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# Effect of N-ion implantation and diamond-like carbon coating on fretting wear behaviors of Ti6Al7Nb in artificial saliva

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Abstract: The tribology behaviors of Ti6Al7Nb, its alloy with N-ion implantation, and its alloy with diamond-like carbon (DLC) coating were investigated in artificial saliva. Fretting wear tests of untreated, N-ion implanted and DLC coated Ti6Al7Nb alloys plate against a  $Si_3N_4$  ball were carried out on a reciprocating sliding fretting wear test rig. Based on the analysis of X-ray diffraction, Raman spectroscopy, 3-D profiler, SEM morphologies and frictional kinetics behavior analysis, the damage behavior of surface modification layer was discussed in detail. The results indicated that the fretting wear behavior of Ti6Al7Nb alloy with N-ion implantation was increased with the dose increase of the implanted nitrogen ions. Moreover, the DLC-coated Ti6Al7Nb alloy with low ion implantation could improve the fretting wear behavior greatly. In addition, the Ti6Al7Nb with DLC coating had better wear resistance due to the special compact structure. All results suggested that the Ti6Al7Nb with DLC coating had better wear resistance than that with N-ion implantation in artificial saliva.

Key words: Ti6Al7Nb alloy; ion implantation; diamond-like carbon coating; fretting wear behavior

### **1** Introduction

Titanium and its alloys are known as the attractive materials for the manufacture of implants for medical and dental applications due to low density, high specific strength, excellent corrosion resistance and good biocompatibility compared with other conventional metallic materials [1-4]. Thus, titanium alloys become the first choice used for artificial bones, dental and surgical implants artificial dentures [5,6]. However, some factors (low hardness) limit the applications of titanium and its alloys. During the long-term clinical applications, it is found that the surface of the oxide film was easy to be peeled off in the contact fretting due to the poor wear resistance, resulting in the abrasive wear acceleration of the implants [7,8]. As a result, metal ions could be released from the implant alloy and were detected in tissues close to titanium implants. Even though the number of released metal ions is small, it can cause local inflammation of the tissues surrounding the implant [8,9]. The crack initiation, wear and adhesion of these implants could happen in the presence of small amplitude oscillatory sliding motion, which are the main reason of

the failure of titanium alloy implants [10].

Commercially pure titanium and Ti6Al4V alloy are the most widely used materials for the manufacture of implants. Due to the potential toxic effects of vanadium compounds, many researchers have studied the medical titanium alloy with good overall properties in recent years. V-free alloys like Ti6Al7Nb alloy have been developed for biomedical applications. recently Ti6Al7Nb alloy is widely used because of its advantages in biocompatibility, mechanical properties and corrosion resistance [11–14]. Meanwhile, some surface technologies are used to modify the surface of titanium alloy to obtain more suitable properties [15-18]. Currently, there are many methods (ion implantation, DLC coating and so on) to improve surface behaviors of titanium alloys for the application of hard tissue repair alternative materials. The common method for the improvement of the wear resistance is to form a hardness coating at the surface of titanium alloy. Plasma immersion ion implantation-deposition (PIIID) is a rapid and effective surface modification technique to modify the physicochemical characteristics of the surface [19,20]. Some surface coatings, especially diamond-like carbon (DLC) coatings, are well known as low-friction coatings.

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During the past decade, the fretting wear of DLC coating has been widely investigated [21–24]. The thermal degradation of DLC coatings can cause a transformation from sp<sup>3</sup> to sp<sup>2</sup> bonds, resulting in low wear resistance. In addition, the tribological behavior of DLC coatings at lower frequencies is better than that of TiN, but it still could not provide very high levels of protection [25–27]. Thus, the further understanding on the tribological behavior of DLC coatings is expected.

