td>
<td>0.13</td>
</tr>
<tr>
<td>4</td>
<td>140</td>
<td>48</td>
<td>0.14</td>
<td>8</td>
<td>572</td>
<td>1.10-1.30</td>
<td>0.28</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>53</td>
<td>0.24</td>
<td>14</td>
<td>566</td>
<td>1.20-1.30</td>
<td>0.27</td>
</tr>
<tr>
<td>6</td>
<td>200</td>
<td>53</td>
<td>0.24</td>
<td>2</td>
<td>570</td>
<td>1.30-1.40</td>
<td>0.31</td>
</tr>
<tr>
<td>7</td>
<td>140</td>
<td>48</td>
<td>0.24</td>
<td>14</td>
<td>517</td>
<td>1.30-1.40</td>
<td>0.17</td>
</tr>
<tr>
<td>8</td>
<td>140</td>
<td>48</td>
<td>0.24</td>
<td>2</td>
<td>570</td>
<td>1.80-2.00</td>
<td>0.22</td>
</tr>
</tbody>
</table>
The elasticity characteristics were investigated in the following sequence. Six consecutive ring diameters (56.5; 55.5; 54.5; 53.5; 52.5 and 51.5 mm) with plasma surfacing coatings were performed on a turning lathe. After each turning, the weight of the remaining sample was measured on a laboratory scale VLA-200 with an accuracy of 0.01 g; the outer diameter of the rings was measured with a micrometer with an accuracy of 0.01 mm, the resonance frequency of oscillations and the cross-section stiffness of the studied sample was calculated according to the obtained data. As a result of the experiment, the dependence of the ring stiffness $B$ on its axial moment of inertia $I_X$ was established, and this can be represented by the expression:

$$E = \frac{dB}{dI_X} \quad (1)$$

The obtained dependence can be approximated, and then the derivative of this function will give us the value of the Young’s modulus $E$ in any coating applied by plasma surfacing and in the base metal. To determine the resonant frequency of the bending vibrations, a circular sample was placed between two piezoelectric elements, one of which is designed to emit sound frequency vibration, and the other serves as a receiver. The transmitter was connected to an oscillator designed to change its frequency. By changing the frequency of the ring forced oscillation, its value is brought to coincidence with the ring natural frequency. By a sharp increase in the oscillations amplitude of the sample, the resulting resonance was recorded on the oscilloscope screen. The exact value of the oscillations resonance frequency was measured with a frequency meter. The bending stiffness function of the ring is a curve, which indicates that the elastic modulus change in thickness [25].

To determine the resonant frequency of oscillations resonance frequency was measured in the coatings applied by plasma surfacing, the elastic modulus have a reduced value. As they move deeper into the surfaced coating, they increase, and in the fusion zone with the base metal, they decrease again. In the base metal, the modulus of elasticity remain constant. The values of elastic modulus in the coatings applied by plasma surfacing and in the fusion zone for all the tested samples are shown in Table 4. The Young’s modulus $E$ of the base material for all the examined samples was $1.92 \times 10^4$ MPa.

Table 4. Elastic moduli of the coatings applied by plasma surfacing and the fusion zone with the base metal

<table>
<thead>
<tr>
<th>Samples</th>
<th>Young’s modulus $E$ $10^4$, MPa</th>
<th>Coating at sample thickness, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.25</td>
<td>10.95 10.65 10.35 9.95 9.55 9.15 8.65</td>
</tr>
<tr>
<td>2</td>
<td>1.36 1.46 1.52 1.53 1.61 1.85 1.40 1.33</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.86 1.34 1.92 2.14 2.00 1.91 1.40 1.37</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.56 1.53 1.43 1.66 1.66 1.55 1.91 1.36</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.42 1.52 1.51 1.61 1.78 1.57 1.43 1.38</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.46 1.59 1.33 1.48 1.63 1.56 1.41 1.40</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.86 1.41 1.49 1.68 1.58 1.40 1.41 1.35</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1.93 1.07 1.14 1.28 1.38 1.32 1.48 1.38</td>
<td></td>
</tr>
</tbody>
</table>

