Chapter 6

Effects of Different Materials on the Tribological Performance of PVD TiN Films under Starved Lubrication Regime

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Abstract

Grit blasting is one simple but effective method to modify the morphology of material surface and can improve the tribological performance. In this study, a thick TiN film was prepared by arc ion plating on the steel disk treated with grit blasting, and the rough surface coated solid film was obtained. The tribological properties of solid film against different materials were evaluated under starved lubrication regime. The results showed that the friction coefficients of rough titanium nitride (TiN) films were lower than those of rough steel disks exclude alumina ball under starved lubrication, and the wear rates of TiN film were negligible due to the high hardness of TiN film and small contact area. For four kinds of balls including steel ball, silicon nitride, zirconia, and alumina, the wear scar diameter of steel ball is biggest, and the wear scar diameters of other balls are small. The hardness of steel ball is less than others, which results in the easy abrasion and increases the contact area to reduce the pressure. So the friction coefficient of TiN against steel is low and steady.

Keywords: TiN film, grit blasting, tribological properties, starved lubrication

1. Introduction

Titanium nitride (TiN) film is applied as a hard coating in industrial fields, which is prepared by physical vapor deposition (PVD), chemical vapor deposition (CVD), and thermal spraying techniques. Because of the B1 NaCl-type structure, titanium nitride exhibits some intrinsic characteristics such as high hardness, high melting point, chemical stability, and wear resistance [1]. For these reasons, TiN is extensively used on cutting blades for longer service life, safe medical instruments, diffusion barrier in semiconductor apparatuses and architectural decoration fields, and so on.

As one wear-resistant coating, the coefficient of friction and wear rate of TiN films are high under dry friction conditions. Efforts to improve the tribological properties of TiN have included changed deposition parameter and doped chemical elements during the film preparation [2–5], surface treatments, and modifications during film post-processing [6–9].

Surface treatments are applied extensively to improve the mechanical properties and tribological performance of many materials, which contain anodizing and hard anodizing, laser texture, mechanical rough, surface hardening, and so on. Among all the methods, blasting with different particles, as one kind of surface treatment technologies, is an effective low-cost surface-modifying method, which can be used to enhance the mechanical character in biomedical [10], automotive [11, 12], aerospace sectors [13], and other industrial applications [14, 15].

Blasting with different particles can enhance mechanical properties of many materials and protected coatings. Lee found that the shear loads for the Al5052/CFRP composites fabricated with treated Al5052 sheet, of which surface roughness (Ra) values were 1.84 and 4.25 μm, were three and five times higher than that of the composite fabricated by using the untreated sheet with Ra value of 0.73 μm, and the bending stress increased from 200 to 400 MPa [12]. During cold rolling process, weight losses for steel sheets finished by conventional acid pickling was greater than those of steel sheets finished using shot blasting [16]. Shot blasting treatment can improve the steam oxidation resistance of austenitic steel compared with previous report [17]. Abusuilik has investigated the effects of various surface treatments on the properties and performance of the hard coating, and found that material transfer and build-up at the coating surface were higher for the surfaces treated by grinding and shot blasting than those treated by other methods [18]. During the open pore metallic foam core sandwich panels prepared by thermal spraying of a coating, Salavati found that the coating porosity and adhesion strength were determined by the substrate surface roughness, which could be controlled by grit-blasting parameters [14]. Other studies of modified surface in metal substrates and some hard coatings on tribological properties are carried out under fully flood lubrication condition. Nakano investigated the effect of pattern texture by grit-blasting method for their tribological properties [19]. Groove pattern texture suppressed the generation of the hydrodynamic pressure, and the lubricating condition of the tests became boundary lubrication. Because the lubrication film became thicker and the hydrodynamic lubrication region was expanded for dimple pattern texture, the lower friction coefficient was lower than that of groove pattern texture. Additionally, some investigations of modified surface under starved lubrication are carried out in last decade, such as laser texture on steel [20, 21], copper [22], hard coatings [23], and piston ring-cylinder [24].