In this work, the fretting wear behaviors of Ti6A17Nb alloy and its alloy with N-ion implantation, DLC coating in artificial saliva were investigated. Ti6A17Nb alloys were implanted with different nitrogen doses  $(1 \times 10^{17} \text{ N}^+/\text{cm}^2, 13 \times 10^{17} \text{ N}^+/\text{cm}^2)$  and diamond-like carbon (DLC) thin film. The fretting wear behaviors of titanium alloy in artificial saliva at 37 °C (body temperature) on a fretting test system had been carried out, the fretting motion was induced by the action of an oscillating normal force in a sphere-on-flat contact. The X-ray diffraction, Raman spectroscopy, 3-D profiler, SEM morphologies, and the fretting running were analyzed in detail. This study focused on the fretting running behaviors and damage mechanisms.

#### 2 Experimental

#### 2.1 Materials

The material used for this study was the biomedical Ti6Al7Nb alloy, with a chemical composition (mass fraction, %): 5.88 Al, 6.65 Nb, 0.03 Fe, 0.10 C, 0.20 O, 0.07 N, 0.02 H and 87.05 Ti. The samples were cut into  $10 \text{ mm} \times 10 \text{ mm} \times 25 \text{ mm}$  for tests. All specimens were ground and polished with 0.05 pm alumina powder to obtain the roughness of  $R_a=0.5 \mu m$ . The Ti6Al7Nb alloy was implanted with N-ion with the concentrations of  $1 \times 10^{17}$  and  $13 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup>. Then, the specimen surface implanted with N-ion with the concentration of  $1 \times 10^{17}$ and  $13 \times 10^{17} \text{ N}^+/\text{cm}^2$  was plating DLC films. The DLC films plating process like this: at first, plant Cr in the sample surface, then plant CrN and CrSiN in the Cr surface, which was used to form the gradient layer of hardness and reduce the film crack under load due to the hardness gap of the substrate and DLC film, at last plant DLC films in the CrN surface. The silicon nitride  $(Si_3N_4)$ counter-body (the sphere specimen) was a bearing sphere (AISI 52100), 10 mm in diameter. The hardness of the Si<sub>3</sub>N<sub>4</sub> specimen was about HV 740, and its average

roughness  $R_a$  reached approximately 0.1 µm. Before the tests, the Si<sub>3</sub>N<sub>4</sub> sphere was carefully cleaned by acetone.

The artificial saliva (0.4 g NaCl, 0.4 g KCl, 0.795 g  $CaCl_2 \cdot 2H_2O$ , 0.78 g  $CaCl_2 \cdot 2H_2O$ , 0.005 g  $Na_2S \cdot 9H_2O$ , 1 g urea, 100 g distilled water) was used to simulate the oral environment.

## 2.2 Surface treatments (nitrogen ion implantation and DLC coating)

The samples were sputter-cleaned with argon and deionized water, and then laid on stainless-steel substrates attached to an insulated stainless-steel electrode in the center of the vacuum chamber. Next, a negative voltage was applied to the electrode. Two doses of nitrogen ion  $(1 \times 10^{17} \text{ and } 13 \times 10^{17} \text{ N}^+/\text{cm}^2)$  were implanted into Ti6A17Nb alloy, which was carried out at the high energy ion implantation and enhanced deposition system of the Lanzhou Institute of Chemical Physics, China. The specific ion implantation parameters were shown in Table 1.

Prior to deposition tests, the specimens were polished mechanically and ultrasonically cleaned in alcohol for about 15 min. Afterwards, Cr/CrN/CrSiN/ DLC multi-layered coatings were deposited on Ti6Al7Nb alloys with nitrogen ion implantation using a combined arc ion plating and magnetron sputtering process in the same chamber. For the deposition tests, the bottom vacuum of chamber was kept to  $4 \times 10^{-3}$  Pa, access to Ar gas to 1 Pa, a bias voltage of -700 V, and use the producing glow clean substrate for 10 min. The targets of Cr and Si were of high purity (99.99%). For Cr film, the target was deposited with argon (99.999%) inlet with a flow of 40 mL/min. For CrN/CrSiN film, argon and nitrogen (99.999%) were introduced into the chamber with a flow of 10 and 40 mL/min, respectively. For DLC film, argon and CH<sub>4</sub> (99.999%) was introduced into the chamber with a flow of 20 and 40 mL/min, respectively. The deposited time of Cr, CrN, CrSiN and DLC film was 30 min for each layer. During the deposition process, the pressure was kept at 0.5-06 Pa. During the whole deposition process, the substrate must not be heated and the sputtering power was set to 1.1 kW.

