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Friction and wear properties of UHMWPE against ion implanted titanium alloy

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Abstract

In this study, a new two-step plasma immersion ion implantation technique was developed and applied for the modification of Ti6Al4V alloy; firstly ion implanting with nitrogen at high temperature and followed with oxygen in high dose. A graded titanium oxide–titanium nitride film was obtained on the surface of the Ti6Al4V alloy. The contact angle and the microhardness of the modified alloys were measured. The friction and wear properties of UHMWPE rubbing against the modified alloys under lubrication of distilled water were investigated using a pin-on-disc tribometer. The wettability and the microhardness of the alloy surfaces were found to be increased significantly after ion implantation. The friction coefficient decreased by nearly 5 times and the wear resistance of UHMWPE increased by about 40 times against the ion implanted Ti6Al4V alloy. Many deep furrows were found on the surface of the un-implanted alloy and were absent in the ion implanted surfaces of the alloy.

Keywords: Ti6Al4V alloy; UHMWPE; Ion implantation; Wear and friction; Artificial joint

1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) has several excellent properties, and has been used as a bearing material for total joint replacement for over forty years. As the service life of artificial joints prolongs, the aseptic loosening and the osteolysis induced by the polyethylene wear particles has become the main cause for the long-term clinical failure of these medical devices. Much effort has been made to enhance the life span of total joint replacements. These include modifying UHMWPE by gamma irradiation [1], ion implantation [2–4], selecting hard and smooth counterfaces [5], and fiber and particle reinforcement [6–8]. Ti6Al4V alloy has good mechanical and biocompatibility properties as well as high strength, high ductility and high fatigue strength. However, the wear resistance Ti6Al4V alloy is poor, thus it is generally not suitable for the femoral head. To enhance wear resistance, many studies have been carried out to modify the bearing surface of Ti6Al4V alloy, such as PVD diamond-like coatings (DLC), nitrogen ion implanted and thermal oxidation (TO)-treatment [9–15].

In this paper, a new two-step plasma immersion ion implantation technique was developed and used for the modification of Ti6Al4V alloy. The tribological behaviours of UHMWPE sliding against the modified alloy were investigated on a pin-on-disc test apparatus.

2. Experimental setup

UHMWPE pin specimens were shaped into 5 mm in diameter and 20 mm in length. The bearing surface of the UHMWPE pin was ground and polished to an average roughness $R_a = 0.08$ μm. The bar stock of Ti6Al4V alloy was machined into $\varnothing 45 \times 4$ mm^2 discs. The surface of the disc was ground using 600$^\#$ grit SiC paper, and polished on diamond paste to an average surface roughness value of 0.06 μm. The discs were firstly implanted with nitrogen ions at a high temperature of 600 °C and followed with oxygen ions at higher doses using a plasma immersion ion implanting (PIII) apparatus as detailed in Table 1. All pins and discs were washed with alcohol and dried before testing.

The structure of the modified alloys was characterized by X-ray diffraction (XRD). The cross-sectional element concentration distribution of the modified alloy was analyzed by EDS

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Table 1
Two-step of plasma immersion ion implant parameters and microhardness

Sample no.	Dose/cm^2		Temperature/°C		Energy/keV	Microhardness/Hv
	N_2	O_2	N_2	O_2		
0#	–	–	–	–	–	390
1#	5×10^{17}	1×10^{18}	600	100	30	580
2#	5×10^{17}	5×10^{18}	600	100	30	586
3#	5×10^{17}	1×10^{18}	600	300	30	589
4#	5×10^{17}	5×10^{18}	600	300	30	600

and the surface wettability was evaluated by a JY-82 contact angle apparatus. The surface microhardness of the modified alloys was determined by a HV-1000 microindentometer with a 25 g indentation load.

A pin-on-disc tribometer was used to evaluate the friction and wear properties of UHMWPE against the modified alloys under distilled water lubricated condition. In wear testing, the contact load was 39 N, giving a nominal contact pressure of 2 MPa, and the sliding speed was 0.12 m/s. The test duration for each specimen was 1440 min. The wear of UHMWPE pins was measured by weight loss using a microbalance, accurate to 0.01 mg.