However, only limited studies can be found in the literature associated with the friction and wear behavior of physical vapor deposited TiN film covered the grit-blasting steel substrate sliding against different materials under starved lubrication regime. This paper was investigated the tribological performance of different friction pairs under starved lubrication regime after grit blasting. And the tribological mechanism for different materials was discussed.

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2. Experimental methods

2.1. Grit blasting and TiN film prepared

AISI 440c stainless steel was chosen as substrate for sand blasting and TiN film prepared. Before grit blasting, the stainless steel substrate was grinded with emery papers and rinsed with acetone and ethanol to get rid of impurity. Grit blasting was carried by a handheld sand blasting machine (China, JICHAN TECH) using 60# Al_2O_3 particles (diamond 300 μm, JICHAN TECH). After then, the morphology of steel substrate was characterized by a JSM-5600LV scanning electron microscope, which attaches with energy disperse spectrometer.

The hard titanium nitride film was prepared using ion plated technology with Hauzer Flexicoat 1200 coating. The deposition parameters were following: 60 A of arc current, 200 V of bias volt, 400 centigrade degree of steel disks, 100 min of deposition time, and 1.8 Pa of N_2 pressure.

2.2. Friction tests

Friction tests were conducted to evaluate the tribological properties of hard TiN film covered the grit-blasting steel substrate against four different material ball counterbodies using a ball-on-disk tribo-tester under starved lubrication regime. The four different upper balls were made of bearing steel, silicon nitride, alumina, and zirconia, which diameter is 8 mm. And the hardness of bearing steel was lower than those of TiN film and other materials. The diameter of the lower disk covered with TiN film was 24 mm. The surface roughness of the test sample was measured with the Micro-Map surface mapping microscope. The initial average surface roughnesses (Ra) of all the upper balls are less than 0.03 μm, and the roughness of lower disk covered TiN film was 8.2 μm which was much higher than upper balls. Friction tests were carried out in ambient temperature and atmospheric environment for 120 min of duration under 5 N of normal load and sliding speed of 31 m/min. The coefficient of friction was recorded automatically during the friction test.

In order to obtain the starved lubrication regime, the small amount of lubricating oil was injected the surface of lower TiN film-covering disk. The calculated thickness of oil film was lower to 3 μm. After friction tests, all the balls and disks were cleaned with acetone by ultrasonic washer for three times. The typical surface morphologies and chemical compositions of friction tracks in lower disks and wear scars in upper balls were analyzed by scanning electron microscopy (SEM), which attached an energy dispersive spectrometer.

3. Results and discussion

3.1. Morphology and roughness

After grit blasting, the substrate surface is nonmetal shiny and matte-like. The surface morphology of as-obtained grit-blasting steel substrate was shown in **Figure 1**. It can be seen that surface roughness of the steel substrate was enlarged obviously than the polished samples.

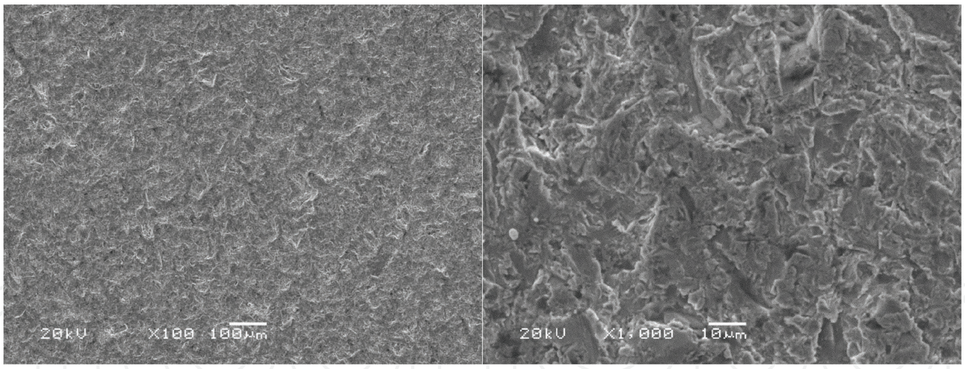

Figure 1. The morphology of grit-blasting steel substrate.

However, there are not clearly defects and concave pits in the substrate surface. The average Ra value of steel substrate and polished samples are 7.5 and 0.03 μm. Grit-blasting substrate was larger than that of polished sample.

