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Wear Mechanism of TC4 Titanium Alloy with TiN Coating against Self-Lubricating Fabric

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Abstract: Vapor deposition technology can improve the surface wear resistance of titanium alloys, and prepare lightweight and corrosion-resistant self-lubricating spherical plain bearings made of titanium alloys. However, titanium alloys with hard films can be worn by soft self-lubricating fabrics. This paper focuses on the wear problem of TiN coating on the surfaces of self-lubricating spherical plain bearings based on titanium alloys. Ring-to-plate wear tests were carried out to study the tribological properties of TiN coating on TC4 titanium alloy against self-lubricating fabric under different working conditions (load: 500–2000 N and speed: 100–500 r/min), along with the investigation of the wear mechanism of TiN coating, and the evaluation of applicable working conditions of GE15 type self-lubricating spherical plain bearings through swing tests. The results have revealed that TiN coatings can maintain a certain friction distance without wear. Increasing friction speed and load can make TiN coatings more prone to wear. A thick transfer film can protect the TiN coating from wear. The main wear mechanism is attributed to fatigue wear induced by the repeated formation and peeling of transfer films. The GE15 bearing has achieved a self-lubricating fabric wear of approximately 0.04 mm when the swinging for 500 m (25,000 times) is under a specific condition of 27 kN and 0.2 Hz without damaging the inner ring of the bearing. The bearing is suitable for swing conditions with applied loads below 27 kN. This study provides a fundamental understanding of designing self-lubricating spherical plain bearings made of titanium alloys.

Keywords: TC4 titanium alloys; TiN coating; self-lubricating fabric; fatigue wear; self-lubricating spherical plain bearing

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1. Introduction

Self-lubricating spherical plain bearings are a typical sliding bearing with a self-lubricating characteristic, which has the advantageous attributes of simple structures, strong load-bearing capacity, self-lubrication, and free maintenance. It is widely used in the aerospace field of aircraft landing gear, operating systems, helicopter rotors, etc. [1–3]. Currently, the main component material for the inner and outer rings of self-lubricating spherical plain bearings is steel. However, steel spherical plain bearings have noticeable disadvantages of heavy weight and poor corrosion resistance, limiting its further applications in aircraft and marine equipment [4]. Titanium alloys directly benefit from low density, high specific strength and strong corrosion resistance, along with widespread aerospace applications [5]. As such, titanium alloys have gradually become a very popular material candidate for the manufacture of self-lubricating spherical plain bearings.

On the flip side, titanium alloys have high and unstable friction performance and high wear rates, thus severely restricting their applications as friction components [6–8]. In order to improve the wear resistance of titanium alloys, many studies have focused on the surface strengthening of titanium alloys using thermal diffusion [9], vapor deposition [10–13], micro arc oxidation (MAO) [14], ion implantation [15], laser cladding [16], as well as high-velocity oxy-fuel (HVOF) [17], with some success.

As a matter of fact, the surfaces of inner ring of self-lubricating spherical plain bearings are not only required to achieve good friction and wear performance but also to warrant a high surface finish. Additionally, the use of physical vapor deposition technology to prepare hard films on titanium alloys is a mature and suitable surface strengthening technology for titanium alloys. The friction and wear performance of hard films is an important factor affecting load-bearing capacity and matrix application.

A great deal of work has been conducted on the wear mechanism of hard thin films. Xia [18] studied the friction and wear properties of CrN film on 304 stainless steel substrate against GCr15 steel balls, which reported that the wear mechanism of CrN film in a dry-friction environment is deemed as adhesive wear and abrasive wear. Mo [19] has studied the sliding friction behavior of CrN film on cemented carbide substrate against Si_3N_4 balls. It has been found that the wear mechanism of CrN film in the sliding against a Si_3N_4 ball is the combination of delamination wear and oxidation wear. Liu [20] studied the friction and wear properties of TiN thin films on YG6 hard alloy against SiC ceramic balls, resulting in mainly oxidation wear and abrasive wear. Huang [21] studied the wear mechanism of TiAlSiN thin film on TG10C hard alloy substrate in a humid environment on different friction pairs. In a similar manner, the wear mechanism of the thin film on stainless steel balls and ZrO_2 balls was also considered as adhesive wear and abrasive wear. Furthermore, the $SiO_2 \cdot nH_2O$ layer generated from the sliding against the Si_3N_4 ball significantly improved the wear rate and friction coefficient of the thin film. Yao [22] compared the wear performance of TiN and CrN coatings against AISI 52100 steel balls and indicated better wear resistance derived from CrN. The wear mechanisms of the two coatings are quite similar, mainly adhesive wear and oxidation wear. Birol [23] prepared CrN, AlCrN, and AlTiN coatings on AISI H13 steel. During the friction process with aluminum, it was found that the CrN coating generated the highest shear stress and the most severe wear. The sliding wear performance of the AlCrN coating was improved, and the AlTiN coating appeared to be the best due to its high chemical resistance to aluminum. Zheng [24] studied the wear mechanism of TiAlN/TiN-coated cutting tools on high-strength steel. It was clearly demonstrated that the wear mechanism of TiAlN/TiN coating could be a combination of peeling, cracking, adhesion, mechanical scratching, element diffusion and oxidative wear. These studies demonstrate the strengthening effect of hard films on the friction and wear properties of the matrix and corresponding wear mechanism. However, the friction pairs used in the experimental process are mostly metal to hard films, and the issue of hard films being worn by soft materials has been rarely discussed. Polymer materials, due to their excellent tribological properties, are widely used in the design of tribological pairs with metal materials [25]. Since a much lower hardness of polymers can be obtained as opposed to general metal materials, most research on material wear focuses on improving the friction and wear performance of polymers. In fact, the phenomenon of hard materials being worn by soft polymers also occurs during the working process of friction pairs [26].

