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Plain and fretting fatigue behavior of Ti6Al4V alloy coated with TiAlN thin film

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ABSTRACT

In this study, plain and fretting fatigue behaviors of Ti6Al4V alloy coated with TiAlN thin film by using closed field unbalanced magnetron sputtering system (CFUBMS) were investigated. Coating process was carried out in two different power parameters as dc bias and pulse. It was observed that both plain and fretting fatigue resistance of Ti6Al4V alloy improved after TiAlN coating process. Pulsed films were more effective than biased films in terms of fatigue resistance. Also, fretting fatigue behavior of uncoated and coated specimens was examined with finite element analysis. The finite element analysis results were analogous with experimental test results.

1. Introduction

Metals and alloys are commonly used as implant materials in orthopedic surgery due to their superior mechanical properties. These metallic materials are stainless steels, titanium alloys and cobalt–chromium alloys [1]. Titanium and its alloys have been widely used as orthopedic and odontological implant materials due to their high strength-to-weight ratio, excellent corrosion resistance and biocompatibility [2]. However the applications of titanium and its alloys as used implant materials are limited because of their low surface hardness, poor wear and fretting fatigue resistance, possibility of losing biocompatibility [3]. For these reasons, titanium alloys need surface treatments.

One of the parameters that determines service life of implant materials used in the body is fretting fatigue mechanism. Fretting is a surface damage that occurs when contacting surfaces between mating bodies experience an oscillatory motion of small amplitude. For instance, modular junction of hip joints or bone plate contact with screw head are the possible areas of fretting damage due to cyclic loads during body movements [4–8]. According to a recent survey, 74% of implant materials are damaged because of fretting fatigue [9]. Such statistics reveal the importance of the failure. Also, the wear products which are produced during the fretting interfere with the body fluids and they may cause long-term health problems, such as Alzheimer disease, neuropathy and ostemomalacia [3]. In order to improve the surface characteristics of implant materials, different surface modification techniques, such as the plasma assisted thermochemical treatment, ion implantation, spray coating and biocompatible thin film deposition have been performed [10,11].

In recent years, transition metal nitrides like TiN, ZrN, TiAlN, NbN, TaN and VN were successfully used as protective coatings against wear and corrosion in order to increase the life expectancy of surgical implants and prosthesis [12]. Among these coatings, TiAlN thin films were chosen due to high hardness, excellent oxidation, corrosion and wear resistance [13]. It was thought that TiAlN coatings would be resistive to wear and fretting failure in mating bodies due to their outstanding features. Fretting fatigue failure is crucial in hip and knee prosthesis, bone plates and dental implants. TiAlN coatings will be effective in preventing this damage. Although there are many studies related to wear and plain fatigue performance of TiAlN coatings [14–22], fretting fatigue behavior of TiAlN coatings have not been encountered in the scientific literature. Therefore, plain and fretting fatigue behavior of Ti6Al4V alloy coated with TiAlN thin film by using closed field unbalanced magnetron sputtering technique (CFUBMS) were investigated experimentally and theoretically in this study.

2. Experimental details

Ti6Al4V (Grade5) specimens with a substrate surface area of 200 mm^2 were cut from cylindrical bars. The specimens were ground by 220–1200 mesh emery-papers, and then polished with

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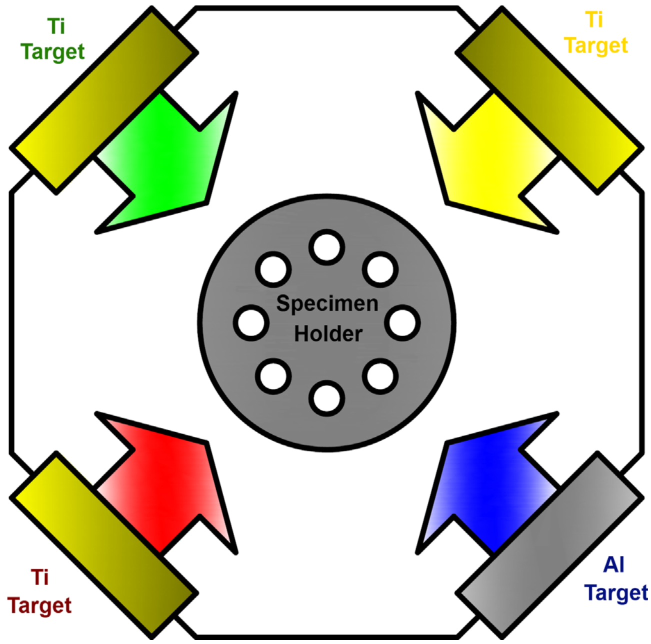

Fig. 1. The schematic illustration of the coating system.

Table 1
TiAlN deposition parameters.