3. Results and discussion

3.1. Effect of ion implantation on structure, composition and wettability

The surface microhardness of both treated and non-treated samples is shown in Table 1. The ion implanted parameters and X-ray diffraction (XRD) patterns for all specimens are shown in Fig. 1. It is clear that the Ti6Al4V specimens treated with the two-step ion implantation method revealed the presence of TiO, Ti_2O and Ti_2N in the subsurface. In the pattern obtained from sample no. 4, which was implanted with oxygen at the highest temperature and highest dose, the TiO and Ti_2O peaks are clearly visible, and relatively large. This suggests that a higher volume fraction of TiO and Ti_2O should exist in the subsurface region of the Ti6Al4V discs.

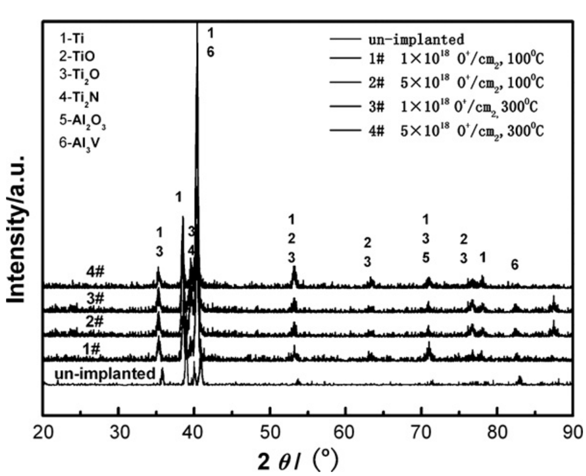

Fig. 1. XRD patterns of Ti6Al4V and ion implanted Ti6Al4V.

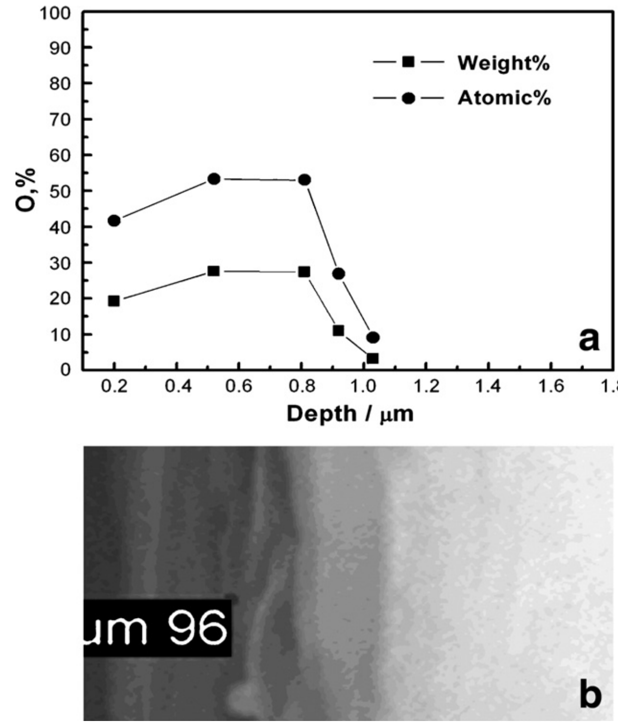

Fig. 2. (a) Cross-sectional oxygen concentration distribution of 4# sample and (b) the corresponding SEM image.

The cross-sectional oxygen concentration distribution of sample no. 4 and the corresponding SEM image are shown in Fig. 2. The concentration of oxygen increased with depth until 0.5 μm. And with the depth increased over 0.5 μm, there was a decreased oxygen concentration. At the depth of 1 μm, there were hardly any oxygen atoms. This suggests that about 1 μm thickness film of TiO–Ti_2O should be produced on the surface of the modified Ti6Al4V alloy. Because the peak of nitrogen energy spectrum coincides with that of titanium energy spectrum, nitrogen concentration distribution can not be determined.

