Surface & Coatings Technology 215 (2013) 253–259

Contents lists available at SciVerse ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Surface morphology manipulation and wear property of bioceramic oxide coatings on titanium alloy

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ARTICLE INFO

Available online 5 November 2012

Keywords:
Titanium alloy
PEO
Porosity
Surface morphology
Impact-sliding instrument

ABSTRACT

Different thickness and surface porosity of TiO_2 coatings on Ti alloys as bio-implants appear to have a different behavioral combination of bioactivity, chemical stability and mechanical integrity. In order to study the wear properties of the coatings under extremely high loading conditions, for instance, sport impacting and crashing, a newly-developed impact-sliding testing instrument was used to simulate the impacting and sliding motions of the implants experienced with extreme contact stresses during the accidents. Traditional Pin-On-Disc (POD) tribotests were also carried out at 2 N and 5 N load conditions with maximum Hertz contact stresses of 471 and 639 MPa, respectively. The tests conducted in dry and simulated body fluid (SBF) environment were to figure out the coefficient of friction (COF) of the TiO_2 coatings and the effect of the SBF on COF. The research results showed that the smooth and uniform surface was beneficial in reduction in COF and also led to a better coating performance in both dry and wet wear tests even if the coating was slightly thinner. The uniform coating had a less degree of surface failure during 1000 cycles of the impact-sliding tests at 80 N/200 N (approximate 0.8–1.2 GPa contact stress) impact-sliding forces. The coating surfaces with larger pores or higher roughness would lead to a higher friction coefficient and earlier coating failures. The test results also showed that the TiO_2 coatings had a low COF of around 0.2, and the performances of thinner coatings were worse in SBF than in dry air, indicating that the SBF might have a corrosion-induced negative effect.

1. Introduction

Although more than 30 titanium-based alloys are commercially available today, the Ti–6Al–4V (Grade 5) alloy, which is mostly used in the aerospace, marine and biomedical industries, occupies 50% of the titanium market. It has excellent combination of strength-to-weight ratio, corrosion resistance, high melting temperature and biocompatibility. However, it usually has unfavorable tribological properties such as poor wear resistance. This limits their applications for highly stressed load-bearing and sliding systems [1]. Therefore, a number of surface modification or coating techniques have been developed for improving the alloy surface properties. For instance, surface oxidation, chemical vapor deposition (CVD)/physical vapor deposition (PVD) and ion implantation, have been well developed [2].

In the recent years, a Plasma Electrolytic Oxidation (PEO) process is considered as an environmentally friendly and cost effective surface treatment technique, which can produce an oxide coating on titanium metal surface and provide good wear and corrosion resistances. Different from the conventional anodizing process, the PEO process utilizes high voltage to initialize plasma discharge to produce oxide coatings in a dilute alkaline solution, which is free of chrome ions and acids. The coating consists of a porous outer layer, nano-structured dense layer and inner diffusion layer [2,3].

The surface of a PEO-coated titanium alloy has a large number of micropores, varying in dimensions from sub-micron to several micro scales [4–8]. The porous surface of TiO_2-coated titanium alloy has been widely studied for orthopedic and dental implant applications, and its porous structure can provide good biological fixation to the surrounding tissue due to bony ingrowth into the porous surface forming a mechanical interlock after implantation [4].

The phase, pore size, thickness and some mechanical properties of PEO-coated surface with different applied voltages were discussed in [4,9]. The effect of electrolytic concentration to the phase compositions, number of micropores, size of pores, porosities, roughness and corrosion resistance of the PEO-coated titanium alloy in Hank's SBF were studied in [10]. The coating properties have been studied using different testing methods including scratch test [11] and tribotests [12–15]. However, the coating damage behavior under extremely high loads, for instance, boxing and sport accidents causing abnormal impact and collision to the bio-implants, is rarely considered.

There are a number of research and development efforts that are to develop new biomedical titanium alloys to match better the mechanical properties of the bone. For instance, Ti–35Nb–7Zr–5Ta (TNZT) alloy has a much lower elastic modulus (55 GPa) than Ti6Al4V alloy, but it is still not close to the elastic modulus of the bone (7–25 GPa)

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0257-8972/$ – see front matter
http://dx.doi.org/10.1016/j.surfcoat.2012.07.093

Table 1
The specimen labels and PEO treatment conditions plus measured coating surface properties.

Sample label	PEO treatment conditions						Coating Surface Properties	
	T_{on} (μs)	T_{off} (μs)	Total treatment time (min)	I-density (A/cm^2)	Peak voltage (V)	Time to reach peak voltage (min)	Thickness (μm)	Roughness, R_a (μm)
ST1	400	100	10	0.08	400	1.72	3.8	0.55
ST2	400	100	10	0.04	400	3.73	3.1	0.795
ST3	400	100	12.5	0.02	400	12.5	6.86	1.175

yet. On the other hand, Ti alloys with a reduced elastic modulus often have a weak mechanical strength [14].