Giltrow [27] suggested that when adhesive wear occurs between polymers and hard materials, the positions where adhesive points are located generally appear on materials with weak cohesive energy or low shear strength. Ludema [28] found that when nylon 66 and polyoxymethylene resin with high shear strength were polymerized against 440C stainless steel surfaces, the components of the transfer film formed were not a completely polymeric material, owing to the existence of iron and chromium elements. Apparently, adhesive wear was the main contributor to metal wear. Buckley [29] indicated that abrasive wear on the surface of hard materials can be caused by particles close to the hardness of hard materials. Bhushan [30] revealed that the high cohesive energy and toughness of polymers could lead to the fatigue wear of hard materials. Harris [31] has found that during the friction process between polytetrafluoroethylene (PTFE) and steel, carboxylate chain ends are grafted onto metal surfaces, leading to the chemical wear of the metal through mechanochemical reactions. Li [32] found that friction between ultra-high molecular weight polyethylene (UHMWPE) and TC4 titanium alloy under water lubrication conditions can cause severe wear of titanium alloy. It was suggested that hydrogen diffusion was the main cause of wear, which supported the wear theory assisted by hydrogen diffusion.

The aforementioned research suggests that soft friction pairs can generate the wear on hard materials, whose mechanism is significantly different from that of metal–metal friction pairs. The existing classical wear theory cannot explicitly explain the phenomenon of polymer wear on hard metal materials. The self-lubricating spherical plain bearing is mainly composed of an inner ring (metal), an outer ring (metal) and a self-lubricating layer (polymer or self-lubricating woven fabric). The self-lubricating layer adheres to the outer ring and forms a friction pair with the inner ring. The self-lubricating spherical plain bearings do not require additional lubricants during working [2]. As for the fabric type of self-lubricating spherical plain bearings, they are metal against PTFE and reinforced fiber woven composite materials [33], relevant tribological research mainly focuses on the wear of fabrics [34], but lacks major work on the wear of self-lubricating fabrics against metal materials, especially for hard thin films. This is not suitable for analyzing the working conditions and the service life of self-lubricating spherical plain bearings with hard thin films. In order to expand the application of titanium alloys in the field of self-lubricating spherical plain bearings, it is necessary to further analyze the friction and wear properties of titanium alloy with hard film against self-lubricating woven composite materials.

TiN coating is a common hard film coating that the RBC company has applied to self-lubricating spherical bearings [35]. Many people have studied the friction and wear properties of TiN coating. Ma [36] studied the friction and wear properties of TiN coatings on GCr15 bearing steel substrate against WC-6% Co balls, and found that the wear particles of TiN coating played a very important role in the friction and wear process. which directly affected the wear life of the TiN coating. Hong [37] studied the wear mechanism of TiN coatings against WC-Co balls, which reported that fatigue, tribo-oxidation and adhesion are the main wear mechanisms for the TiN coating. Kara [38] studied the tribological properties of TiN coatings against Al_2O_3 balls under vacuum conditions, and the results showed that because the TiO_2 film generated in the friction process was weak, the coating had a higher wear rate under vacuum conditions compared to atmospheric conditions. Mendibide [39] studied the friction and wear behavior of TiN-coated balls (Z200C12 steel) against uncoated discs (M2 steel), and analyzed the cracking mechanism of TiN coating; it was found that TiN was subjected to transversal crack propagation along the columnar grain boundaries, until the peeling of the coating. Zhang [40] studied the tribological properties of TiN coatings on 316L steel against Si_3N_4 ceramic balls under dry friction and synthetic perspiration lubrication, which reported that the damage of TiN coating is attributed to abrasive wear under synthetic perspiration lubrication and complex interactive mechanisms, including abrasive and adhesive wear, along with plastic deformation under dry friction. The researches on the wear mechanism of TiN coatings are mostly focused on the wear mechanism of TiN coatings against hard materials such as metals or ceramics, and there is still a lack of relevant research on the wear mechanism of TiN coatings against soft materials such as self-lubricating fabrics.

This paper focuses on the coating wear problem of self-lubricating spherical plain bearings made of titanium alloy with hard films. With reference to the RBC company's design of self-lubricating spherical plain bearings made of titanium alloy with TiN coating, the friction and wear performance of TiN coating on TC4 titanium alloy against self-lubricating fabric under different working conditions were holistically investigated. The wear mechanism of TiN coating was analyzed, and the applicable working conditions of GE15 bearings under swing conditions were further elaborated. This offers a fundamental understanding for the design and preparation of self-lubricating spherical plain bearings made of titanium alloy with hard thin films.

2. Materials and Methods

The setup of the ring-to-plate test (MMU-5G, Jinan Chenda Instruments Co., Ltd., Jinan, China) according to ISO 7148-1:2012 (E) standard is shown in Figure 1. In order to ensure that the working conditions of the ring-to-plate test and the bearing swing test are similar, a pressure–velocity product (PV) value close to the bearing swing test was used, along with a load range of 500–2000 N and a speed range of 100–500 r/min. The test sample is a self-lubricating fabric with outer and inner diameters of 20 and 10 mm, respectively, for a circular ring, which is made of PTFE/Kevlar composite fabric (Shanghai Textile Research Institute Co., Ltd., Shanghai, China). The self-lubricating fabric was bonded to the surface of the steel upper sample using a phenolic resin (Shanghai Xinguang Chemical Plant, Shanghai, China). Before bonding, the inner surface of the half ring was sandblasted, and then the self-lubricating fabric was cured in a drying oven at a curing temperature of 180 °C for 2 h.