The surface morphology of ion plating TiN film covered a grit-blasting substrate is shown in **Figure 2**. Compared with the surface morphology before covered TiN films, there is not notable difference for surface morphology of TiN-covered samples. The average Ra value of as-prepared TiN film covered grit-blasting steel substrate was 8.2 μm, which is similar to that of grit-blasting substrate. The film thickness of TiN film is 4 μm, which is measured with the profile meter.

3.2. Friction test results

The histogram of average friction coefficient of grit-blasting steel substrate and TiN films sliding against with different upper balls was shown in **Figure 3**. Because of the shorter friction duration for only few minutes, the average friction coefficient of alumina ball is not presented in the figure. For three other different balls, the average friction coefficient of silicon nitride ball against grit-blasting steel substrate is as same as that of silicon nitride ball sliding against TiN films. The average friction coefficients of TiN films were lower than those of grit-blasting steel substrate for steel ball and zirconia ball under the same lubrication conditions.

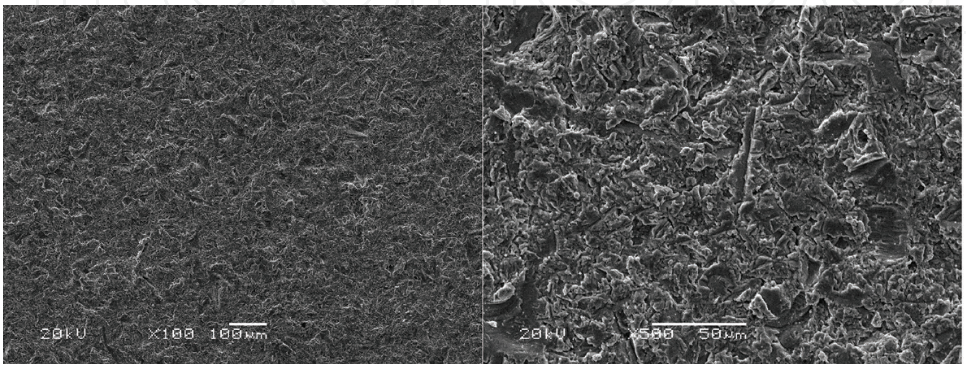

Figure 2. Surface morphology of ion plating TiN film covered the grit-blasting substrate.

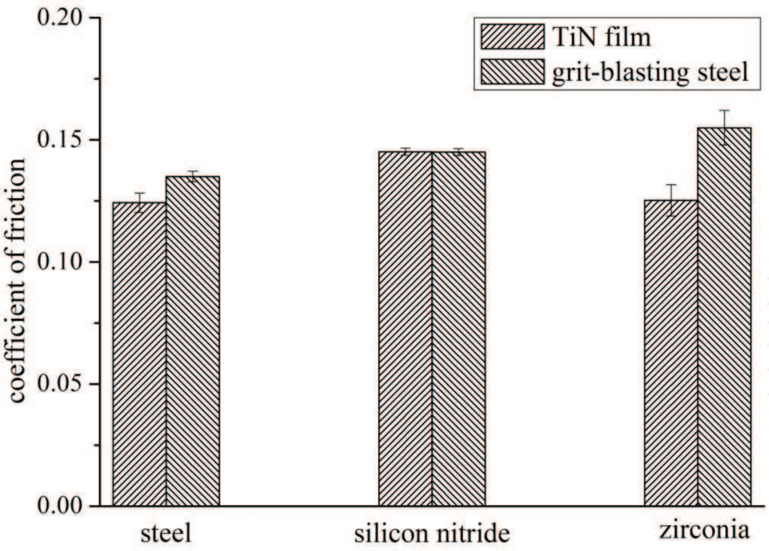

Figure 3. Histogram of average friction coefficient of grit-blasting steel substrate and TiN film sliding against with different upper balls.

The average friction coefficients of TiN film and grit-blasting steel substrate sliding against steel ball were 0.125 and 0.135, respectively, which reduced by 7%. For zirconia ball, the average friction coefficients of TiN film and grit-blasting steel substrate were 0.125 and 0.155, respectively, which reduced by 19%.

