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ABRASIVE WEAR BEHAVIOR OF NITRIDED TEXTURED TITANIUM

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Abstract: In order to improve the anti-friction and anti-wear performances of titanium and expand its application in aerospace and aircraft area, a commercial pure titanium grade 2 (TA2) was chosen and treated by compositing surface treatment. Dimple textures were prepared on the titanium surface by laser surface texturing (LST), and then the textured titanium was treated by ion nitriding. Tribological behaviors of the textured titanium and nitrided textured titanium were investigated under abrasive wear on a tribo-tester. The result shows that the anti-friction and anti-wear properties of textured titanium can be greatly improved by 47.1% and 79.3% after nitriding treatment, respectively. In addition, the dimple density has a significant effect on anti-friction and anti-wear behaviors.

Key words: Laser surface texture; Nitride; Abrasive wear; Dimple

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1. Introduction

Lightweight materials are of great significance to the development of national defense technology and equipment. Titanium is a kind of lightweight material which has high strength, low density and good corrosion resistance. The application of titanium in aviation and aerospace has a growing trend in the recent years [1-6]. However, the poor wear resistance limits its application. Especially in the three-body abrasive wear condition, titanium always exhibits a worse anti-friction and anti-wear performance [7, 8].

A series of methods to improve the abrasive wear behavior have been widely conducted, among which the surface texturing treatment is attractive due to the effects like the storage and distribution behavior of wear particles under abrasive wear [9-16]. Wu [17] studied the tribological properties of dimple-textured titanium alloys under dry sliding contact and found that the wear mechanism of titanium surface mainly included abrasive wear, adhesive wear and plastic deformation. In addition, the space between the dimples was proved as a great effect on friction reduction and wear resistance. Mishra[18] investigated the tribological behaviors of textured surface under starved lubrication conditions which indicated the textured surface had better wear-resistant property than the untreated substrate surface. Although the previous studies demonstrated that the textured surface could improve the abrasive wear performance of titanium, the method of texturing treatment on titanium is far from perfect. The wear duration is a big limitation in abrasive wear condition for textured titanium. Therefore, it is necessary to introduce more work to improve the durability of textured titanium under abrasive wear.

The purpose of this paper is to enhance the wear duration of textured titanium by ion nitriding treatment, and illustrate the abrasive wear behavior of three body wear particles on the surface of dimple textured titanium. In addition, the effect of dimple parameters on the abrasive wear performance is considered. The results here are expected to improve the abrasive wear performance of the titanium in application of national defense area.

2. Experimental method

The current investigation involves the enhancement of wear duration performance and the effect of dimple textured parameters on the abrasive wear behaviour. The substrate is a commercial pure titanium grade 2 (TA2) which is widely used in national defense area, and the element composition of TA2 is shown in Table 1. The size of the test sample was processed to 50 mm×50 mm×3 mm, and the surface roughness was machined as Ra0.4 μm.

Table 1 TA2 composition (wt%)

Fe	C	N	H	O	Ti
≤0.3	≤0.1	≤0.05	≤0.015	≤0.25	Bal.

The dimple parameters were designed into 9 groups as shown in Table 2. The dimple characteristics were processed by a laser machine with an Nd: YAG laser. This laser has a power of 20 W with a wavelength at 1064 nm. The dimple parameters such as dimple diameter (*d*), dimple density (*ε*) and dimple depth (*h*) were ensured by the size, power and moving space of the laser beam, respectively. The textured titanium samples were obtained in this way, and the samples were numbered as 1-9. With each group of dimple parameters two samples were made and named as sample A and B.

Table 2 Dimple parameters for the textured titanium.

Sample number	*d*/μm	*h*/μm	*ε*/%
1	100	10	10
2	100	20	20
3	100	30	30
4	200	20	10
5	200	30	20
6	200	10	30
7	300	30	10
8	300	10	20
9	300	20	30

Afterwards, all the textured titanium samples B were ultrasonically cleaned with ethanol for 15 min.

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After drying, the nitrided textured titanium samples were prepared via a treatment by a LDM2-25 plasma nitriding furnace. And the nitrided textured titanium samples were prepared. The nitride parameters are shown in Table 3.