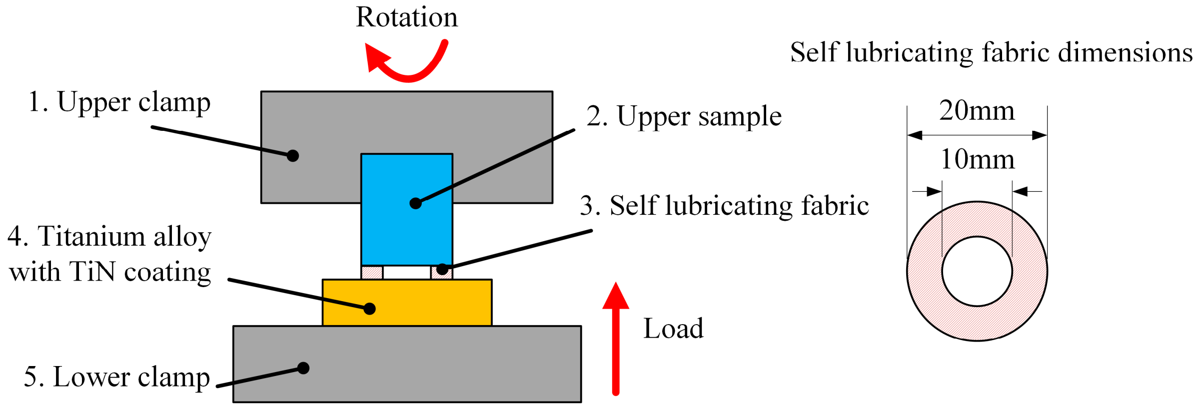


Figure 1. Schematic diagram of ring-to-plate test setup.

The sample used in this study is a TC4 titanium alloy sheet with TiN coating (2 × 30 × 30 mm). A TiN coating (Shenzhen Chuangfulong Industrial Co., Ltd., Shenzhen, China) was deposited on the surface of TC4 titanium alloy using physical vapor deposition. Before the deposition, the outer surface roughness of TC4 titanium alloy was polished to obtain Ra 0.2. During the preparation process of TiN coating, the chamber pressure was 0.6 Pa, the nitrogen flow rate was 30 sccm, the substrate bias voltage was −70 V, and the deposition time was 120 min. The morphology of the TiN coating is clearly illustrated in Figure 2. The coating uniformly covers the TC4 titanium alloy surfaces. According to the EDS analysis, the proportion of Ti element is approximately 80% from the starting position of the line scan to the position of approximately 53 μm, and there are also a small amount of Al and V elements, indicating that this part is mainly a titanium alloy matrix. Then, the percentage of Ti element decreased to approximately 70%, while the percentage of N element increased to approximately 20% (positing 53 μm to 56 μm), indicating that this part was mainly composed of TiN coating, with a coating thickness of approximately 3 μm. It was found by using coating nanoindentation (CPX-NHT2, Anton Paar (Shanghai) Trading Co., Ltd., Shanghai, China) that the hardness of the coating could reach approximately 17 GPa.

The friction coefficient was calculated using the following equation:

$$\mu = F_f/F_N$$

where μ is the coefficient of friction, F_f is the frictional force (N) and F_N is the applied load (N).

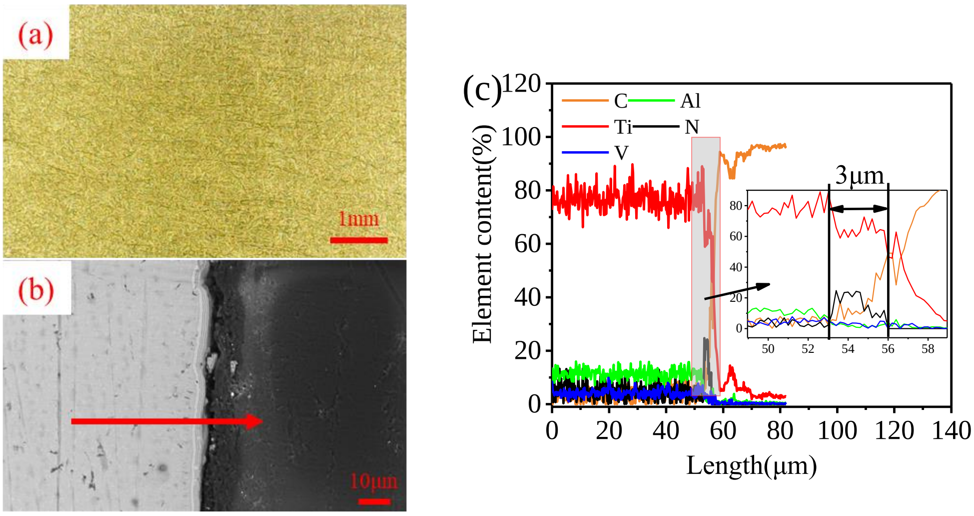


Figure 2. Morphology and EDS composition of TiN coating on TC4 titanium alloy surface: (**a**) morphology of TiN coating on TC4 titanium alloy surface; (**b**) SEM cross-section of TiN coating; (**c**) EDS distribution of elements in TiN coating cross-section.