The contact angles of Ti6Al4V and ion implanted Ti6Al4V are shown in Fig. 3. The contact angles of the two-step ion implanted Ti6Al4V alloys are clearly lower than those of the Ti6Al4V, and the decrease in the contact angle is about 15° in average. This implies that the wettability of ion implanted Ti6Al4V alloys is

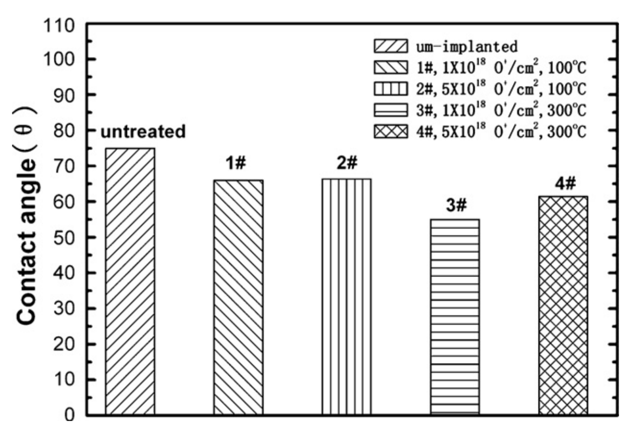

Fig. 3. Contact angle of Ti6Al4V and ion implanted Ti6Al4V.

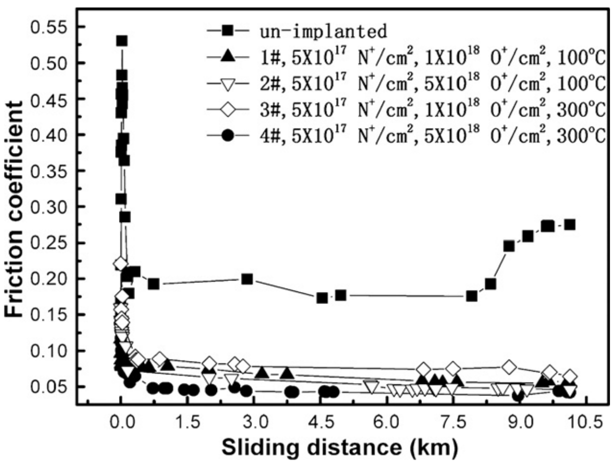

Fig. 4. Friction coefficients of UHMWPE sliding against Ti6Al4V and ion implanted Ti6Al4V.

greatly improved, and this can potentially affect the friction coefficients under water lubrication. With increased wettability of the surfaces, the retention of fluid-film or boundary lubricants in the articulating area would be improved.

3.2. Friction and wear

The variation of friction coefficients of UHMWPE sliding against Ti6Al4V and ion implanted Ti6Al4V counterfaces with sliding distance under distilled water lubrication is shown in Fig. 4. It can be seen that, the friction coefficients of all rubbing pairs were high at the initial stage, but rapidly decreased and stabilized with sliding distance. The friction coefficients of UHMWPE rubbing with the two-step ion implanted Ti6Al4V alloys are much lower than those of rubbing with the un-implanted specimens. The steady friction coefficient of UHMWPE rubbing with the un-implantedTi6Al4V is approximately 0.2, while rubbing with sample no. 4, which was implanted with oxygen at the highest temperature and highest dose, is reduced to approximately 0.04.