#### 2.3 Electrochemical corrosion tests

The electrochemical tests were performed on a PARSTAT 2263 electrochemical workstation. The test

Table 1 Parameters of N-ion implantation technology

Table 1 Talameters of N-fon implantation technology							
Source	Filament current/A	Arc		Suppression		Accelerate	
		Voltage/V	Current/A	Voltage/V	Current/A	Voltage/kV	Current/mA
Cleaning source	12.5	42.5	1.0	200	6.5		
Gas source	11.2	66.5	0.2	1000	0.6	40	8.0

appliance was a three-electrode system consisting of a saturated calomel electrode (SCE), a platinum reference electrode and a working electrode (samples). The experiments were performed in 50 mg/g Cl (KCl as the solute) solution with distilled water. The value of the pH was 7. The samples were dipped in the solution before test until the open circuit potential became stable. Then, the linear polarization curves were acquired by the potential sweep in the anodic direction in the range of  $\pm 30$  mV (vs SCE). The scanning rate of the linear polarization reduced to below 1 mV/min. The scanning rate of the potential was 2 mV/s for potentiodynamic polarization tests.

#### 2.4 Reciprocating sliding fretting tests

The fretting wear tests were conducted with a flat on-ball contact on an improved reciprocating sliding fretting rig in the Senior CETR experimental machine [27–30]. The flat specimen was fixed on a lower holder, the Si<sub>3</sub>N<sub>4</sub> sphere was fixed to the upper clap linked to the sensor. Fretting tests were performed under laboratory control conditions (temperature 23 °C; relative humidity (60±10)%). The loads ( $F_{max}$ ) were 10 N and 50 N (equivalent to average Hertz contact pressure of 0.9971 and 1.705 GPa) [31,32]. The displacement amplitude was 200 µm. Number of cycles was ranged from 1 to 1×10<sup>4</sup>. All the tests were under the artificial saliva condition. Prior to the tests, all specimens were ultrasonically cleaned in acetone.

#### **3** Results and discussion

#### 3.1 XRD analysis

XRD was performed on the implanted surface of the specimens by Xpert PRO MPD) made diffractometer using Cu K<sub>a</sub> radiation with incident angle of  $0.5^{\circ}$ , with a scanned range from 20° to 80°. The diffraction patterns of the specimens are shown in Fig. 1. The pattern showed a single  $\alpha$  peak before ion implantation. At the nitrogen dose of  $1 \times 10^{17} \text{ N}^+/\text{cm}^2$ , there were growing peaks at  $2\theta$  values of 37.4° and 43° compared to un-implanted specimen, resulting from TiN. As nitrogen dose increased to 13×10<sup>17</sup> N<sup>+</sup>/cm<sup>2</sup>, several new peaks appeared at  $2\theta$  values of  $39^{\circ}$  and  $52.7^{\circ}$ , which were detected as Ti<sub>2</sub>N. The transformation process was Ti-TiN-Ti<sub>2</sub>N, in which the first step was the transformation of Ti to TiN by changing the stacking sequence from ABAB, in the HCP structure to ABCABC in the FCC structure of TiN. The nitrogen atoms could stay at octahedral interstitial sites during this process. The second step was the transformation of TiN to Ti<sub>2</sub>N, in which the nitrogen atoms were harmonized in octahedral interstitial sites during this transformation. The XRD patterns of the DLC (Cr-CrN-CrSiN) of three

substrates (un-nitrided Ti6Al7Nb and nitrogen doses of  $1 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup> and  $13 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup>) were given in Fig. 1(b). The CrSiN composite film was face-centered cubic structure consisting (111), (200) and (220) diffraction peaks [33]. It could be seen that the structures of CrSiN composite film were almost the same, although the substrate was different.



