Flame sprayed and plasma sprayed $\text{Al}_2\text{O}_3$-$\text{TiO}_2$ coatings

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Abstract. $\text{Al}_2\text{O}_3$–$\text{TiO}_2$ coatings were received by flame sprayed of flexible cord and plasma sprayed using powder. Shown higher mechanical and tribological properties of flame sprayed coating compared plasma sprayed coating.

1. Introduction

Thermal spraying is a widespread method of sputtering coatings to increase service life and reliability of rubbing elements of machines [1–3], each of the varieties of which has its advantages and disadvantages. Aluminium and titanium oxides-based composite thermal sprayed coatings protect against abrasive wear, erosion, and wear during sliding friction at elevated temperatures [4, 5].

In this work, we carried out a comparative study of the properties of flame sprayed $\text{Al}_2\text{O}_3$ – $\text{TiO}_2$ coatings using flexible cord (series 1) and plasma sprayed coatings formed by using a mixture of initial powders (series 2).

2. Spraying and studies of coatings properties techniques

$\text{Al}_2\text{O}_3$–$\text{TiO}_2$ coatings were deposited on steel (DIN 17202) cylindrical substrates. Flame spraying was carried out using Top Jet-2 spraying system. A flexible cord based on aluminum (83 % (wt.) $\alpha$-$\text{Al}_2\text{O}_3$) and titanium (13 % (wt.) $\text{TiO}_2$) oxides was chosen as starting material. The dispersion of the initial powders varied in the range of 10-40 μm, the supply rate of the cord was 36 cm/min, the spraying distance was 75 mm. An acetylene-oxygen flame was used as a heat source. The gas pressures during coating were acetylene - 1.2 atm, propane - 1.8 atm, and oxygen - 3.2 atm. The modes of coating formation (concentration of titanium and aluminum oxides powders, their dispersion in a flexible cord, supply rate of cord, and the distance of spraying) were selected based on earlier studies [6]. These parameters of deposition ensured in the obtained coatings the minimum porosity and the maximum value of the hardness of the coatings.

Argon-hydrogen plasma spraying of $\text{Al}_2\text{O}_3$–$\text{TiO}_2$ coatings was performed using F4-MB plasma spray gun of initial powder mixture (10-40 μm) with flow rate 45 g/min. The arc current of the plasma torch was 600 A, the spraying distance was selected considering the temperature of ~ 500 °C on the substrate. The thickness of $\text{Al}_2\text{O}_3$ $\text{TiO}_2$ coatings deposited by two methods was about 450 μm.

To investigate the morphology, elemental and phase composition, and porosity of the coatings, cross-sections of the samples were prepared, which were examined on a JSM-6700 field scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS) (JEOL, Japan). The porosity of the coatings was determined from the SEM images. The phase composition was carried out by X-ray diffraction on a DRON-3M diffractometer using CoKα radiation. The hardness of
the coatings was measured according to the Rockwell B (HRB) scale on a TH-300 stationary hardness tester (TIMEGroup, China) at a maximum load of 980 N. The microhardness of the structural components of the coating material was carried out on a Micro-Hardness Tester (CSM, Switzerland) equipped with a Berkovich diamond indenter, under a load of 2 N for 15 s. The hardness and Young's modulus of the local areas of the coatings were determined by the Oliver – Pharr method. Measuring scratching of the coated samples was carried out on a scratch tester "REVETEST" by CSM (Switzerland) MVI AKP / 09. Tribology properties were carried out on a Nanovea Tribometers T50 (Nanovea, USA) using the Pin-On-Disk method at normal load 5 H using a corundum counterbody. The bond strength of the coating with the substrate was determined by the pull-off test for adhesion. The tests were carried out at a room temperature of 20 °C on an Instron5969 electromechanical tensile testing machine with a force of 2 tons.

3. Results and discussion

It was found that coatings formed by two different methods have an unsimilar structure (figure 1). Flame sprayed coatings have grains (dark in figure 1a) embedded in the matrix (light in figure 1a). Plasma sprayed coatings have a characteristic layered arched structure, including, as for flame sprayed coatings, light and dark areas (figure 1b). Based on the ratio of the element concentrations in these areas of the coatings, determined by EDS-analysis, it can be assumed that these structural components are aluminum oxide (dark phase) and a complex oxide (Al$_2$TiO$_5$) formed by interaction Al$_2$O$_3$ and TiO$_2$.

This assumption is consistent with the results of XRD analysis, which confirmed the presence of the α- and γ-modification of aluminum oxide and the Al$_2$TiO$_5$ phase in the coatings of both series. Figure 2 shows the X-ray diffraction patterns of the coatings. The metastable phase γ-Al$_2$O$_3$ could be formed from the melt of the initial Al$_2$O$_3$ upon quench during the formation of the coating.