The bar charts in Fig. 5 present the wear factors of UHMWPE sliding against Ti6Al4V and ion implanted Ti6Al4V counterfaces. It is clear that the wear factors of UHMWPE sliding

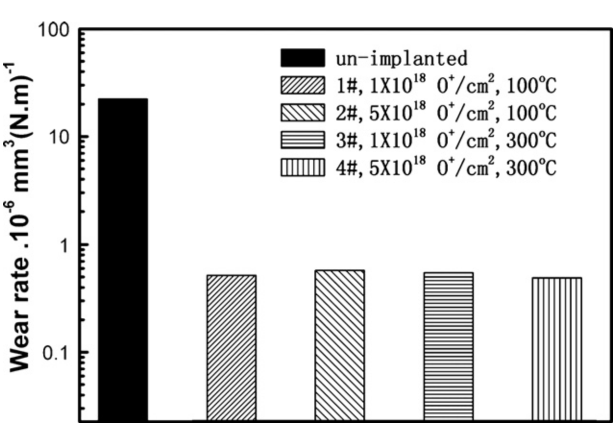

Fig. 5. Wear factors of UHMWPE sliding against Ti6Al4V and ion implanted Ti6Al4V.

against ion implanted Ti6Al4V are much lower than those against Ti6Al4V. The wear resistance of UHMWPE sliding against ion implanted Ti6Al4V increased about 40 times that of the un-implantedTi6Al4V alloy.

3.3. Surface analysis and discussion

Fig. 6 shows the worn surfaces of (a) un-implanted Ti6Al4V alloy and (b) UHMWPE counterface. The wear track on the un-implanted Ti6Al4V specimens was characterized by numerous grooves (Fig. 6a), an indication of severe abrasive wear. The surface of the corresponding UHMWPE specimen also underwent severe ploughing characterized by deep and wide grooves (Fig. 6b).

Fig. 7 shows the worn surfaces of (a) the two-step ion implanted Ti6Al4V alloy disc with high temperature N^+ and high dose O^+ (no. 4 sample) and (b) corresponding UHMWPE counterface. Almost no wear trace was visible on the modified alloy. Furthermore, the worn surface of the corresponding UHMWPE

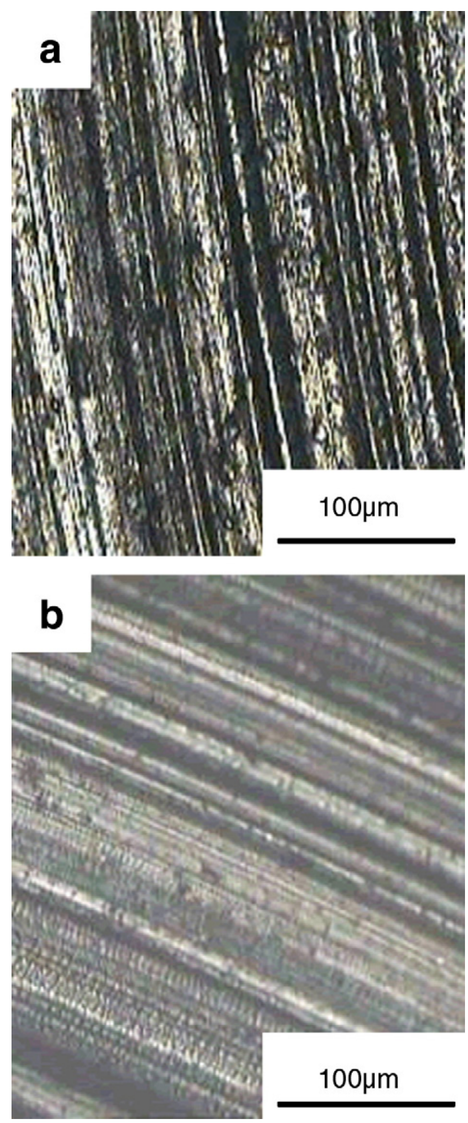

Fig. 6. Worn surfaces of (a) un-implantedTi6Al4V alloy and (b) UHMWPE counterface.