Table 3 The nitriding parameters

Pressure	Voltage	Current	Temperature	Duration
600 Pa	900 V	12 A	850 °C	8H

With the sample preparation had been completed. The three body abrasive wear test was performed on an MS-T3000 ball-on-disk tester. The upper pairing ball was an AISI 52100 steel with a diameter of 6 mm. The lower pairing pieces were the textured titanium samples and the nitrided textured samples. The simulated lunar soil was chosen as wear medium which was mainly composed of silica, aluminum, calcium, iron and titanium. The particle size of the simulated lunar soil was filtered as 60-75 μm. The wear medium with volume of 100-150 cm^3 was added into the sliding pairs. The wear test parameters are shown in table 4. All the tests were repeated for 3 times and the average value were taken.

Table 4 Wear test parameters.

Applied load	Sliding linear velocity	Sliding duration
2 N	62.8 mm/s	30 min

In order to analyze the influence of dimple parameters on the friction and wear performances of the nitrided textured titanium, a three-factor and three-level orthogonal table was established. The three factors refer to the dimple diameter, dimple density and dimple depth, respectively. The three levels refer to the variables under each factor (eg, three levels of dimple density are 10%, 20%, and 30%).

For the purpose of clarifying the mechanical properties of the sliding pairs, Workbench (the program used to run finite element method) was used to analysis the stress distribution on the textured surface during wear test. The model is shown in Fig. 1. The contact form of friction pairs is surface to surface contact. And the upper contact pair is subjected to a positive pressure and a displacement while the lower contact pair is fixed. The model grid subdivision is free meshing.

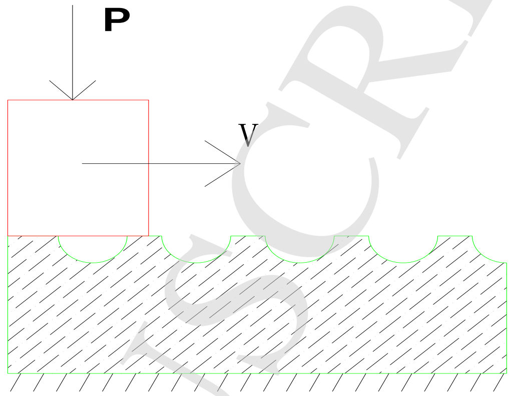

Fig. 1 FEM model.

Moreover, the phase composition was analyzed by D/max-2550 X ray diffractometer (XRD). The wear volume was measured by using a Nano Map-D type 3D white light interferometer. The wear patterns and element composition were observed byJSM-7001F field emission scanning electron microscopy (FE-SEM) and EDS.

In this experiment, the method of laser surface texture was adopted to prepare the dimple characters on the surface of titanium. This method can possibly generate a certain machining error which might influence the experimental results.

3. Results

This study mainly made a tribological comparison between the textured titanium samples and the nitrided textured samples. Fig. 2 illustrates the surface topographies of the textured titanium sample 6A and the nitrided textured titanium sample 6B. The surface topographies show no difference between the two samples. But the element distribution on the sample surfaces, as listed in Table 5, shows much difference. The nitrogen fraction on the surface of nitrided textured titanium sample increases significantly compared with that on the textured titanium sample.

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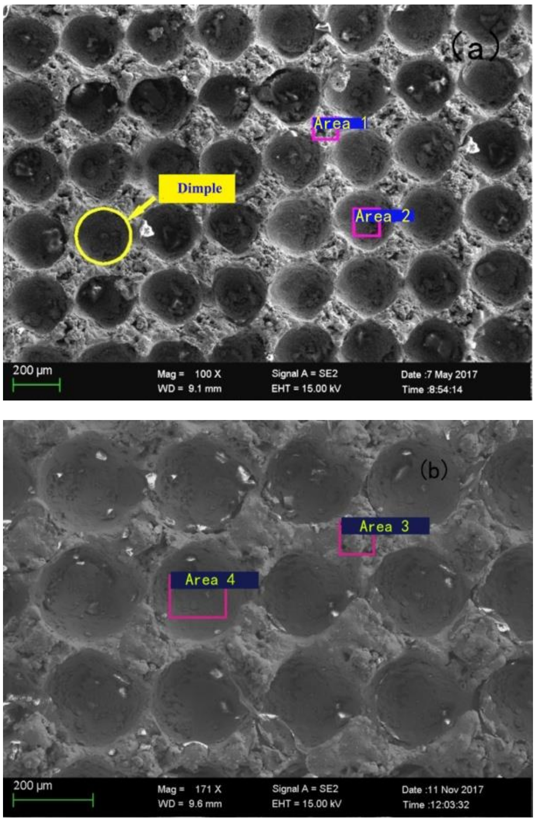


Fig. 2 SEM images of the samples, (a) the textured titanium sample, (b) the nitrided textured titanium sample.

