Investigating Tribological Characteristics of HVOF Sprayed AISI 316 Stainless Steel Coating by Pulsed Plasma Nitriding

Mindivan H
Bilecik Seyh Edebiyi University, Department of Mechanical Engineering, 11210, Bilecik, Turkey
harun.mindivan@bilecik.edu.tr

Abstract: In this study, surface modification of aluminum alloy using High-Velocity Oxygen Fuel (HVOF) thermal spray and pulsed plasma nitriding processes was investigated. AISI 316 stainless steel coating on 1050 aluminum alloy substrate by HVOF process was pulsed plasma nitrided at 793 K under 0.00025 MPa pressure for 43200 s in a gas mixture of 75 % N₂ and 25 % H₂. The results showed that the pulse plasma nitriding process produced a surface layer with CrN, iron nitrides (Fe₃N, Fe₄N) and expanded austenite (γₐ). The pulsed plasma nitrided HVOF-sprayed coating showed higher surface hardness, lower wear rate and coefficient of friction than the untreated HVOF-sprayed one.

Keywords: Duplex surface treatment, HVOF process, pulsed plasma nitriding, stainless steel coating, wear.

1. Introduction

Aluminum alloys have numerous industrial applications due to their attractive properties such as light weight, high specific strength and favorable mechanical formability. Unfortunately, hardness and tribological properties of pure and unprotected aluminum with high pitting corrosion tendency are poor comparing with cast iron and steel [1, 2]. The surface modification of aluminum can be classified into three categories: (1) coating with hard materials [3]; (2) forming alloyed or composite layers [4-6]; (3) hardening with ion or gas nitriding [7]. Until now, electrodeposition or electroless codeposition [8], reactive spraying [5], and nitriding [9] have been used as the process, although some of these techniques cause difficulties in matching aluminum substrates.

Duplex surface treatment can improve the anti-wear property of aluminum alloy against severe environmental uses by application of thermally sprayed steel coating plus pulsed plasma nitriding. An effective coating system combined a diffusion process and a coating has been recently developed in an attempt to further improve the tribological and tribocorrosion performances [10]. It is well known that since the thin oxide layer forming the deposition process is hard and brittle, the abrasive particles are occurred during wear and wear rate increases. Therefore, it might be required to apply a diffusion process on thermal sprayed surfaces for improving the wear resistance properties of the resulting coating due to its porosity, oxide content and lamellar boundaries in the weakest link in most thermally sprayed coating itself or along the interface, which would lead to cracking and delamination.

In the present research, a duplex coating can be divided into two steps, namely depositing AISI 316 stainless steel coating on 1050 aluminum alloy substrate by High-Velocity Oxygen Fuel (HVOF) thermal spray process, and pulsed plasma nitriding of HVOF-sprayed AISI 316 stainless steel coating.
in a mixture atmosphere made of nitrogen and hydrogen. The microstructure and wear property of duplex coatings were also investigated

2. Experimental Procedure

1050 aluminum alloy plates were cut to the dimensions of 20 mm×20 mm×4 mm. Initially, the aluminum plates were coated with an intermediary Ni-Al layer that increases the adhesion of coating. The duplex coating was prepared on 1050 aluminum alloy substrate with two procedures (deposition/nitriding). AISI 316 stainless steel coatings were applied by HVOF thermal spray process on the aluminum plates. Before pulsed plasma nitriding, the surfaces of the HVOF-sprayed AISI 316 stainless steel coating were ground using 1200 grit SiC paper and mechanically polished with a fine grade Al\textsubscript{2}O\textsubscript{3} paste to achieve a certain surface uniformity. Finally, the surfaces were ultrasonically cleaned in an acetone bath for 10 min. The coatings were then pulsed plasma nitrided at 793 K under 0.00025 MPa pressure for 43200 s in an industrial furnace (Er-Mir Textile and Machine Ltd) in a gas mixture of 75 % N\textsubscript{2} and 25 % H\textsubscript{2}. The coatings were cross sectioned and ground with successive SiC papers (grit 320–1200) and polished mechanically for metallographic examinations.