A GE15 titanium alloy self-lubricating spherical plain bearing was prepared in this study. The outer ring material of the bearing was TC4 titanium alloy while the inner ring material was TC4 titanium alloy with a deposited TiN coating. The self-lubricating layer was made of PTFE/Kevlar composite fabric, which was the same as that used in the ring-to-plate test. The bearing structure is displayed in Figure 3. Bearing swing tests and associated test parameters were carried out according to SAE AS81820 standard. A performance evaluation testing machine was utilized for spherical plain bearings made by Yanshan University (The Key Laboratory of Aviation Science and Technology of Yanshan University for self-lubricating bearing technology). The specific setup of the test is illustrated in Figure 4. The applied loads in the friction test were set to 27 and 46 kN with a swing frequency of 0.2 Hz and a swing angle of ±25° at room temperature, and a relative humidity of 25%.

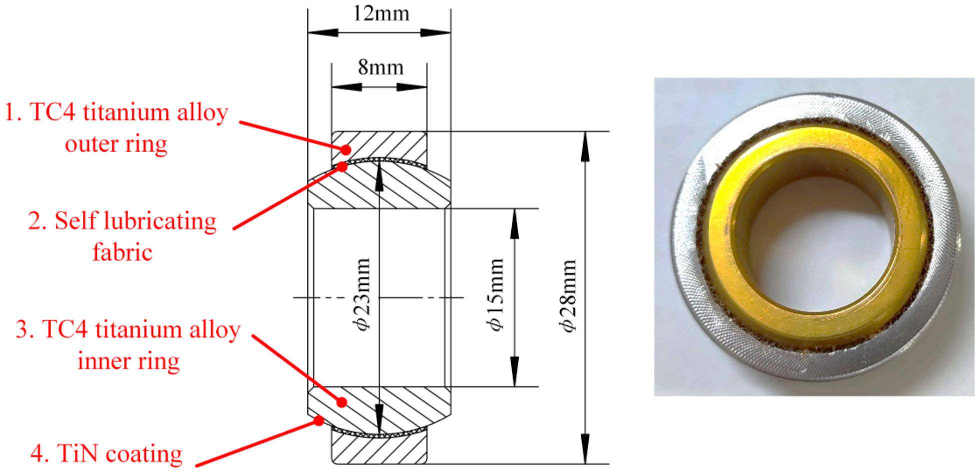


Figure 3. Schematic diagram of structure of GE15 self-lubricating spherical plain bearing with TiN coating.

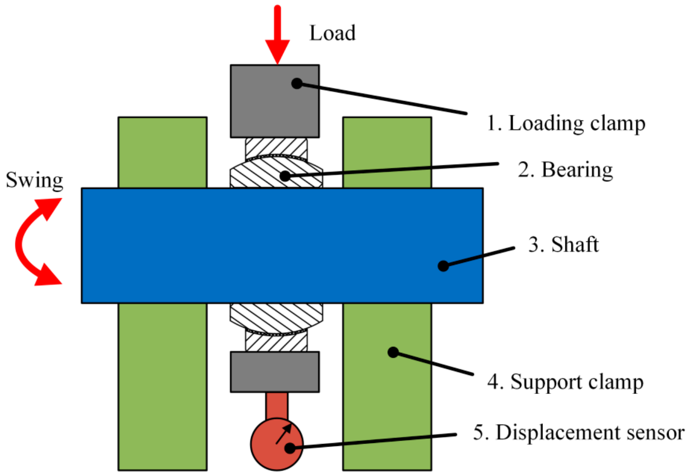


Figure 4. Schematic diagram of bearing swing test setup.

Each test was repeated three times and average data and standard deviations were reported accordingly for test reproducibility. A scanning electron microscope (SEM, Pro X, Holland Phenom, Funa Scientific Instruments (Shanghai) Co., Ltd., Shanghai, China) and an optical microscope on Anton Paar Conscan were employed to analyze the wear morphology. A supplementary analysis of worn surfaces of the sample using EDS (EDS, Pro X, Holland Phenom, Funa Scientific Instruments (Shanghai) Co., Ltd., Shanghai, China) was also conducted for elemental composition.

3. Results and Discussion

The friction coefficient under different working conditions is shown in Figure 5. When the load was 1000 N, the rotational speed increased from 100 to 400 r/min, and the friction coefficient decreased from 0.19 to 0.1. When the rotational speed was 200 r/min, the load increased from 500 N to 2000 N, and the friction coefficient decreased from 0.2 to 0.1. This phenomenon may be ascribed to the relatively small amount of debris generated by the fabric under lower working conditions, as well as the thin transfer film formed between the upper and lower samples. With increasing pressure and speed, the wear depth of the fabric increased from 0.06 to 0.09 mm, as shown in Figure 6. More debris formed a thick self-lubricating material layer under the relative motion of the upper and lower samples. With the increasing of load and rotational speed, the friction coefficient significantly decreased due to the relative sliding motion of PTFE debris as the intermediate layer between the upper and lower samples.