**Fig. 1** XRD patterns of Ti6Al7Nb alloys before and after iron implantation and DLC: (a) Substrate and iron implantation; (b) Iron implantation and DLC

#### **3.2 Electrochemical studies**

The cyclic polarization curves of the Ti6Al7Nb alloy with different treated ways are shown in Fig. 2. The corrosion potential ( $\varphi_{corr}$ ), corrosion current density ( $J_{corr}$ ), and polarization resistance ( $R_p$ ) can be obtained by corresponding analogy computing program. Compared with implanted and un-implanted Ti6Al7Nb alloys, the polarization curve of DLC exhibited a high positive potential, and its corrosion current density decreased significantly. In addition, the increasing nitrogen dose resulted in the decrease in the passive current density and the positive potential, which indicated that the stability of the passive film against dissolution decreased. However, the DLC on the un-implanted specimen possessed the highest positive potential. Based on the aforementioned results, it can be concluded that the diamond-like carbon

(DLC) coating had better corrosion resistance compared to the two different surface modifications.



Fig. 2 Cyclic polarization curves of different specimens: (a) Substrate; (b) Implanted at dose of  $1 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup>; (c) Implanted at dose of  $13 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup>; (d) DLC coated after implanted at dose of  $13 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup>; (e) DLC coated after implanted at dose of  $1 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup>; (f) DLC coated on substrate

#### 3.3 Raman tests

Figure 3 showed the Raman spectra of nitrogen ion implantation layer acquired between 100 and 700 cm<sup>-1</sup> and DLC (Cr-CrN-CrSiN) coating acquired between 800 and 2000 cm<sup>-1</sup>, which could be deconvoluted into two sub-peaks: G band (graphitic) around 1565 cm<sup>-1</sup> and D band (disorder) at approximately 1348  $cm^{-1}$ , which are typical characteristics of diamond-like carbon coatings [34,35]. It could be seen that the implanted Ti6Al7Nb alloy had three apparent positions of the peaks, which were located at 210-250, 310-350 and 550-600 cm<sup>-1</sup>. These peaks were corresponding to the first-order peak of the Ti-N. The three peaks were relatively flat and low-frequency peaks were located at the vicinity of 240 and 330 cm<sup>-1</sup>, when the implantation dose was  $1 \times 10^{17} \text{ N}^{+}/\text{cm}^{2}$ . As the implantation dose increased, the two peaks with low frequency trended to be stable near  $215 \text{ cm}^{-1}$  by moving to a low wave. The frequency peak position had no obvious changes substantially, while the peak intensity was significantly enhanced. Based on the above results, there was a positive correlation between the number of nitrogen atoms in Ti-N and the increase in the nitrogen ion dose.

#### 3.4 Wear scars observation

The typical morphologies of worn surfaces of the samples against a  $Si_3N_4$  ceramic counter face under the normal loads of 10 N and 50 N carried out on a flat-on-ball contact on an improved reciprocating sliding fretting are shown in Figs. 4 and 5, respectively. It was found that the shape of wear scars was oval. The wear



**Fig. 3** Raman spectra of specimens: (a) Ion implantation; (b) Ion implantation and DLC

scar after implantation became small and slight compared with that of the un-nitrided samples (Figs. 4 and 5), which were worn seriously with wide and deep grooves along the sliding tangential direction. There was a lot of debris generated. In addition, the scar became smaller and the damage became slight with increasing nitrogen dose. At the dose of  $13 \times 10^{17} \text{ N}^+/\text{cm}^2$ , the wear damage was very slight and only surface impression could be found. Compared with the implanted Ti6Al7Nb alloy, the samples with DLC coating had the slightest damage (Figs. 4(b), 4(d), 4(f) and 5(b), 5(d), 5(f)). The wear scar was too small to be seen. The damage of three different DLC was contrary to the implanted Ti6Al7Nb alloy mentioned above. The DLC on un-nitrided surface had smaller and slighter wear scar than that on implanted surface, which was consistent to the results of the wear rate shown in Fig. 6. This phenomenon could be attributed to the roughness of the base body. The roughness of surface became larger and the CrSiN films on it were less smooth. Thus, it wore seriously in reciprocating sliding movement situation. In general, the two methods of surface modification (nitrogen ion implantation and DLC coating) had a significant improvement for the wear resistance, specifically for the