Tab. 5 Atomic fraction of elements on different regions at%

elements	(a)		(b)	
	Area 1	Area 2	Area 3	Area 4
C	15.73	19.83	2.58	3.37
O	15.79	10.53	13.71	13.67
N	4.31	3.22	30.90	40.09
Ti	64.17	66.42	52.81	42.87

In order to analyze the phase composition of the nitrided textured titanium sample, XRD analysis phases can be found. As observed in fig.3, TiN and Ti_2N are generated. These two phases can improve the hardness of titanium by about 30%[19-21].

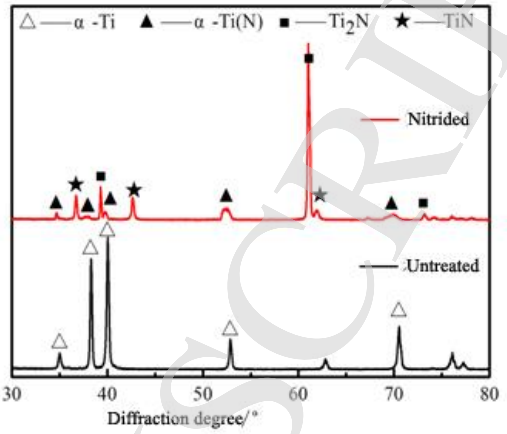


Fig. 3 XRD patterns of the samples.

The comparison of anti-friction and anti-wear behaviors of the samples is displayed in Fig. 4. It is evident from Fig.4(a) that the friction coefficients of the nitrided textured titanium samples are smaller than that of the textured titanium samples, and the decrease of friction coefficients of the nitrided textured titanium can be up to 47.1%. Meanwhile, the wear rates of the nitrided textured titanium samples are smaller than that of the textured titanium samples (shown in fig. 4(b)), and the decrease of wear rates of the nitrided textured titanium can be up to 79.3%.

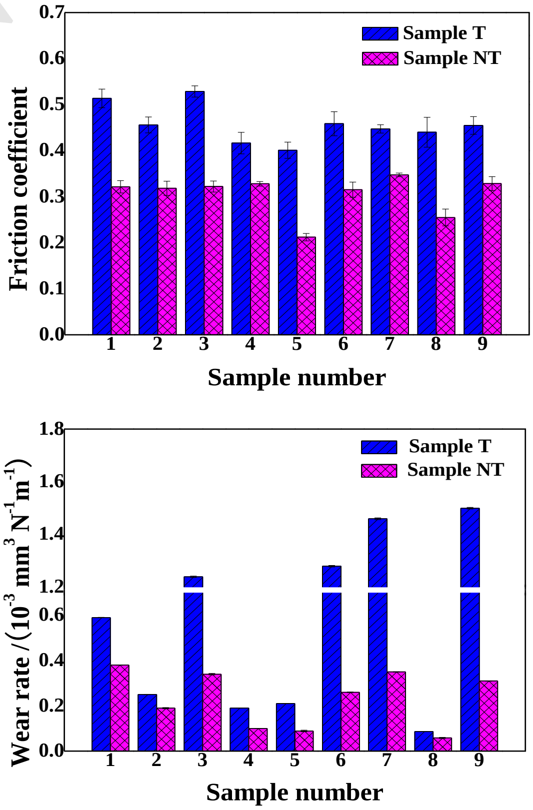


Fig. 4The friction coefficients and wear rates.

For the sake of investigating the effect of dimple parameters on the anti-friction and anti-wear performances, an orthogonal analysis was carried out.

Table 6 shows the effect of dimple parameters on anti-friction performance. The F values of the variance of friction are 0.828, 3.614 and 0.722 for the dimple diameter, dimple density and dimple depth, respectively. Obviously, the influence of dimple parameters on the anti-friction performance is less than 90% confidence. However, the contribution of dimple density to the anti-friction performance is 69.98%, which is much larger than the contribution of dimple diameter and dimple depth.

Table 6 Effect of dimple characters on anti-friction performance.

