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Feasibility study on preparation of coatings on Ti–6Al–4V by combined ultrasonic impact treatment and electrospark deposition

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ABSTRACT

A novel method combining ultrasonic impact treatment (UIT) with electrospark deposition was developed to prepare coatings on Ti–6Al–4V substrates. The microstructure, phase composition, residual stress, microhardness, and wear performance of the coating were studied, and new amorphous and nanocrystalline phases (titanium carbide nitride and iron titanium oxide) were found. In addition, the residual stress in the coating and in the substrate near the coating is compressive stress. The maximum compressive residual stress is about −717 MPa, and its depth is about 470 μm. Because of contributions from multiple factors, the wear volume loss of the sample subjected to combined UIT and electrospark processing was reduced by four orders of magnitude compared with that of the base material.

1. Introduction

Titanium and its alloys are widely used in aviation and space technology because of their excellent mechanical properties (high strength and fatigue resistance) and chemical stability (corrosion resistance). However, titanium alloys have poor tribological properties, which reduce their scope of possible usage [1]. To enhance the wear resistance of the material, many surface modification methods have been developed, such as mechanical milling [2], powder sintering [3], electrospark deposition [4], physical vapor deposition [5], plasma immersion ion implantation [6], laser cladding [7], and micro-arc discharge oxidation [8].

Ultrasonic impact treatment (UIT) [9] was originally developed as a method to relax residual welding stress, reduce the stress concentration coefficient of the weld toe, and form compressive residual stress to improve the fatigue performance of the welded structure [10–13]. In recent years, UIT and its variants have been used for surface self-nanocrystallization modification of materials [14]. However, because UIT is a surface mechanical treatment that does not alter the elemental composition, the application range of UIT surface modification is significantly limited. Compared to UIT, electrospark deposition can easily transfer electrodes or other elements to the target [15,16]. However, it creates a molten pool during conventional deposition, and the tensile residual stress in the coating due to the solidification of the molten pool can have large potential negative effects on the wear, fatigue, and stress corrosion performance [17].

This short communication explores the feasibility of the preparation of coatings by combined UIT and electrospark deposition. The microstructure, microhardness, residual stress, and wear performance of the coating are investigated in detail.

2. Experiment and principle

A self-developed machine for combined UIT and electrospark deposition was used to prepare the coatings. A typical photograph of the combined UIT and electrospark processing is shown in Fig. 1a. The principle of the combined processing equipment can be described as follows (Fig. 1b). The ultrasonic transducer converts electrical energy from the ultrasonic generator into ultrasonic vibration with a frequency of 20 kHz. Under a static pressure, the shock ball vibrates rapidly between the ultrasonic transducer and the target surface. The shock ball was made of steel (GCr15) and had a diameter of 15 mm. Its chemical composition (in wt.%) is 0.98% C, 1.51% Cr, 0.15% Si, 0.36% Mn and balance Fe. To combine the electrospark process with UIT, the target and shock ball were connected to the anode and cathode, respectively, of a DC power during the UIT.

The principle of the combined process is shown in Fig. 1c. When the shock ball touches the target (impact process), there is a short in the circuit. During the impact process, various changes occur in target surface, such as plastic deformation and the introduction of compressive residual stress. Then, when the shock ball bounces off

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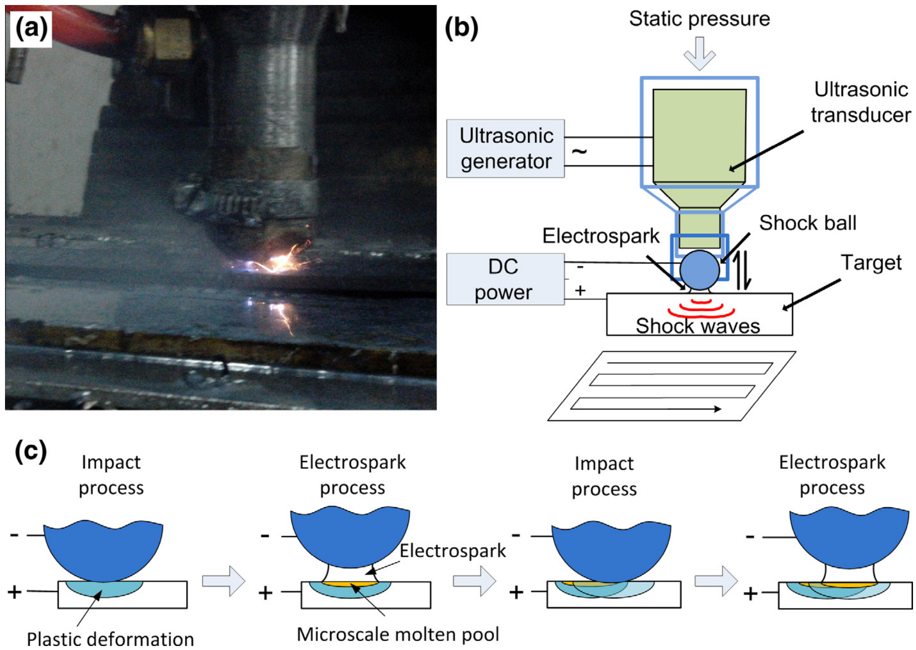