The tribological properties of grit-blasting steel and TiN film against four different upper balls were carried out by a rotating tribometer with ball-on-disk of configuration. The coefficient of friction of grit-blasting steel substrate was shown in **Figure 4**. For different upper balls, their friction behaviors are different. The friction duration of alumina balls is worse than steel, zirconia, and silicon nitride balls. The friction duration was only 2 min when the coefficient of friction is over the limited value. During the alumina ball sliding against grit-blasting steel disk, its coefficient of friction was 0.13 and increased drastically after 1 min. Its friction duration was very shorter than other balls. For other different upper balls of steel, silicon nitride and zirconia balls, they exhibited the similar trend that the coefficient of friction elevated gradually and reached the steady value of 0.17. However, the friction duration of three different upper balls is as long as 120 min, the reaching time of steady-state friction coefficient is different. The coefficient of friction raised to steady state for steel ball after 50 min. For silicon nitride and zirconia balls, the times to reach the steady-state friction coefficient are 10 and 25 min, respectively.

The real-time friction coefficients of TiN films covered grit-blasting steel substrate against four different upper balls are shown in **Figure 5**. The friction coefficient of TiN film against alumina ball elevated drastically and over the limited value of friction coefficient for a very short time, which was similar with the trend of grit-blasting steel substrate against alumina ball. For three other upper balls, the friction duration of TiN films can last with a steady-state friction coefficient until friction experiment ended up. However, the undulations of friction coefficient of TiN films sliding against silicon nitride, steel, and zirconia balls are smaller than those of grit-blasting steel disks.

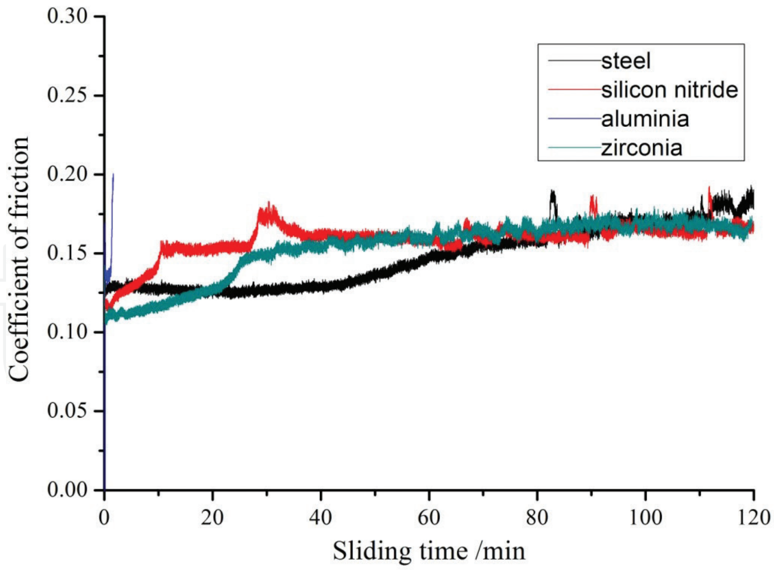

Figure 4. The coefficient of friction of grit blasting steel-disk sliding against different upper balls.

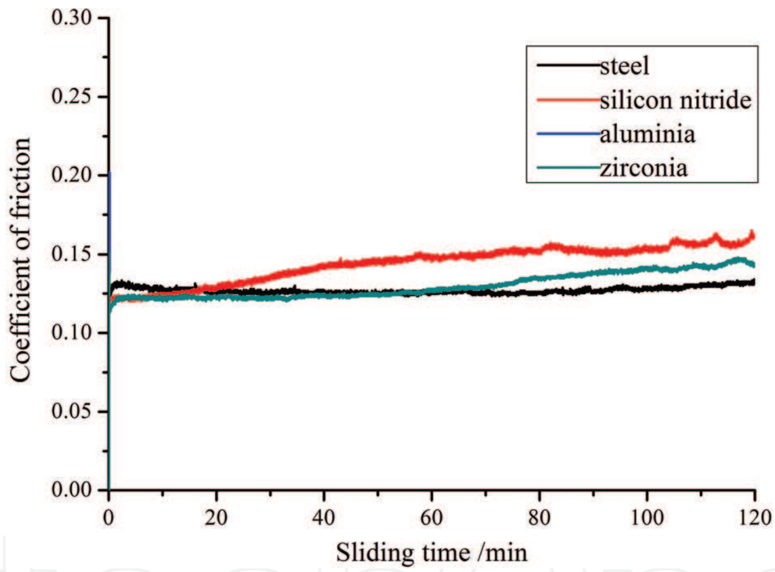

Figure 5. The coefficient of friction of TiN films sliding against different upper balls.