In this study, a commercially available Ti6Al4V was used as a model biomedical Ti alloy for the plasma electrolytic oxidation coating process in which unipolar-pulsed DC powers with different current densities were applied for the coating preparations. Traditional POD tribotests were also carried out at commonly-used load conditions. The tests conducted in dry and simulated body fluid (SBF) environments were to figure out the coefficient of friction (COF) of the TiO_2 coatings and the effect of the SBF on COF. A newly-developed

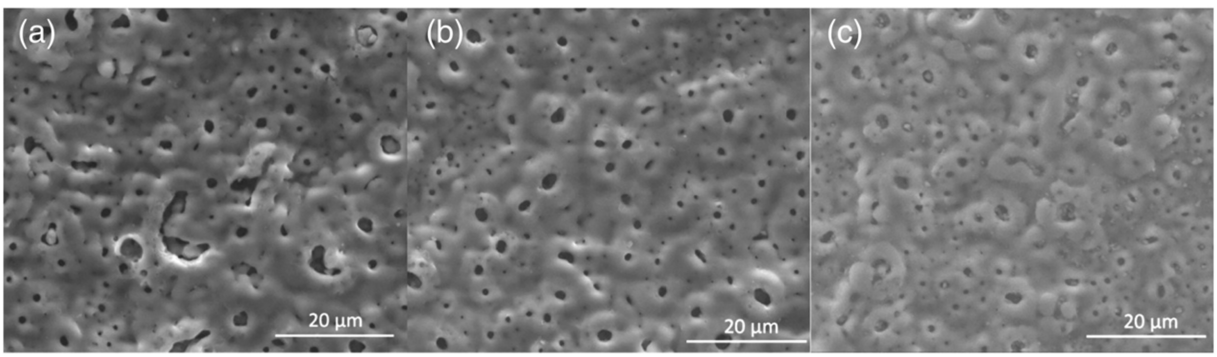

Fig. 1. Scanning electron micrographs of PEO-coated specimens: (a) ST1, (b) ST2 and (c) ST3.

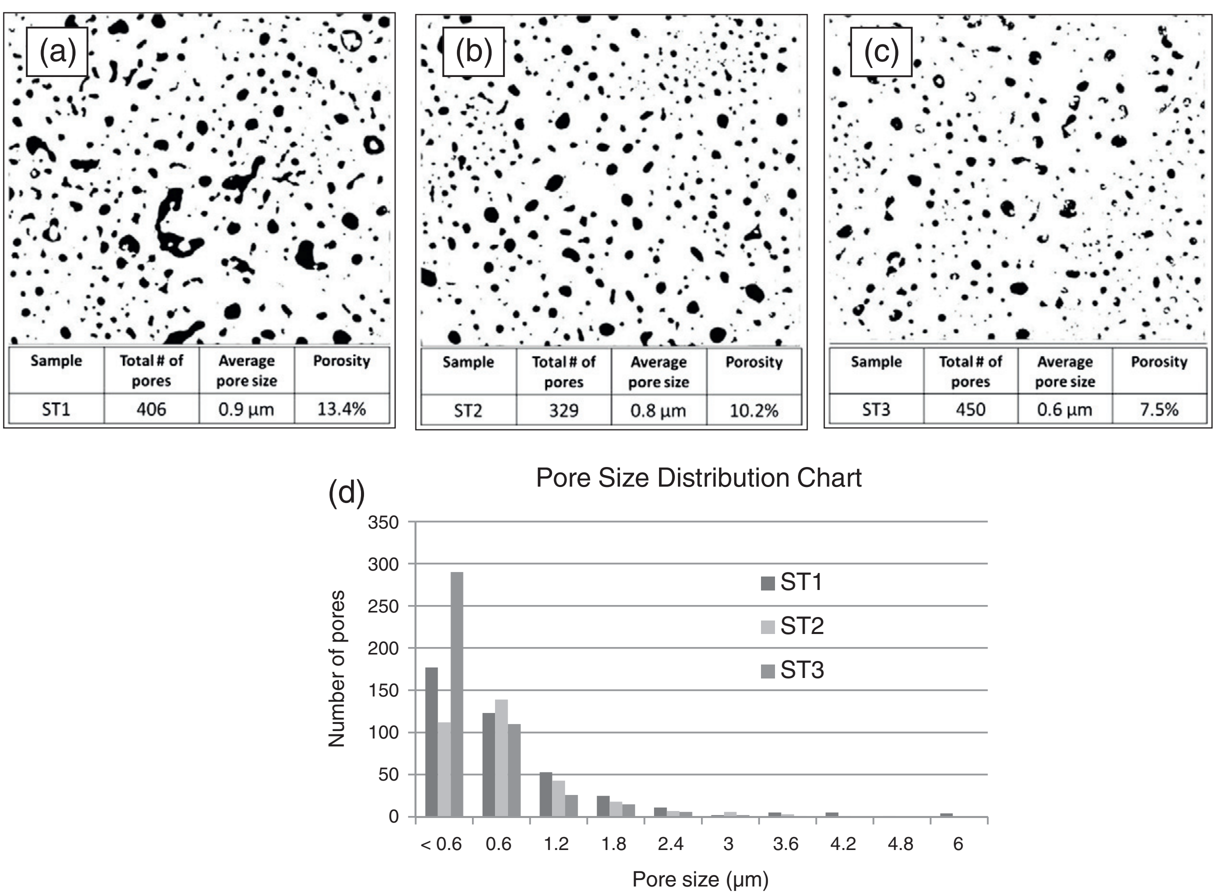

Fig. 2. Processed images with corresponding porosities: (a) ST1, (b) ST2 and (c) ST3, and (d) pore size distribution chart.