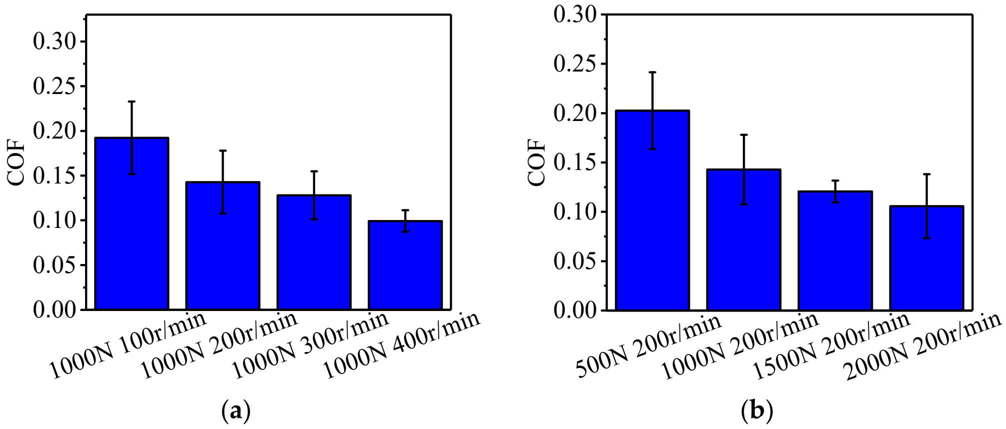


Figure 5. COF of TC4 titanium alloy with TiN coating on self-lubricating fabric under different working conditions (friction distance 560 m): (**a**) a fixed load of 1000 N and (**b**) a fixed speed of 200 r/min.

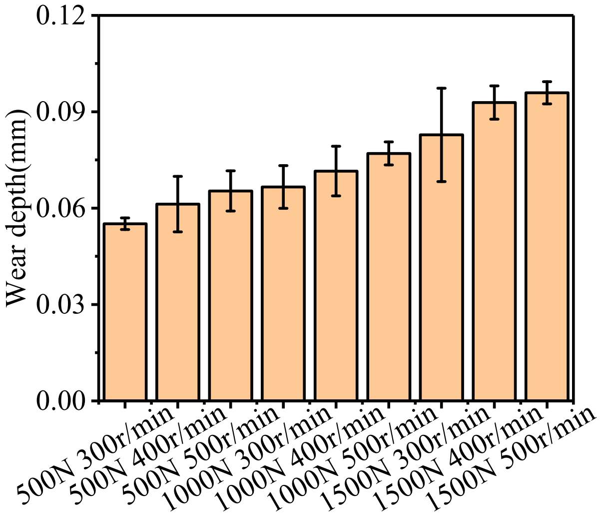
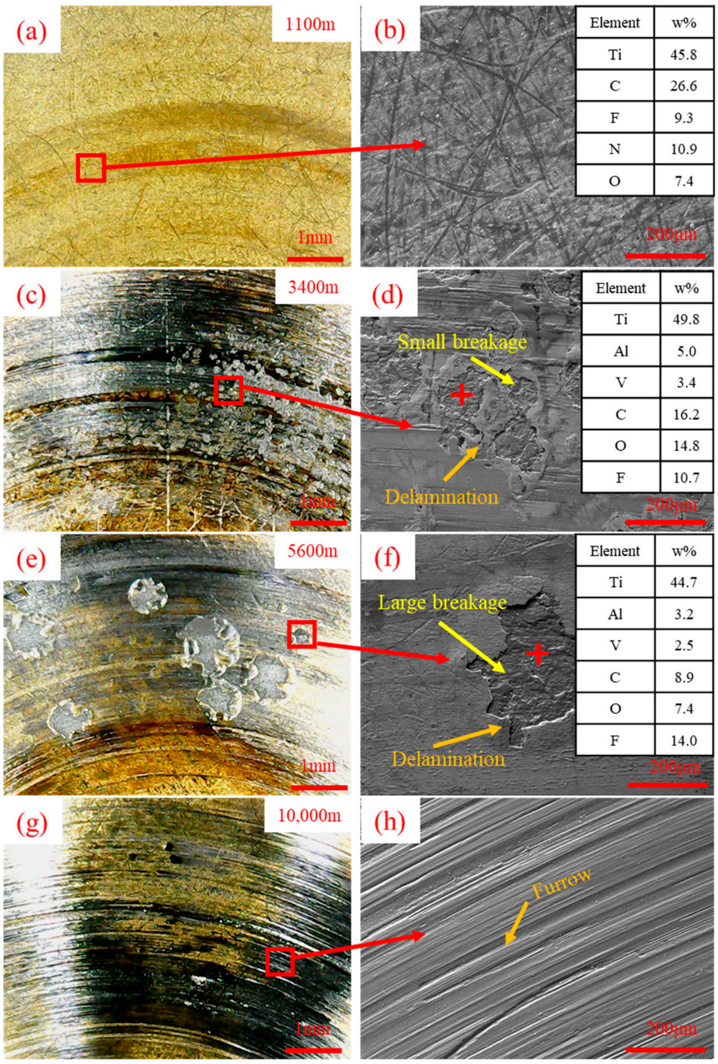


Figure 6. Wear depth of self-lubricating fabric under different working conditions (friction distance is set to 560 m).

The wear morphology of TiN coatings at different friction times is shown in Figure 7. As observed in Figure 7a,b, TiN coating surfaces are intact after friction taking place for 1100 m, and the EDS composition of the friction surfaces demonstrates the presence of F element, indicating a thin transfer film on top of the coating. After 3400 m, the surface appears to be damaged (Figure 7c), and the damage morphology becomes mainly scattered along with continuous small breakage. In addition, some transfer films changed color to black. This is probably because the surface of damaged TC4 titanium alloy produces metal element debris and oxide mixed with the transfer film generated during the friction [41,42]. As evidently shown in Figure 7d, the damage morphology of the coating possesses a layered feature, and the EDS analysis at the damaged area is indicative of Al and V elements, which means that the TC4 substrate is exposed after the wear of the coating. After 5600 m, the wear morphology of the coating is mainly reflected in large-scale coating peeling (Figure 7e). According to the EDS diagram, there is more apparent delamination damage taking place, as evidenced in Figure 7f.