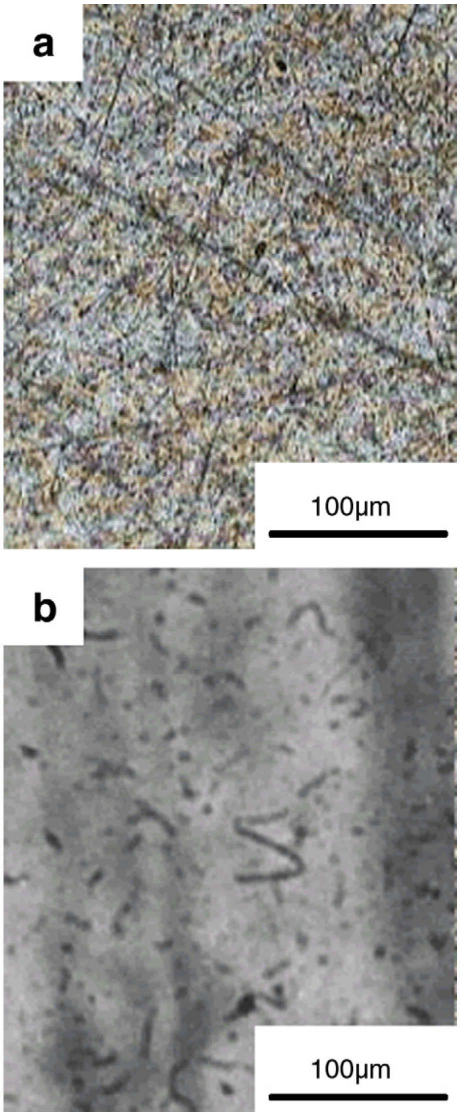

Fig. 7. Worn surfaces of (a) ion implanted Ti6Al4V alloy (sample no. 4) and (b) UHMWPE counterface.

counterface was burnished; the only notable feature being ‘polishing’ of the UHMWPE surface. This phenomenon was consistent with the low wear factors of UHMWPE as presented in Fig. 5.

From the above experimental results, after two steps of plasma immersion ion implantation, the TiO, Ti_2O and Ti_2N compounds formed on the subsurface of Ti6Al4V alloy (see Fig. 1). The formation of TiO, Ti_2O and Ti_2N compounds can be considered responsible for the Ti6Al4V surface hardening (increases in the surface microhardness) and the improvement of the wettability (Table 1 and Fig. 3). All these resulted in the friction coefficient to decrease from 0.2 to 0.04 (Fig. 4). Because the atomic weight of nitrogen is lower than that of oxygen, the first implanted nitrogen ion would diffuse deeper into the surface during the period when the samples were implanted with oxygen ion. This suggested that a graded layer of titanium oxide–titanium nitride (TiO–TiN) should be produced on the surface of Ti6Al4V alloy. The graded titanium oxide–titanium nitride film is hard and strong enough to resist the abrasive action of the UHMWPE counterface and maintaining smooth surface under water lubrication conditions (see Fig. 7a). All of these factors may contribute to the improved wear resistance of UHMWPE. Sample no. 4, implanted with oxygen at the highest temperature and highest dose, gave the lowest friction coefficients and wear rates of UHMWPE in the present study, and was associated with the largest volume fraction of TiO and Ti_2O in the subsurface (Fig. 1) and the highest surface hardness (Table 1). However, the differences in the measured friction and wear between different ion-implanted samples against UHMWPE are relatively small.

There are a number of limitations of the present study. Only distilled water lubrication was considered in the present study, rather than more realistic lubricants such as bovine serum. The uni-directional pin-on-disc wear testing machine was adopted in the present study, rather than a more realistic multi-directional motion. All these will be considered in future studies.

4. Conclusions

1. After the two-step ion plasma immersion ion implantation, the graded titanium oxide–titanium nitride film was formed in the subsurface of Ti6Al4V alloys, and the wettability and the microhardness of the modified alloy surfaces were increased significantly.
2. Under water lubrication, the friction coefficient decreased by nearly 5 times and the wear resistance of UHMWPE increased by about 40 times against the ion implanted Ti6Al4V alloy.
3. There are many deep furrows on the surface of the un-implanted Ti6Al4V alloy, while there are almost no notable wear features on the ion implanted surface of the alloy.

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