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Characterization and mechanical properties of the duplex coatings produced on steel by electro-spark deposition and micro-arc oxidation

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ABSTRACT

In this study, the ESD (electro-spark deposition) and the MAO (micro-arc oxidation) processes were used to improve the mechanical properties and the tribological performance of steel. This study has focused on forming a duplex surface coating on the steel. The ESD method was carried out a titanium alloy (Ti6Al4V) deposit layer on the steel substrates at the first step, and then the MAO process was employed to improve properties of the titanium alloyed layer at the second step. Phase structure, surface morphology, elemental composition, hardness, adhesion strength and tribological property of the ESD and the ESD + MAO coating (the duplex coating) were analyzed by X-ray diffraction (XRD), scanning electron microscope (SEM), energy dispersive spectroscopy (EDX), micro Vickers tester, micro scratch tester and tribometer, respectively. The XRD results indicated that the duplex coating consists of α-Al_2O_3 (corundum) and γ-Al_2O_3 phases while $AlFe_3$, TiN and $AlTi_3$ phases were detected in the ESD coating. The hardness of the duplex coating was significantly improved compared to the uncoated steel and the ESD coating. The adhesion strength of the duplex coating was greater than the ESD coating due to the existence of high hardness and high thickness. In addition, the tribological properties of the ESD and the duplex coatings were significantly improved with compared to the uncoated steel.

1. Introduction

Titanium and its alloys have high strength to weight ratio, great corrosion resistance, excellent mechanical properties and biocompatibility [1–3]. Thus, titanium and its alloys have been used in aerospace, marine, chemical, petrochemical, sports and biomedicine industries because of their outstanding properties [4,5]. However, titanium and its alloys limit to their various applications such as engineering components because they exhibit poor tribological properties such as high and unstable friction coefficients, strong tendency to adhesion, low fretting wear resistance and poor corrosion resistance in some aggressive corrosive environment such as hot chloride solutions [6]. These properties were improved by using some surface engineering methods such as ion implantation [7], thermal oxidation [8], chemical or physical vapor deposition (CVD, PVD) [9,10], magnetron sputtering techniques [11] or the duplex surface treatments [12]. However, these methods are very expensive and difficult to produce complex shaped component. The high cost of titanium and its alloys is another restriction for their use of those applications compared to aluminum and steel alloys which are low cost materials.

The micro-arc oxidation (MAO), also known as plasma electrolytic oxidation (PEO), combines the high voltage spark and electrochemical oxidation. This is a relatively convenient and effective technique to deposit various functional ceramic coatings with porous structures on the surfaces of Ti, Al, Mg and their alloys [13–15]. The MAO coatings on titanium and its alloys provide high hardness, excellent wear resistance and excellent corrosion resistance in terms of high manufacturability and economic efficiency [16–19]. In addition, the MAO forms an oxide film that strongly adheres to a metal substrate with complex geometries [20].

In this study, a duplex coating on St35 steel was produced by using electro-spark deposition (ESD) and micro-arc oxidation (MAO) methods. The ESD method was carried out in order to deposit a titanium alloy (Ti6Al4V) layer on the steel (St35) substrates at the first step. And then, Al_2O_3 based on a duplex layer was formed to improve mechanical and tribological properties of the titanium alloyed layer on the ESD surface by MAO process at the second step. The mechanical and tribological properties of the ESD and the duplex coatings were investigated in detail.

2. Experimental details

2.1. Materials and methods

The Ti6Al4V alloy, which was selected as an electrode, is deposited on a steel (St35) substrate in the ESD process experiments. Tables 1

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Table 1
Chemical composition of St 35 steel substrate (wt. %).

C	Si	Mn	Cr	Ni	Mo	Cu	Co	Fe
0.14	0.28	0.81	0.25	0.17	0.02	0.03	0.01	Balance

Table 2
Chemical composition of Ti6Al4V alloy (wt. %).

Al	V	Fe	Si	C	N	H	O	Ti
5.5	4.5	0.3	0.15	0.10	0.05	0.015	0.15	Balance

and 2 show the chemical compositions of St35 steel and Ti6Al4V alloys, respectively. The electrode has a cross-section of 3 × 5 mm^2 and the steel substrate samples are in the form of rectangular plates with the dimensions of 3 mm × 20 mm × 25 mm. After the ESD process, some of these samples were used for MAO process.

In this study, a special electro spark deposition (ESD) machine was operated at the first step. Power consumption was 180 W and the output of stabilized voltage was kept constant at 40 V. The ESD coating system was described in detail in our previous studies [21,22]. The ESD process was performed using a hand-held applicator in unipolar mode under constant temperature as seen in Fig. 1. In the system, the voltage dropped at the inter electrode gap (17 V) and the amount of electricity (3 C) was kept constant. The ESD process was conducted in air with a series of rectangular pulses of duration time of 100 μs, and the amplitudes of current 100 A. The frequencies of pulses were estimated as 100 Hz by considering the requirement of maintaining the constant electricity (3 C) of process.

The MAO with the application of bipolar impulses was used for the fabrication of oxide layer on titanium coated steel samples at the second step. Electrolyte solution was prepared by mixing 1.65 g/L Na_3PO_4, 8 g/L $NaAlO_2$ in distilled water. The MAO process was carried out by transforming metal oxidation on the surfaces of steel samples which were coated Ti6Al4V alloy by using ESD technique. In the experiments of MAO process (Fig. 2), cathodic and anodic voltage were applied as U_c = 160 V and U_a = 550 V, respectively and the electrical energy of flux which was chosen in respect to the area of sample surfaces was 1.8 μF/cm^2. The treatment time was 30 min, since the rate of the coating growth was about 0.6–0.7 μm/min.