**Fig. 4** Morphologies of fretting wear scar at F=10 N: (a) Substrate; (b) Un-implanted+DLC; (c)  $1 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup>; (d)  $1 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup> + DLC; (e)  $13 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup>; (f)  $13 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup> + DLC

second method. The first method could be explained that with the increase in the effective range of nitrogen ion implantation and the zone of  $Ti_xN_y$ , one was attributed to the increase of the thickness of implanted layer and the other was due to the structural characteristics of the composite film: little size crystalline grain and compact structure, which could effectively prevent the friction process of crack and due to the high strength hardness of the film.

Figure 6 shows the hardness and wear rate during fretting in artificial saliva under normal loads (10 N and 50 N). The hardness increased as the implantation dose increased, and the DLC film deposited on the substrate can increase the hardness greatly. The wear rate was significantly larger under 10 N than that under 50 N for uncoated and plasma nitrided alloys as well as DLC coating. It can be observed that DLC coated sample had revealed drastically reduced wear rate compared to substrate materials due to high resistance towards fretting

in high load as well as low load.

#### 3.5 Friction coefficient of samples under normal load

Figure 7 shows the comparison of variation in friction coefficients for surface modified alloys tested under normal loads (10 N and 50 N). In these two conditions, the unmodified and plasma nitrided alloys had exhibited high friction coefficients (between 0.4 and 0.5) compared to the DLC coating, which had very low friction coefficients (below 0.1). For uncoated and plasma nitrided alloys, the friction coefficients decreased from 0.54 to 0.4 as the normal load increased from 10 to 50 N, which could be attributed to the gradual change in contact condition induced by the increasing normal load. A similar slight trend was observed in the DLC coating alloy. For the plasma nitride samples tested under low load (10 N), the friction coefficient had a peak value after a few hundred cycles and then there was a drastic reduction in its value for the low dose  $(1 \times 10^{17} \text{ N}^+/\text{cm}^2)$ . It



Fig. 5 Morphologies of fretting wear scar, F=50 N: (a) Substrate; (b) Un-implanted + DLC; (c)  $1 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup>; (d)  $1 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup> + DLC; (e)  $13 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup>; (f)  $13 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup> + DLC



Fig. 6 Hardness (a) and wear rate (b) of Ti6Al7Nb alloy before and after iron implantation and DLC in artificial saliva

remained low for the next thousands of cycles, indicative of steady property. It indicated the gradual erosion of the nitride layer with the progression of fretting cycles. Under high load (50 N), it was similar with that at high dose  $(13 \times 10^{17} \text{ N}^+/\text{cm}^2)$ . But the low dose  $(1 \times 10^{17} \text{ N}^+/\text{cm}^2)$  was different. In the case of DLC coated samples, the friction coefficient decreased after a few hundred cycles. A gradual transition was observed and finally reached a

value of 0.07. The number of cycles after which there was a sharp increase in friction coefficient was considered as the life of the coating. It was worth noting that only one test was conducted in each condition and more carefully planned and repeated experiments were necessary to determine the coating life accurately. However, with the available data in the present study, it might be said that the number of cycles at which failure occurred decreased when the normal load increased. So it could be seen in Fig. 7 that the DLC (Cr–CrN–CrSiN) had no observed decrease, and still was in a stable stage of low friction coefficient. The DLC (Cr–CrN–CrSiN) had superior fretting behavious with low friction coefficients.