Overall, the coating undergoes wear after friction in the range of 3400–5600 m, mainly in the form of coating peeling and delamination wear in different areas. Ludema [28] also observed a similar phenomenon when studying the friction between rubber and hard materials. It is well documented that when the rubber reaches the fatigue sliding distance for the surface failure of a hard material, typical wear can take place on the hard material surfaces. In addition, Sinhask [43] has indicated that defects such as pits and marks on hard material surfaces can cause a concentration of stress under a certain load due to repeated friction. After reaching a certain number of stress cycles, large cracks often appear in the stress concentration areas leading to the typical wear of hard materials.

After 10,000 m, there are a large number of furrow scratches (Figure 7g,h), and the coating at the scratch area is almost completely worn. Buckley [44] indicated that the d-bond value in the titanium electronic layer only accounts for 27%, resulting in high chemical activity on titanium alloy surfaces that are prone to adhesive wear. After friction with the fabric, a pile of debris mixed with titanium alloy and fabric debris can be formed [45]. Finally, after prolonged friction, the entire coating is completely worn off, further generating an abrasive wear morphology with large furrow scratches on the titanium alloy surfaces.



(b)

Element	w%
Ti	45.8
C	26.6
F	9.3
N	10.9
O	7.4

(d)

Element	w%
Ti	49.8
Al	5.0
V	3.4
C	16.2
O	14.8
F	10.7

(f)

Element	w%
Ti	44.7
Al	3.2
V	2.5
C	8.9
O	7.4
F	14.0

Figure 7. Wear morphology of TiN coating with different wear distances at 1000 N and 400 r/min: (**a**,**b**) 1100 m; (**c**,**d**) 3400 m; (**e**,**f**) 5600 m; (**g**,**h**) 10,000 m.

The wear morphology of the TiN film under different working conditions is illustrated in Figure 8. There is no wear effect on the TiN film at the speed of 300 r/min under a 500 N load (Figure 8a), while the TiN film at a speed of 500 r/min produces severe furrow wear marks (Figure 8c). Such a phenomenon suggests that the coating is more prone to wear with higher speed. However, under an applied load of 1500 N, there appeared to be no wear marks on the TiN surfaces, and a thick transfer film was formed on their surfaces. At the speed of 500 r/min, a self-lubricating layer formed by a large amount of debris was also generated on the TiN surfaces, as demonstrated in Figure 8b,d. This may be attributed to the relatively thin transfer film formed under a load of 500 N. At this time, the relative sliding position of the upper and lower samples was mainly associated with the transfer film between the TiN and the fabric, and the transfer film continuously occurred and peeled off during the friction process. After a period of time, the TiN coating underwent apparent fatigue damage, and the wear of the fabric increased under an applied load of 1500 N, resulting in an increase in wear debris per unit time. The relative sliding position of the upper and lower samples was mainly between the transfer film and polymer debris, and a large amount of debris from the fabric debris could be accumulated and compressed between the transfer film and the fabric with the formation of a thick self-lubricating layer [46].

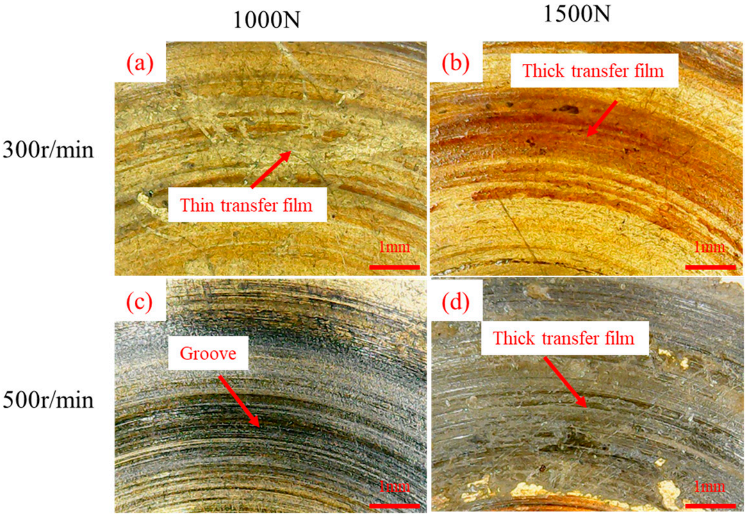


Figure 8. Wear morphology of TiN coating under different working conditions, (friction distance 8000 m): (**a**,**b**) 300 r/min, 1000 N, 1500 N; (**c**,**d**) 500 r/min, 1000 N, 1500 N.

The wear morphology of the fabric under different working conditions is displayed in Figure 9. As illustrated in Figure 9c, the scratches are manifested on the fabric at a load of 1000 N and a speed of 500 r/min. In the SEM image, large delamination has been detected, mainly arising from the scratches on the fabric after the wear of the titanium alloy substrate. In other working conditions shown in Figure 9a,b,d, the wear morphology of the fabric became relatively uniform, and the worn appearance of the fabric was rather flat (Figure 9e,f), which corresponds to the wear morphology of titanium alloy surfaces.