Microstructural characterization of the treated and untreated HVOF-sprayed AISI 316 stainless steel coatings was made by microscopic examinations, X-ray diffraction (XRD) and microhardness measurements. Microscopic examinations were performed on the cross-sections of the coatings by utilizing Nikon Eclipse LV150 Light Optical Microscope (LOM). XRD analysis was carried out by utilizing CuK\textalpha radiation with a Panalytical Empyrean diffractometer in order to identify the phase structures present in the surface layers. The cross-sectional microhardness measurements were carried out using a Knoop microhardness tester with at the indentation load 10 g for 15 s.

Dry sliding wear tests of the coatings were performed on a reciprocating wear tester operating in ball-on-disc configuration. In this configuration, wear tests were carried out for testing distance of 50 m by rubbing an Al\textsubscript{2}O\textsubscript{3} ball with a diameter of 10 mm to the untreated and treated surfaces under normal loads of 5 N and 10 N, respectively. The stroke and the sliding speed of the ball were 10 mm and 1.7 cm s\textsuperscript{-1}, respectively. During the wear tests, the temperature and the relative humidity were maintained as 25 ± 1 °C and 30 ± 1 %, respectively. The coefficient of friction (COF) was recorded automatically by the sensing cell mounted in the tester. Width and depth of the wear tracks were measured by a surface profilometer (Mitutoyo Surftest SJ-400) to calculate wear rate of the coatings. Following the wear tests, wear tracks were examined using Zeiss Supra Field Emission Gun Scanning Electron microscope (FEG-SEM).

3. Results & Discussion

Figure 1 gives the low and high magnification cross-sectional LOM micrographs of AISI 316 stainless steel coated 1050 aluminum alloy before and after pulsed plasma nitriding. The HVOF-sprayed AISI 316 stainless steel coating had a dense microstructure but oxide inclusions between the particle interfaces can be clearly observed. It should be noted that black spots in the micrographs represent the porosity while dark grey regions represent the oxidation. Pulsed plasma nitriding produced a layer with a thickness of about 10 μm on the surface of the HVOF-sprayed AISI 316 stainless steel coating. The cross-section morphology of pulsed plasma nitrided HVOF-sprayed AISI 316 stainless steel coating consisted of an outer compound zone and an inner diffusion zone. Generally, the compound zone contains nitrides formed from nitride-forming elements in the material.
Figure 1. (a) Low and (b) high magnification cross-sectional LOM micrographs of the pulsed plasma nitrided HVOF-sprayed AISI 316 stainless steel coating.

The XRD examinations shown in Figure 2 demonstrate the transformation of the phases present in the treated and untreated HVOF-sprayed AISI 316 stainless steel coatings. The results show that the dominant phases in the surface layer of the untreated HVOF-sprayed coating were $\alpha$-Fe, $\gamma$-Fe and $\text{Fe}_3\text{O}_4\cdot\text{CrO}$. However, the pulsed plasma nitriding treatment induced new phases corresponding to $\gamma_N$, CrN, Fe$_3$N, and Fe$_4$N peaks.

Figure 2. XRD patterns of the untreated and treated HVOF-sprayed AISI 316 stainless steel coatings.

Figure 3 shows the cross-sectional microhardness values of the untreated and treated HVOF-sprayed AISI 316 stainless steel coating layers. It is clearly observed that the surface microhardness of the coating subjected to pulsed plasma nitriding was above 1250 HK$_{0.01}$, three times greater than that of the coating produced without nitriding (430 HK$_{0.01}$). Microhardness values of the untreated HVOF-sprayed coating strongly depend on porosity, oxidized, unmelted and semimelted particles, and inclusions. Pulsed plasma nitrided coating maintained a high microhardness above 1250 HK$_{0.01}$ from the surface to a depth of $\sim$10 $\mu$m due to the presence of the CrN, Fe$_3$N, and Fe$_4$N hard phases in the compound layer. Moreover, the microhardness of the pulsed plasma nitrided HVOF spray coating decreased depending on the depth from the surface. The decrease of the microhardness on the case depth profile of the pulsed plasma nitrided coating can be attributed to the reduction of the solubility of nitrogen in the diffusion zone [11].
Figure 3. Cross-sectional microhardness variation of the coatings.