Figure 1. SEM-image of a cross-section of flame sprayed (a) and plasma sprayed (b) Al$_2$O$_3$–TiO$_2$ coatings.

Comparative properties of the obtained coatings are shown in table 1. The values of the porosity of the coatings were 3.2 and 5.1 % for the samples of the first and second series, respectively. A possible reason for the lower porosity of flame sprayed coatings can be the use of a flexible cord, which provides efficient heating of the sprayed material than the use of a mixture of powders in plasma spraying.

| Method of spraying | P, % | HRB | $H_p$, GPa | $W_p$, % | $\mu_{\text{max}}$ | $I$, mm$^2$·N$^{-1}$·m$^{-1}$ |
|-------------------|------|-----|------------|----------|-----------------|--------------------------|
| Flame             | 3.2  | 108.6 | 9.9±1.4 | 8.0±0.5 | 53 0.7 | 20.8·10$^{-5}$ |
| Plasma            | 5.1  | 101.1 | 10.1±1.1 | 7.9±0.7 | 43 0.7 | 44.2·10$^{-5}$ |

P – porosity; HRB – Rockwell hardness; $H_p$ - microhardness of structural components; $W_p$ – relative work of plastic deformation; $\mu$ – coefficient of friction; $I$- wear rate
Investigation of the resistance to abrasive wear was carried out for both coating series. Simulation of the movement of a solid abrasive particle over the surface of the coating with an increasing load was carried out by Revetest scratch tester (CSM Instruments, Switzerland). The results for flame and plasma sprayed coatings were the same. The typical dependence of the measured values of acoustic emission (AE), friction force ($F_f$), coefficient of friction ($\mu$), and the appearance of a scratch are shown in figure 3. From the AE signal in figure 3a, the process of scratch formation on the coating surface from the beginning occurs by the brittle fracture mechanism. In this case, the AE intensity does not change during the entire experiment.

Figure 2. X-ray diffraction patterns of the flame sprayed (a) and plasma sprayed (b) $\text{Al}_2\text{O}_3$–$\text{TiO}_2$ coatings.

The appearance of the substrate material on the bottom of the scratch was not observed till load 90 N, which indicates the absence of the adhesion fracture mode of coating and strong bond between coating and substrate. Smoothly increasing values of $F_f$ and $\mu$ depending on the load on the indenter (figure 3a) indicates the presence of a focal cohesive fracture. With increasing load, the size of the separating fragments of the coating material increases (figure 3b).

Figure 3. Typical dependences of the friction force ($F_f$), friction coefficient ($\mu$) and acoustic emission (AE) (a) and images of a scratch on the surface of $\text{Al}_2\text{O}_3$–$\text{TiO}_2$ thermal coatings (b) at different loads on the indenter.

The results of tribological tests of sprayed coatings are shown in Figure 4. From the data obtained, the friction coefficient of the flame sprayed coating at the start of wear does not exceed 0.2, and then there
jump and the amplitude of its oscillations is increased (figure 4a). This may be due to the accumulation of fatigue cracks in the coating during the test and the onset of the fracture process with the formation of relatively large fragments of the coating, which subsequently participate in wear as an abrasive. The wear rate of the coating material was $20.8 \times 10^{-5}$ mm$^3$·N$^{-1}$·m$^{-1}$. It follows from the profile of the wear track that the substrate was saved during the test. The depth of wear was ~ 86 µm, which is much less than the coating thickness (~ 450 µm).

The friction coefficient for plasma sprayed coatings has a value of ~ 0.7 immediately from the beginning of the test (figure 4b), the wear rate is $44.2 \times 10^{-5}$ mm$^3$·N$^{-1}$·m$^{-1}$. This is in twice the wear rate of flame sprayed coatings, which is associated with their higher porosity and, accordingly, lower cohesive strength. For samples of the 2nd series, the depth of wear was ~ 140 µm.

The bond strength of flame and plasma sprayed Al$_2$O$_3$ – TiO$_2$ coatings with the substrate is ~ 26 MPa. Failure during test occurred along with the coating-substrate interface and was adhesive.

![Figure 4](image)

**Figure 4.** Dependence of the friction coefficient on the number of revolutions of the counterbody for flame (a) and plasma (b) sprayed Al$_2$O$_3$ – TiO$_2$ coatings.

4. Conclusion

To sum up, the use of flame spraying by a flexible cord of the Al$_2$O$_3$ – TiO$_2$ system makes it possible to obtain a higher value of density and wear resistance than for plasma sprayed coatings with keeping the same values of other functional properties. Wherein, energy consumption for coatings formation by flame spraying method is lower than for plasma spraying.

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