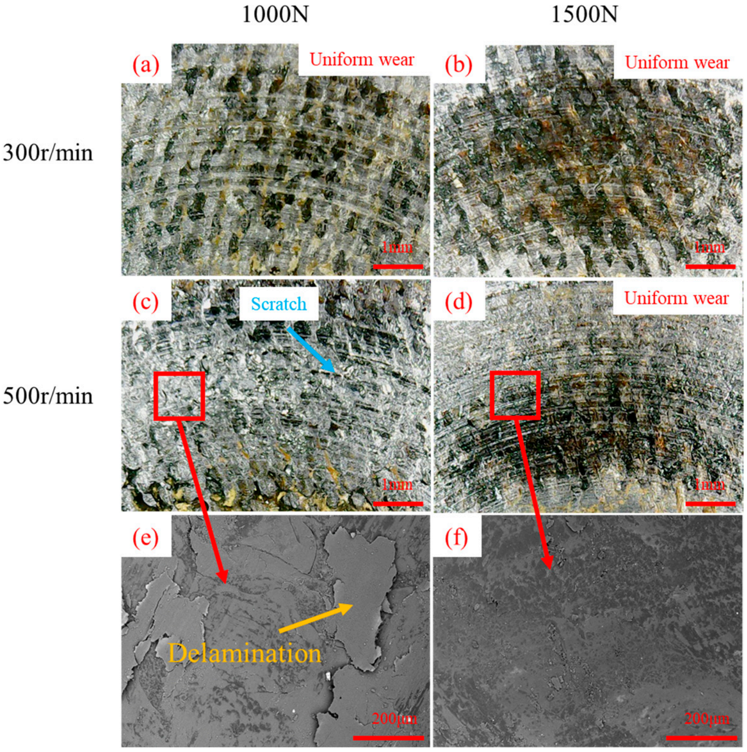


Figure 9. Wear morphology of self-lubricating fabric under different working conditions, (friction distance: 8000 m): (**a**,**b**) 300 r/min, 1000 N, 1500 N; (**c**,**d**) at 500 r/min, 1000 N, 1500 N; (**e**,**f**) 500 r/min, 1000 N, 1500 N. All SEM morphological images have local magnifications.

The wear depth of the fabric in terms of swinging distance is shown in Figure 10. As the bearing swung for 500 m (25,000 times), the wear amount of the fabric reached 0.06 and 0.04 mm at 46 and 27 kN, respectively. This confirms that the bearing can meet the service life requirements of SAE AS81820 standard. The fabric wear was faster at the early stage of the test at 46 kN, reaching 0.014 mm after swinging for about 20 m. Moreover, the fabric wear increased significantly after the swinging for 120 m at 27 kN. Overall, this result indicates that the load had a significant impact on bearing wear at the early stage.

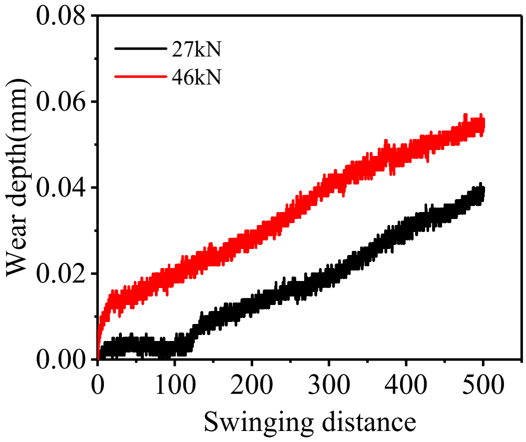
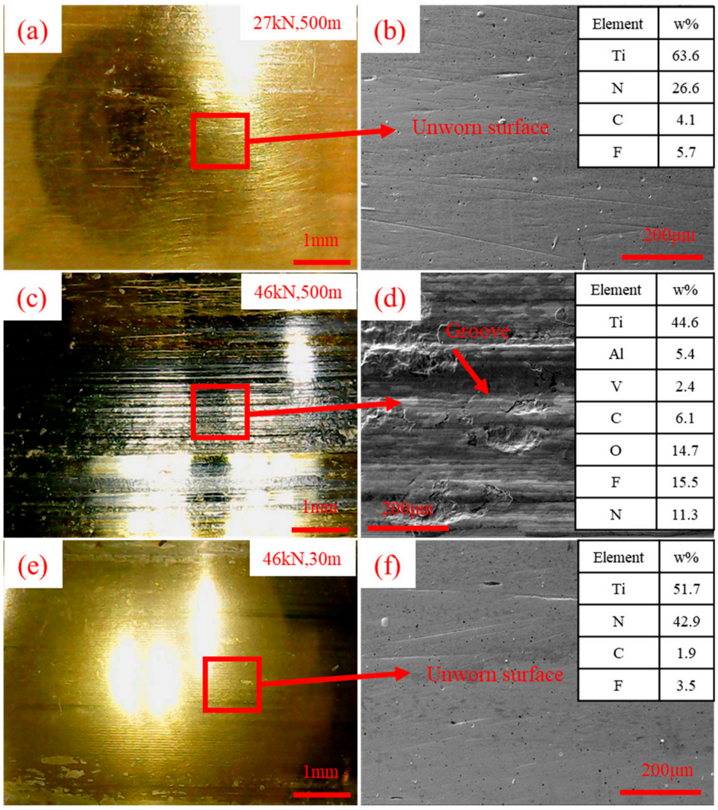


Figure 10. Wear depth vs. swing distance diagram for self-lubricating spherical plain bearing fabric.