3. RESULTS AND DISCUSSION

The analysis of the obtained study results demonstrated that the change in the elasticity characteristics is significantly influenced by the plasma surfacing modes. As a result of the mathematical processing of the results of the experiments performed in the sequence specific for the method of planning a complete factor experiment [26-27], a mathematical model in the form of a regression equation was obtained:

$$\hat{Y} = 1.48 + 0.10X_1 - 0.115X_2 - 0.15X_3 + 0.22X_1^2 + 0.17X_2^2 - 0.10X_3^2 \quad (2)$$

and adequately describes the field of experimentation (variance of adequacy $S_{r.d^2} = 0.0093$, dispersion of experience $S_{y^2} = 0.0052$, the calculated Fisher criterion is $F_p = 1.79$, tabular $F_T = 19.3$) and allows the estimation of the cumulative effect of plasma surfacing modes on the maximum values of their elastic moduli.

Table 3. Matrix of variation of plasma surfacing modes

<table>
<thead>
<tr>
<th>Name</th>
<th>$I, A {X}$</th>
<th>$V, m/min {X}$</th>
<th>$Al, % {X}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic level</td>
<td>170</td>
<td>0.24</td>
<td>8</td>
</tr>
<tr>
<td>Variation interval</td>
<td>30</td>
<td>0.10</td>
<td>2</td>
</tr>
<tr>
<td>Upper level</td>
<td>200</td>
<td>0.34</td>
<td>10</td>
</tr>
<tr>
<td>Lower level</td>
<td>140</td>
<td>0.14</td>
<td>6</td>
</tr>
</tbody>
</table>
For practical calculations, the resulting regression equation is more convenient in the transformed form. After appropriate transformations in the natural scale it will take the final form:

\[
E = (9.484 - 0.080I - 9.31V + 0.175Al + 2.44 \times 10^{-4}I^2 + 17V^2 - 0.025Al^2) \cdot 10^4, \text{MPa} \quad (3)
\]

Graphical interpretation of the dependence of the optimization criterion \(E\) on the varying factors that have a significant effect on the physical and mechanical properties of the applied coatings is shown in Fig.2.

![Fig. 2. Dependence of Young’s modulus \(E\) on arc current of plasmatron \(I\), its travel speed \(V\) at constant values of voltage \(U\) = 48 V and aluminum \(Al\) content in composite powder material 8%](image)

The most optimal in terms of obtaining high elastic properties is the plasma surfacing mode, at which \(I = 170\) A, \(U = 48\) V, \(V = 0.14\) m/min. At the same time, the powdered aluminum content in the composite powder material was 8% [28]. It should be noted that the highest hardness of the surfaced coating, which was \(HV = 580\) was obtained in this plasma surfaced mode.

The samples for determining the elasticity characteristics were used as samples for determining residual stresses [29].

Residual stresses were calculated using the following methodology:

1. The coated samples were consistently turned on the lathe in a special fixture and after each turning the circumferential strains were recorded.

Strain measurements were carried out using strain gauges at two points on the circumference. Strain gauges on the samples were fixed with glue. To measure the rings strains, an electrical circuit was assembled, which included the working and compensation rings under study with glued electronic sensors measuring statistical strains. Measurements were taken after each turning and coating layers removal.

2. Based on the obtained and processed experimental data using statistical methods, the strain curve \(\varepsilon_r(r)\) was plotted. When developing a method for plotting the calculated conditional strain curve in the presence of characteristic values, one of the requirements for its schematization is that the schematization parameters can be selected by comparing them with experimental strain curves (Fig.3).

![Fig. 3. Strain curves: I – experimental, II – conventional](image)

The accuracy of the resulting curve directly depends on the number and quality of the primary experimental strain curves [30].

According to the results of this research, an approach to the construction of calculated conditional strain curves consisting of four sections has been developed:

- the first section is linear by points;
- the second section is the spline between the points;
- the third section is the section of a sharp rise in the curve between points, which is described by the logarithmic function;
- the fourth section is the hardening section described by a fourth-order polynomial.

It should be noted that in the case of a large number of experimental strain curves, it is advisable to follow the MMPDS requirements for the design curves plotting [30].