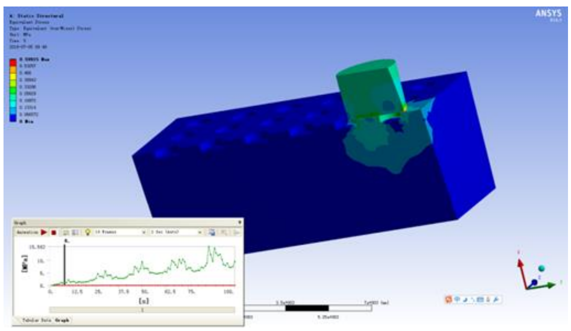
Source of variances	Sum of squares	DOF	Variance	Test F	F	percentage of contribution/%
d	0.0020	2	0.0010	0.828	9 (0.90)	16.00
ε	0.0087	2	0.0044	3.614	19 (0.95)	69.98
h	0.0017	2	0.0008	0.722	99 (0.99)	13.98
error	0.0024	2	0.0012			0.04
	0.0149	9	0.0017			1

Table 7 shows the effect of dimple parameters on anti-wear performance. The F values of the variance of wear are 1.743, 7.722 and 1.236 for the dimple diameter, dimple density and dimple depth, respectively. Obviously, the influence of dimple parameters on the anti-wear performance is less than 90% confidence. However, the contribution of dimple density to the anti-wear performance is 72.15%, which is much larger than the contribution of dimple diameter and dimple depth.

Table 7 Effect of dimple characters on anti-wear property

Source of variances	Sum of squares	DOF	Variance	Test F	F	percentage of contribution/%
d	0.1055	2	0.0528	1.743	9 (0.90)	16.29
ε	0.4672	2	0.2336	7.722	19 (0.95)	72.15
h	0.0748	2	0.0374	1.236	99 (0.99)	11.55
error	0.0605	2	0.0303			0.01
	0.7080	9	0.0787			0

It can be easily deduced that the dimple density affects the anti-friction and anti-wear performance stronger than the dimple diameter and dimple depth. To illuminate the micro mechanisms, the mechanical properties of the textured surface during sliding test are calculated. Fig. 5 shows the equivalent stress on the textured surface by finite element analysis. One of the dimples is called pit and the area between the pits is called embossment. It can be seen that the maximum stress is at the embossment which means that this part of the area is most likely to be damaged during wear test.



(a) The equivalent stress diagram

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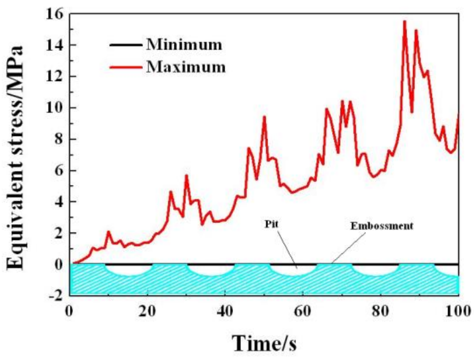

(b) Curve of equivalent stress over time

Fig. 5 The FEM results.

Fig.6 shows an SEM photograph of the wear track morphology of the textured titanium sample (for sample number 6A). The dimple has been worn away on the wear track. The wear track surface is mainly composed of furrows and plastic substance. By EDS analysis of the elements on the area5 in Fig. 6, the main components (atomic fraction) are 12.40% C, 45.77% O, 1.47% Si, 40.36% Ti, indicating that the surface of the wear track consists primarily of titanium, oxide and a small amount of elements from the lunar soil medium.

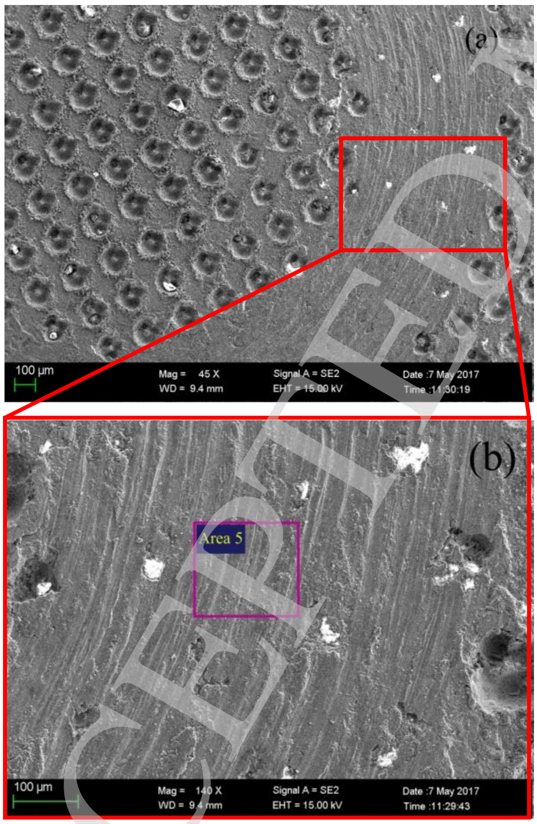

Fig. 6 Wear track morphologies for textured titanium sample.