Further researches on wear scar of unmodified and the plasma nitrided alloys were carried out in a non-contact 3D surface profiler as shown in Fig. 8. As shown in Fig. 8, the wear scar was mainly composed of plough grooves and micro cracks. The wear scar of nitride specimen was much smaller and shallower than the untreated ones (Figs. 8(b) and (c)), especially the high dose of nitrogen ion (Fig. 8(c)). The wear scars of DLC coated specimens (Figs. 8(d) and (e)) were the lightest. The damage of DLC coated at high ion dose was worse than that at low ion dose, which was consistent with the results in Figs. 4, 5 and 6. Compared with the untreated wear scar (Fig. 9), the ion implantation surface damage was slighter (Fig. 10). Only micro-cracks and small debris appeared in the superficial zone. The 3D morphologies of the wear scar illustrated the above difference significantly (Fig. 8).

SEM images of fretting scar in artificial saliva lubrication for untreated Ti6A7Nb alloys are shown in Fig. 9. The fretting scars exhibited plough and scratch damage on the fretting area (Fig. 9(a)). The distinct plastic grooves, deformation and the metallic particles



**Fig. 7** Evolution of coefficient of friction of implanted and un-implanted Ti6Al7Nb and several DLC specimens during fretting tests in artificial saliva at 37 °C: (a) *F*=10 N; (b) *F*=50 N



Fig. 8 3D-morphologies of wear scar at F=50 N: (a) Substrate; (b)  $1 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup>; (c)  $13 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup>; (d)  $1 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup>+DLC; (e)  $13 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup>+DLC



Fig. 9 Fretting wear scar profile of substrate alloy at F=50 N

adhesion were obviously observed in the larger magnification of the worn surfaces (Fig. 9(b)). These results indicated that severe material transfer through adhesive and abrasive wear could occur. The damage mechanism of Ti6Al7Nb alloy was combining with oxidation wear and abrasive wear [36]. The fretting scars of nitrogen ion implanted and DLC coated Ti6Al7Nb alloys were observed in Fig. 10. It can be seen that the damage of the implanted specimens was slighter. Only with slight plough (Fig. 10(a)). With the increase of ion dose, the damage became slighter. The damage mechanism of implantation Ti6Al7Nb layer was slight abrasive wear. There were only surface impressions on the surface of different ion implantation with DLC coating (Figs. 10(c) and (d)). In addition, the unworn zone (A) had high roughness like grain boundary and the worn zone (B) became flatter (Fig. 10(d)). Thus, it could be concluded that the DLC coating almost had no damage except for slight sliding.



Fig. 10 Morphologies of wear scar of nitrogen ion implantation specimens at F=50 N: (a)  $1 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup>; (b)  $13 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup>; (c)  $1 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup>+DLC; (d)  $13 \times 10^{17}$  N<sup>+</sup>/cm<sup>2</sup>+DLC

#### **4** Conclusions

1) The damage of Ti6Al7Nb with DLC coating was slighter and smaller than that with ion implantation.

2) The resistance against fretting wear of ion implantation became better with increasing injection ion concentration. However, the DLC coated alloy with low ion implantation layer had better fretting wear behaviors.

3) Due to the presence of special structure, the DLC coating had better corrosion resistance than untreated and

plasma nitride Ti6Al7Nb alloys in artificial saliva.

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### 氮离子注入及 DLC 涂层对 Ti6Al7Nb 合金在人工唾液中微动磨损性能的影响

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摘 要:通过往复滑动微动磨损实验研究 Ti6Al7Nb 合金、氮离子注入 Ti6Al7Nb 合金、DLC 涂层 Ti6Al7Nb 合金 在人工唾液环境下的磨损性能。运用 X 射线衍射分析、拉曼光谱分析、三维轮廓分析、扫描电镜形貌和摩擦动力 学行为分析等方法,详细讨论了表面改性层的磨损特性。结果表明:随着氮离子浓度的增加,Ti6Al7Nb 合金的抗 微动磨损性能提高。具有 DLC 涂层的低氮离子注入 Ti6Al7Nb 合金显示出良好的抗微动磨损性。此外,由于其特殊的结构,DLC 涂层组具有更好的耐腐蚀性能。在人工唾液环境下,DLC 涂层 Ti6Al7Nb 合金组相比氮离子注入 Ti6Al7Nb 合金组具有更好的就磨损性能。

关键词: Ti6Al7Nb 合金; 离子注入; DLC 涂层; 微动磨损行为

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