	TiAlN deposition parameters					
	Pressure (Pa)	Bias voltage (V)	Current (A)		Frequency (kHz)	Duty time (μs)
			Ti	Al		
Bias-DC	0.4	70	5	1.5	–	–
Pulse-DC					125	1.5

alumina powder with a grain size of 1 μm. TiAlN thin films were deposited using CFUBMS system manufactured by Teer Coatings Ltd. The schematic illustration of the coating system was presented in Fig. 1. As seen in the figure, Ti and Al solid targets and N_2 gas were used to produce TiAlN thin film. Before TiAlN deposition, Ti interlayer was deposited at 6 A current for 250 V bias and for 0.4 Pa pressure for 5 min to improve adhesion between the film and the substrate. Then, TiAlN thin film was deposited on the substrates as both biased and pulsed-dc for which the deposition parameters are given in Table 1.

The surface hardness values were measured by using a Buehler Omnimet MHT1600-4980T instrument at loads of 10, 25, 50 and 100 g and a loading time of 15 s. XRD-Rigaku for phase analyses was operated at 30 kV and 30 mA with CuKα radiation. The cross-section images of both coating and fracture surfaces were also investigated using a scanning electron microscope (SEM) Jeol 6400. The surface roughnesses of coated specimens were measured by a profilometer Mitutuyo. The adhesion investigations were carried out using Revetest (CSEM) scratch tester. The critical load (L_{c1}) was measured with a 2 mm tip radius Rockwell-C diamond indenter and a sliding speed of 10 mm/min.

The fatigue tests of both untreated and TiAlN coated Ti6Al4V alloy were carried out using uniaxial fatigue test machine, Instron Fast Track 8872, at a frequency of 15 Hz and the loading type was fully reversed ($R=-1$). Fig. 2 shows the schematic drawing of the fretting fatigue test apparatus (a), test specimen (b) and contact pad (c). A pair of cylindrical contact pads (made of Ti6Al4V and diameter of 50.8 mm) was clamped on the gauge length of the fatigue specimen by means of two loading screws. Normal contact load between contact pads and specimens was monitored by a load cell. The maximum static contact pressure was calculated as 40 MPa. Twenty six specimens were used to draw the *S–N* curves of the plain and fretting fatigue for the coated and untreated specimens; i.e. 15 specimens for the fatigue life, (three specimens at each of five levels of stress amplitude) and 11 specimens for the finite fatigue life region. The staircase method was employed to determine fatigue strength. In each test, the number of cycles to the fatigue failure was noted on semi-log (*S*-log *N*) graphs.

3. Finite element analysis

Finite element (FE) analysis was carried out using ANSYS Workbench 11.0 [23]. Three-dimensional fretting fatigue model used in the analysis was shown in Fig. 3. This model was used in our earlier study and the model contained 30.396 elements for which a higher order 3-D Solid187 10 node quadratic tetrahedron was selected as element type [24]. For the contact zone, however, Conta174 and Targe170 elements were selected. A face-to-face surface algorithm with asymmetric pairs was adopted for contact detection. The augmented Lagrangian method was selected as the contact algorithm. The contact surfaces were meshed more densely than the other regions (Fig. 3). Non-proportional loading type was used for FE analysis. Loading is likely to be non-proportional in the neighborhood of the contact, even if the external loads are applied in a proportional fashion.

The substrate (core material) and coating layer were considered as a single part during the finite element analysis. If the coating layer and substrate were considered separately, the values of stress–number of cycles for the both model must be defined in the finite element software. Although it is possible to determine the plain fatigue life values of substrate experimentally, the plain fatigue life values of the coating layer as a material property cannot be determined. Therefore, the substrate and coating layer were considered as a whole. But in this case, elastic modulus and plain fatigue life values of the coated material must be determined in order to carry out the FE analysis. Guagliano and Vergani have proposed a simulation model to determine elastic modulus of the layered material by using two parallel springs [25]. Therefore in this study, the elastic modulus of the coated material was calculated adopting this approach for which the details are schematically given in Fig. 4 and following equations are used.

$$K_{Total} = K_{Layer} + K_{Substrate} \tag{1}$$

$$\frac{E_{Total}A_{Total}}{L} = \frac{E_{Layer}A_{Layer}}{L} + \frac{E_{Substrate}A_{Substrate}}{L} \tag{2}$$

$$E_{Total} = \frac{E_{Layer}A_{Layer} + E_{Substrate}A_{Substrate}}{A_{Total}} \tag{3}$$

In Eqs. (2) and (3), E_{Total} and A_{Total} are the elasticity modulus and cross-sectional area of the coated material, E_{Layer} and A_{Layer} are the elasticity modulus and cross-sectional area of the coating layer, $E_{Substrate}$ and $A_{Substrate}$ are elasticity modulus and cross-sectional area of substrate.

The mechanical properties of the uncoated Ti6Al4V alloy were determined using tensile testing, and the obtained results ($E=114$ GPa, $\upsilon=0.342$) were regarded as the material properties of both fatigue specimen and pads. In addition, experimental plain fatigue life values of Ti6Al4V alloy was entered to the finite element software. Friction coefficient between fatigue specimen and pads was considered as 0.75 [26].