Determination of mechanical properties of coatings obtained by non-vacuum electron beam cladding

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Abstract. A study on the mechanical properties of composite materials obtained by the method of non-vacuum electron-beam cladding of refractory powders on a steel substrate was carried out. The mechanical properties of composite with coatings were investigated by a three-point bending test at room temperature. The strength of the obtained composite was 4.5-6 times higher compared to that of low carbon steel depending on the deposition modes.

1. Introduction

One of the advanced methods for applying hardening coatings is the method of electron beam cladding in air. This technology is based on the use of an accelerator of relativistic electrons [1, 2]. The method allows obtaining cladded layer with a uniform structure, possessing higher hardness, wear resistance, corrosion resistance, heat resistance and almost complete absence of cracks, cavities and micropores [3].

There are numerous investigations devoted to determining the elastic and strength characteristics of coatings obtained by the method of plasma and thermal spray, laser and electron beam cladding, and other methods [4-6]. However, deep knowledge is required in the field of structural strength under various loading conditions for widespread adoption of new coatings. The experience of their use is insufficient, and the influence of various factors has been little studied [7, 8].

The hardening coatings are basically used to protect metal elements of constructions and parts from various external influences (corrosion, wear, destruction, etc.). In order to establish the strength limits of the surface layers of most structural elements and parts, special studies must be carried out. One of the most common tests of materials and constructions is the quasi-static bending test. This method is used to determine the ability of a material to withstand a given plastic deformation and identify the ultimate bending strength. These properties complement the basic information about the coating (structure, phase composition, hardness) which predetermines its purpose. This type of test applies to cast iron, tool steel, steels after surface hardening and ceramics.

The aim of the work is to determine the mechanical properties of the composites obtained by the method of non-vacuum electron-beam cladding of the powder mixture (Cr, C + TiC) on low carbon steel. In this study, the ultimate strength and deflection of composite with coating were determined depending on the deposition modes.

2. Experimental

The powder mixture for cladding consisted of chromium carbide (Cr3C2, 54 wt%), titanium carbide (TiC, 6 wt%) and fluoride magnesium (MgF2, 40 wt%), it was used as a flux, protecting the melt from oxygen. The particles of all powders were 2 – 5 μm in size. The electron-beam energy was 1.4 MeV. The beam current was 25 mA. The distance from the beam outlet to the workpiece was 90 mm. The
Gaussian diameter of the electron beam on the specimen surface was 12 mm. The width of the scanning was 50 mm. Five coatings were obtained corresponding to different velocities (v) of the samples under the beam and irradiation energies (W) (Table 1).

Table 1. Processing modes

| Number | 1   | 2   | 3   | 4   | 5   |
|--------|-----|-----|-----|-----|-----|
| v (cm/s) | 0.95 | 0.8 | 0.7 | 0.6 | 0.55 |
| W (kJ/cm²) | 7.4  | 8.8 | 10.0 | 11.7 | 12.7 |
| Layer thickness (mm) | 1.7 | 1.3 | 1.5 | 3.7 | 4 |

The tests on quasi-static three-point bending (GOST 14019-03) were carried out on an Instron-1185 with automatic recording of the “load P- indenter displacement” diagrams. The indenter speed was 0.5 mm/min. The preload was 100 N. The distance between the supports was 35 mm. All tests were carried out at room temperature. The samples were fabricated using the electric spark machine. The final sample size of $5 \times 5 \times 50$ mm was obtained manually by grinding and polishing. All samples were the same size, but the thickness of the cladding layer varied from 1.3 to 4 mm (see table 1). Bending tests were carried out before the first crack in the stretched zone of cladded layer.

The sample was installed on two supports. The load was applied exactly in the middle of the sample. Hardened cladding layer had tensile stresses during lowering of the upper indenter of the machine. The substrate subjected to compressive stresses. This method has become widespread due to the ease of implementation. The strength of the samples was determined by the test results. The amount of deflection was also estimated. Simultaneously, the pattern of crack formation from the moment of their origin to the transition to the substrate metal with subsequent plastic deformation was investigated on the side polished surface of the samples.