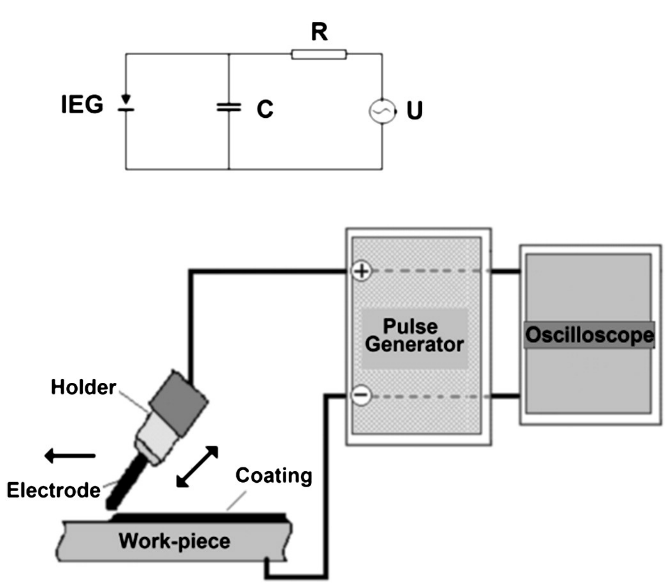

Fig. 1. Schematic representation of electro-spark deposition (ESD) coating system set up.

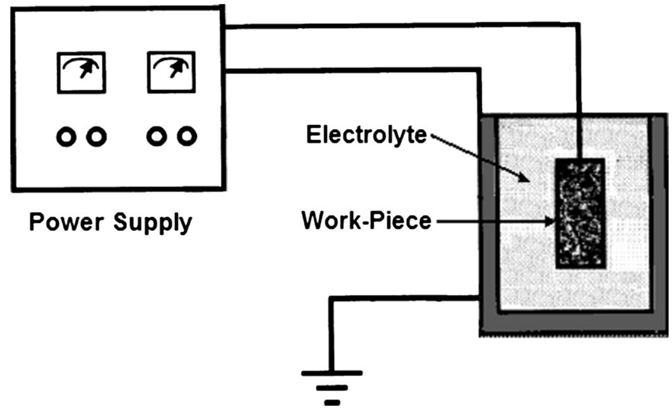

Fig. 2. Schematic representation of micro-arc oxidation (MAO) coating system set up.

2.2. Characterization of the coatings

The thickness of the ESD and the duplex coatings was measured by using an eddy current method (Fischer Dualscope MP40) at 50 randomly selected locations. The surface roughness measurements were conducted by using a profilometer (SJ-400 Mitutoyo) with a precision of 0.01 μm after the ESD and the MAO processes. The average roughness values (Ra) of five measurements were reported for all surfaces of the samples. Investigation of the surface morphology and its quality (porosity, fracture, etc.) on the ESD and the duplex coatings conducted samples was performed using a scanning electron microscope (SEM, Philips XL 30 SFEG). In addition, the EDX spectrum analyses were performed using the embedded EDX digital controller and software attached to the SEM. The phase composition of steel, Ti6Al4V, the ESD and the ESD + MAO layers were investigated by using XRD (Bruker D8

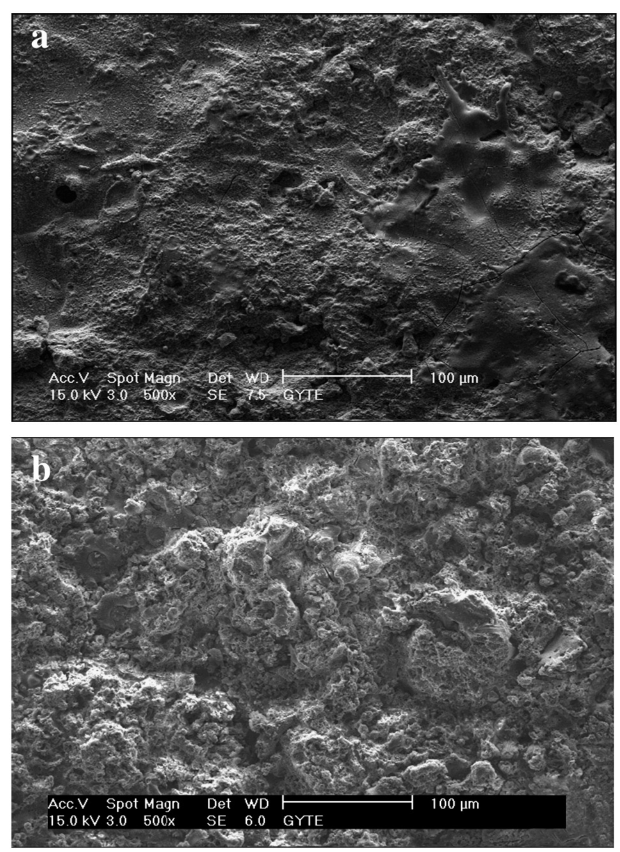

Fig. 3. The surface morphologies of the coating surfaces: (a) the ESD technique and (b) the MAO process.