3. The residual circumferential stresses were determined from the following expression:
\[
\sigma_b = -\frac{AK(r) + B(r)D}{4R_2^2r} \frac{d\varepsilon_b}{dr} - \frac{E_1A91 + \mu_2}{2R_2^2} \varepsilon_b(r) + \frac{AK(r) + B(r)d}{4R_2^2r} \varepsilon_b(r)
\]

\[A = (1 - \mu_1)R_2^2 + (1 + \mu_2)R_1^2\]

\[K(r) = E_2(r^2 - R_2^2)\]

\[B(r) = (1 - \mu_2)R_2^2 + (1 + \mu_2)r^2\]

\[D = E_1(R_2^2 - R_1^2)\]

Where:
- \(R_1, R_2, r\) – respectively the radius of the ring inner surface, the ring-coating interface and the current radius \((R_2 \leq r \leq R_1)\);
- \(E_1, E_2\) – elastic moduli of the inner and outer parts of the ring;
- \(\mu_1, \mu_2\) – respectively Poisson’s coefficients for these parts.

The values of residual stresses \(\sigma_b\) in the coatings applied by plasma surfacing to the samples, depending on the value of the variable radius \(r\), are presented in Table 5. Note that the radial residual stresses are quite insignificant and can be neglected.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Ring radius (r), mm</th>
<th>(\sigma_{\sigma1}), kg/mm²</th>
<th>Sample number</th>
<th>Ring radius (r), mm</th>
<th>(\sigma_{\sigma1}), kg/mm²</th>
<th>Sample number</th>
<th>Ring radius (r), mm</th>
<th>(\sigma_{\sigma1}), kg/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28.40</td>
<td>4.24</td>
<td>3</td>
<td>28.35</td>
<td>19.37</td>
<td>5</td>
<td>28.00</td>
<td>10.50</td>
</tr>
<tr>
<td></td>
<td>27.00</td>
<td>2.82</td>
<td></td>
<td>27.00</td>
<td>13.52</td>
<td></td>
<td>27.00</td>
<td>3.80</td>
</tr>
<tr>
<td></td>
<td>26.00</td>
<td>1.88</td>
<td></td>
<td>26.00</td>
<td>10.26</td>
<td></td>
<td>26.00</td>
<td>1.79</td>
</tr>
<tr>
<td>2</td>
<td>28.00</td>
<td>3.05</td>
<td>4</td>
<td>27.50</td>
<td>4.59</td>
<td>6</td>
<td>28.35</td>
<td>-6.84</td>
</tr>
<tr>
<td></td>
<td>27.00</td>
<td>7.54</td>
<td></td>
<td>26.00</td>
<td>5.44</td>
<td></td>
<td>27.00</td>
<td>2.73</td>
</tr>
<tr>
<td></td>
<td>26.00</td>
<td>8.20</td>
<td></td>
<td>25.00</td>
<td>5.84</td>
<td></td>
<td>26.00</td>
<td>3.11</td>
</tr>
</tbody>
</table>

The results of the analysis of the obtained data show that in almost all cases (except for sample No. 6) there are circumferential tensile stresses on the surface. The main reasons for their occurrence are the uneven cooling in the process of plasma surfacing and the nature of the structures of the surfaced coatings.

**4. CONCLUSION**

The key research results in this paper are as follows:

1. Tensile stresses that reduce fatigue resistance are formed in the surfaced coating during plasma surfacing with powder composite alloys. Fatigue resistance of the parts restored by plasma surfacing with the given alloys decreased by 20-25% from the maximum worn parts level.

2. The carried-out researches on optimization of plasma surfacing by the method of full multifactorial experiment allowed establishing the optimization criteria which is most influenced by the plasma surfacing speed and oscillation amplitude. Relative wear resistance of coatings surfaced with powder hard alloys is 3-5 times higher in comparison with hardened steel 45. At the same time the addition of 8% aluminum powder to the initial powder hard alloys provides the increase in their wear resistance

3. The results of the study to determine the elasticity characteristics and residual stresses in the coating demonstrated that in the surface layers of the surfaced coatings, the elastic moduli have reduced values and tensile residual stresses arise.

**REFERENCES**