Fig. 1. (a) Typical photograph of the combined process, and (b) schematic diagram of the experiment, and (c) principle of the combined UIT and electrospark process.

the target, electrosparks form between them (electrospark process). This process is equivalent to the contact arc ignition process in arc welding. A microscale molten pool is formed on the surface of target because of the electrospark heating, while the cooling liquid and air in the electrospark area are ionized. Thus, there are many elements from the substrate, electrode, cooling liquid, and air in the microscale molten pool. During the subsequent impact process, the electrospark is extinguished. The surrounding cooling liquid causes rapid solidification of the microscale molten pool. Meanwhile, the target is again subjected to UIT. Then, the shock ball bounces off the target, and the electrospark appears again. The impact process and electrospark process continue in cycles, which constitute the combined process.

A Ti–6Al–4V substrate with the thickness of 3 mm was cut into a rectangle with dimensions of 60 mm × 30 mm and ground using SiC abrasive paper to a 600 grit finish for combined UIT and electrospark processing. Its chemical composition (in wt.%) is 90.31% Ti, 6.13% Al and 3.56% V. The details of the parameters in the combined process are listed in Table 1. The cooling liquid was the cutting fluid for electrical discharge machining.

The cross-sectional microstructure of the coating was observed by scanning electron microscopy (SEM) after metallographic polishing and etching with Kroll's reagent (2 vol% HF and 10 vol% HNO_3 in H_2O). The high-resolution images of the microstructure were obtained by transmission electron microscopy (TEM). The samples for TEM were scraped from the coatings. The phase compositions in the coatings were studied by X-ray diffraction (XRD). The residual stresses at the surface and subsurface of the coatings were determined by applying standard XRD techniques using shifts of XRD peaks with the $\sin^2 \psi$ method. Lattice strain measurements were carried out using Cu/Kα radiation at the {114}-planes of the hexagonal α-phase. The depth profiles of subsurface residual stress were determined by successive electrolytic material removal. For the stress calculation, the Poisson's ratio and elastic modulus of the specimen were set to be 0.31 and 119 GPa, respectively. After polishing, the microhardness distribution of the coatings was measured by a digital microhardness tester (MHV-2000) under an applied load of 0.49 N for a load time of 15 s. The wear tests were carried out on a ring-on-block tester using 43.4 mm diameter GCr15 rings as counterparts. Unlubricated wear tests with a sliding distance of 436 m were carried out with a sliding speed of 0.45 m/s and normal loads of 50 N at room temperature. The widths of the wear scars, which were used to calculate the wear volume loss, were measured by optical microscope. Each test was carried out three times.

3. Results and discussion

Fig. 2 shows the typical cross-sectional microstructure and the titanium and iron distributions in the coatings. After it was treated by combined UIT and electrospark processing, the sample consisted of an outer coating, an inner plastic deformation region, and the substrate (see Fig. 2a). It is noted that the coating has a thickness of about 12 μm, is very compact without obvious cracks, and is bonded to the substrate tightly. The coating was formed by rapid solidification of the microscale molten pool, and the plastic deformation layer was formed by the impact process. Compared with the grains in the heat-affected zone between the coating and substrate formed during laser cladding [7], the grains in the region between the coating and substrate in the sample treated by combined UIT and electrospark processing did not grow. In contrast, they were obviously refined as a result of the severe plastic deformation during the impact process, which may improve the toughness of the bonding zone between the coating and substrate. The coating mainly consists of titanium and iron, as shown in

Table 1
Details of the parameters in the combined UIT and electrospark process.

Transducer amplitude (μm)	Static pressure (N)	Feeding velocity of UIT (mm/min)	Step distance of UIT (mm)	Current of electrospark (A)
20	100	185	0.3	15