The friction coefficients vs sliding distance curves of the treated and untreated HVOF-sprayed coatings are shown in Figure 4. The stable friction coefficients of the tested coatings were found to be similar (1.06 for the untreated one, 0.97 for the nitrided one). However, the sliding curves of the untreated HVOF-sprayed coating exhibited larger fluctuation than the treated one. This large fluctuation in the sliding curves resulted from the lower surface hardness of the untreated one.

Figure 4. Friction curves of treated and untreated HVOF-sprayed coatings.

2D profiles of the wear tracks developed on the treated and untreated HVOF-sprayed coating surfaces by Al₂O₃ ball are presented in Figure 5. On the treated HVOF-sprayed coating surface, very small or no wear tracks has been formed when compared to untreated HVOF-sprayed coating surface. The wear rates of the untreated and treated HVOF-sprayed coatings were calculated as $9.35 \times 10^{-4}$ mm³/Nm and $0.5 \times 10^{-4}$ mm³/Nm, respectively. When compared to the untreated HVOF-sprayed coating, the wear rate of the treated HVOF-sprayed coating is almost negligible.
Figure 5. Wear track profiles of the (a) untreated and (b) treated HVOF-sprayed coatings.

Figure 6 presents low and high magnification SEM micrographs of the worn surfaces of the untreated and treated HVOF-sprayed coatings. It can be seen from the micrographs that, on the untreated surfaces wear progressed by extensive shear deformation due to the ploughing action of the ball under the test load of 5 N. On the worn surfaces of treated coating, there is no indication of nitrided layer failure; it still has capability to support the test load of 10 N by remaining largely intact. When compared to the untreated surface, it is possible to see the change in wear mode from the heavy ploughing to the combination of limited ploughing and polishing.

Figure 6. Low and high magnification SEM micrographs of wear tracks generated on the (a) untreated, (b) treated HVOF-sprayed coatings.

Figure 7 shows the morphologies of the wear scars of Al₂O₃ balls mating with the untreated and treated HVOF-sprayed coatings at applied loads of 5 N and 10 N, respectively. It was clearly to see that the contact surface of Al₂O₃ ball sliding against the untreated HVOF-sprayed coating was rough and appeared as dark region within the wear scar, while the wear scar surface of Al₂O₃ ball sliding against the treated HVOF-sprayed coating exhibited very smooth, light and flat. The reduced incidence of delamination phenomena in the treated HVOF-sprayed coating might also be explained by a somewhat lower tendency to adhere to the Al₂O₃ counterpart, witnessed by the lower friction coefficient with minor fluctuation (Figure 4).
Figure 7. Morphology of the worn scars of Al₂O₃ balls mating with the (a) untreated and (b) treated HVOF-sprayed coatings at applied loads of 5 N and 10 N, respectively

4. Conclusions

Pulsed plasma nitriding process was performed on HVOF-sprayed AISI 316 stainless steel coating. The coatings were characterized by microstructure analysis, microhardness measurements and干 sliding wear tests, and the most relevant conclusions can be summarized as follows:

(1) A novel duplex coating was fabricated on the surface of 1050 aluminum alloy by pulsed plasma nitriding.

(2) Pulsed plasma nitriding formed a surface layer with a thickness of about 10 μm. This layer is composed of CrN, iron nitrides (Fe₃N, Fe₄N) and expanded austenite ($\gamma_N$) phases and exhibits extremely high hardness (more than 1250 HK₀.₀₁) compared to the untreated HVOF-sprayed coating (430HK₀.₀₁).

(3) The wear rate of the treated HVOF-sprayed AISI 316 stainless steel coating decreased remarkably compared with that of the untreated one.

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