The surface morphology of the titanium alloy inner ring under friction is presented in Figure 11. According to Figure 11a, the titanium alloy inner ring surface is intact without any damage morphology at 27 kN. The EDS results show the evident presence of C and F elements (Figure 11b), indicating a thin transfer film on the surface. However, the TiN coating on the surface of the titanium alloy inner ring possessed a large area of peeling and deep furrow scratches at 46 kN (Figure 11c). The EDS results indicate the presence of Al and V elements. The TC4 titanium alloy substrate has been externally exposed (Figure 11d) during the swinging process of the inner spherical surface of the bearing because the stress on the fabric at this location could reach its highest level, along with the greatest fabric wear [2]. After the occurrence of debris, a portion of the debris could contribute to the formation of a transfer film while a large portion of the debris became squeezed out of the contact surfaces with the arc part of the inner ring surface, which would not be able to generate a thick self-lubricating layer. The formation and peeling process of the transfer film on the TiN coating surfaces appeared to be more severe under large loads, thus resulting in coating damage and furrow scratches. However, there was no wear effect on the surface of the titanium alloy inner ring within 30 m for the bearing swung at 46 kN (Figure 11e,f). It is suggested that the wear of the TiN coating could not occur in the early stages of wear, and the wear distance had a significant impact on the wear of the coating.

The wear morphology of the bearing fabric is displayed in Figure 12. The fabric wear was relatively uniform under an applied load of 27 kN, and the wear surface of the fabric in SEM analysis was relatively flat with a small amount of layering and cracks (Figure 12a,b). The fabric wear was closely related to the coating damage position of titanium alloy inner ring at the load of 46 kN, and there was a clear sign of large delamination in the fabric at the coating damage position (Figure 12c,d). This phenomenon implies that the fabric wear at this location was more severe. The bearing test results suggest that prepared titanium alloy self-lubricating spherical plain bearings with a TiN coating are more suitable for use under a load of 27 kN.



Element	w%
Ti	63.6
N	26.6
C	4.1
F	5.7

Element	w%
Ti	44.6
Al	5.4
V	2.4
C	6.1
O	14.7
F	15.5
N	11.3

Element	w%
Ti	51.7
N	42.9
C	1.9
F	3.5

Figure 11. Wear morphology of the inner ring surface of self-lubricating spherical plain bearings: (**a**,**b**) applied load of 27 kN, swinging distance of 500 m; (**c**,**d**) applied load of 46 kN, swinging distance of 500 m; (**e**,**f**) applied load of 46 kN, swinging distance of 30 m.

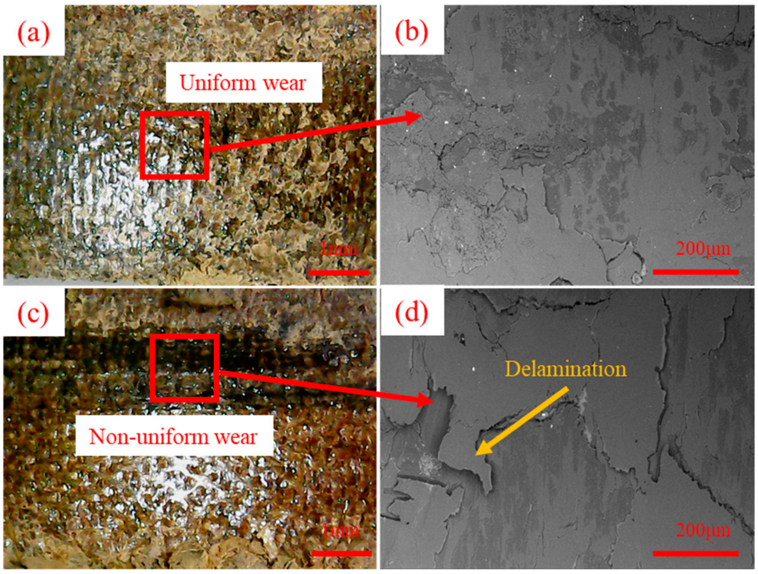


Figure 12. Wear morphology of self-lubricating fabrics: (**a**,**b**) applied load of 27 kN, swinging distance of 500 m; (**c**,**d**) applied load of 46 kN, swinging distance of 500 m.

4. Conclusions

This study focused on the problem of coating damage in titanium alloy self-lubricating spherical plain bearings with a TiN coating. The friction and wear properties of the TiN coating against the self-lubricating fabric under different working conditions were holistically studied, and the wear mechanism of the TiN coating was explicitly analyzed.

The applicable working conditions of GE15 type bearings were further studied as well. The main conclusions can be made as follows.

The friction coefficient between the TiN coating on the titanium alloy surface and the PTFE/Kevlar self-lubricating fabric ranges from approximately 0.1 to 0.2, and increasing working conditions can reduce the friction coefficient accordingly.

TiN coatings can maintain a certain friction distance without wear. Increasing friction speed and load can make the TiN coatings more prone to wear. A thick transfer film can protect the TiN coating from wear. The mechanism of TiN coating wear using PTFE/Kevlar self-lubricating fabric is mainly ascribed to fatigue wear caused by the repeated formation and peeling of the transfer film. After the coating is damaged, the fabric and titanium alloy substrate are directly prone to friction leading to abrasive wear, which further causes extensive wear on the substrate and coating.

When taking into account the self-lubricating spherical plain bearing made of GE15 titanium alloy with a TiN coating, the fabric wear of the bearing after swinging for 500 m (25,000 times) at 27 kN was found to be approximately 0.04 mm. At the same time, the inner ring of the bearing with a TiN coating appeared not to be damaged, which suggests that the bearing is more suitable for low-speed swinging conditions at a load of 27 kN.

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