Fig. 7 shows an SEM photograph of the wear track morphology for the nitrided textured titanium sample (for sample number 6B).The dimple has not been completely worn away on the wear track. It is obvious that the nitrided textured titanium sample has longer wear duration than the textured titanium sample. In this figure, there are white deposits appeared inside the dimple pocket. By EDS analysis of the white deposits (on area 6 in Fig. 7(b)), it is mainly composed of O, Ti, Fe and some elements from the three body wear medium. Meanwhile, the EDS analysis conducted on the area 7 in Fig. 7(b) shows that it mainly contains Ti, O and N, indicating that the nitrided layer has not been completely worn away after rubbing test.

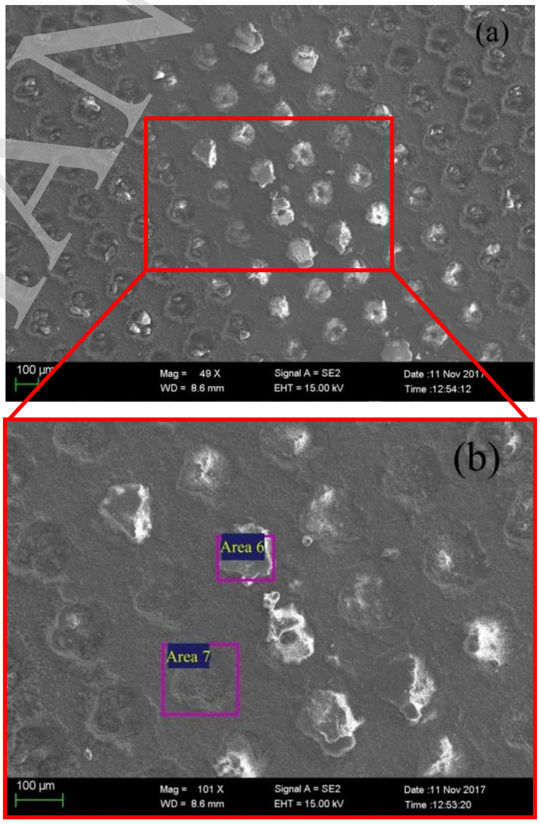

Fig. 7 Wear track morphologies for nitrided textured sample.

4. Discussion

Prior studies have documented the tribological behavior of textured titanium under abrasive wear condition. Nevertheless, the wear duration is less considered [9-18]. In this study, the textured titanium samples are nitrided and have been demonstrated to

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have longer wear duration than the textured titanium samples. In addition, the dimple density is found to have greater influence on anti-friction and anti-wear performance than the dimple diameter and the dimple depth.

In this experiment, the hard upper steel ball has a plow cutting into the softer titanium surface and it caused severe plastic deformation. The elements distribution analysis on the wear track of textured titanium sample shows that the three body particles increase the extent to which the surface was ploughed and deformed [22]. Obviously, the wear mechanism for textured titanium is adhesive wear and abrasive wear. However, the wear mechanism for nitrided textured titanium is abrasive wear due to the strengthening effect of nitriding treatment, as well as the function of the dimples that stored the debris [23, 24] which can be verified in the SEM graphs. That's the reason of the anti-friction and anti-wear properties for the nitrided textured titanium can be greatly improved.

The area ratio of the embossment is related to the dimple density. The dimple density has greater effect on the anti-friction and anti-wear properties than the dimple diameter and dimple depth. The embossment area on the textured surfaces experiences the maximum stress and this part of the area is tending to be damaged during wear test [25]. However, nitriding treatment can improve the hardness and wear resistance properties of the textured titanium sample which can be accused to two aspects.. On the one hand, TiN and Ti_2N were generated on the surface during wear test which can help improve the hardness of the sample. On the other hand, the dimple characteristics have effect on the plasma energy distribution during nitriding treatment, leading to the nitrogen accumulation in the embossment [26].

5. Conclusion.

(1) Compared with the textured sample, the nitrided textured sample exhibits better anti-friction and anti-wear performance, and the reduction of friction coefficient and wear rate can be up to 47.1% and 79.3%, respectively.

（2）The nitrided textured sample performs longer wear duration than the textured sample as the embossment area on the textured surfaces has been enhanced by nitriding treatment.

(3) The dimple density has greater effect on anti-friction and anti-wear properties than the dimple diameter and dimple depth.

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