The bending strength on the outer surfaces of the sample (on the cladding side) was calculated by the formula:

$$\sigma_b = \frac{3PL}{2bh^2},$$

where $P$ is the load (N), $L$ is the distance between the supports (mm), $b$ is the sample width (mm), $h$ is the sample thickness (mm).

3. Results and Discussion

The dependence of the applied load $P$ on the indenter displacement was obtained for different samples (Fig. 1). The maximum bending deflection for each sample was determined from the diagram (Table 2).

The deflection $f$ can be divided into two regions (Fig. 1): $f_{pl}$ determines a certain reserve of plasticity of the coating and $f_d$ determines the nature of the fracture.

Thus, the analysis of the diagrams showed that samples 1, 3, 4, and 5 had increased ductility and strength. Composition with coating 5 was the strongest $\sigma_b = 877.128$ MPa. The maximum plasticity with the value $f_{pl} = 1.256$ mm was observed in sample 1. Sample 2, possessing some plasticity, was the most brittle. The maximum load on the curve of diagram was $\sigma_b = 677.124$ MPa.
The character of coating destruction follows from loading curves (Fig.1). In our case of statistical bending, the destruction of two main types is possible: fragile and viscous. However, mixed destruction occurs most often in practice. Sometimes destruction can begin as viscous, and end as fragile.

Analysis of composite deflection indicated (Fig. 1) that a crack in sample 5 was formed due to brittle fracture. The length of $f_d$ decreased to almost zero (see Table 2). In samples 1 and 4, segment $f_d$ had the form of ductile fracture until the first crack appears. The fracture mode $f_d$ before the appearance of the first crack corresponded to the case of ductile failure for the samples 1 and 4. The fracture mechanism of samples 2 and 3 was mixed (elastic-plastic).

**Table 2. Bend test results**

| Number | P [N] | $f$ [mm] | $f_p$ [mm] | $f_d$ [mm] | $\sigma_b$ [MPa] |
|--------|-------|----------|------------|------------|------------------|
| 1      | 1807  | 1.359    | 1.256      | 0.103      | 758.94           |
| 2      | 1612.2| 0.585    | 0.548      | 0.037      | 677.124          |
| 3      | 1735.1| 1.173    | 1.131      | 0.042      | 728.742          |
| 4      | 2021.7| 1.13     | 1.064      | 0.066      | 848.82           |
| 5      | 2088.4| 1.019    | 1.016      | 0.003      | 877.128          |
| low carbon steel | | | | | 150 |

As visual inspection of the samples after bending tests showed, the composite with coating 2 was broken with the formation of one crack passing through the entire coating both in width and in thickness (Fig. 2a). The crack was developed under the action of relatively low stresses but it development was brittle or quasi-brittle. The main crack penetrated into the substrate (low carbon steel) and branched into several small. This phenomenon is due to plasticity of steel. As shown in curve 2, Fig. 1a, the development of cracks was inhibited and stopped by the steel substrate. In samples 1, 3, 4 and 5, only nucleation of cracks were observed. Coatings were deformed at elevated loads fig. 1a before the formation of a single sinuous crack, while possessing some plasticity. Figure 2b shows a metallographic image of the side surface of the coating 4 after bending. The nature of the sinuous crack and the deformation curve of the coating 4 in Fig. 1a indicate a quasi-brittle fracture. Also, the presence of a small zone of plastic deformation in front of the edge of the crack and small secondary cracks shows a quasi-viscous fracture.

**Figure 1.** Force versus indenter displacement for samples with different thick coatings (a) and a schema the bending strain curve (b).
Since this work investigated samples of the same size, but with different thicknesses of the deposited layer and obtained under different processing conditions. Further research is needed to understand the reasons for the observed effects. In particular, it is necessary to conduct a fractographic study of the specimen destruction - fracture, the establishment of the relationship between the mechanical properties, structure and microhardness of the deposited coatings. This is the subject of further research.

4. Conclusion
The method of non-vacuum electron-beam surfacing allows obtaining coatings with different thickness of the deposited layer. Depending on the processing mode, coatings have different properties. Mechanical tests of compositions with a three-point bending at room temperature showed that surfacing the powder mixture (Cr$_3$C$_2$ + TiC) on a steel substrate can increase the tensile strength by 4.5–6 times compared to the ultimate strength of low carbon steel.

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