3.3. Surface analysis

Figure 6 shows the surface morphology of wear track in TiN film and upper steel ball under the starve lubrication regime. It is not seen that there is notable wear trace in the track from the low-resolution figure, which amplification is 100. However, there is some smooth pit in the wear track from the high-resolution figure, which amplification is 500. It can be attributed to the transfer phase from the upper steel ball and the plastic deformation of micro-bulge in the lower steel substrate. Because TiN is much hard than the soft steel ball, so the TiN film covered the grit-blasting steel substrate plays a similar role of sandpaper for upper steel ball. It is confirmed from the surface morphology of upper steel ball that there is a round wear scar with the diameter of 0.63 mm in the upper steel ball. The bigger wear scar of steel ball can result in reduced normal pressure, so the friction coefficient of TiN film against steel ball was steady.

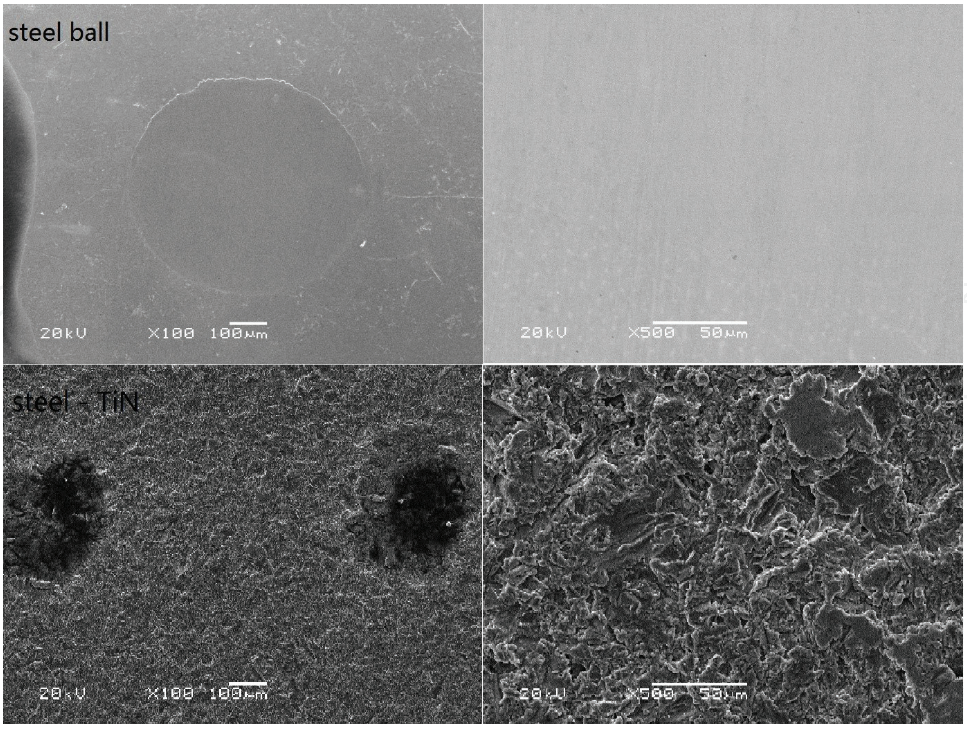

Figure 6. The morphology of wear track in TiN film and wear scar in upper steel ball after friction tests under the starve lubrication regime.

The surface morphology of wear track in TiN film and wear scar in upper silicon nitride ball were shown in **Figure 7**. It is seen that there is not obvious wear and more smooth pits in the wear track of TiN film. There is a wear scar with the diameter of 0.37 mm in the upper silicon nitride ball. Although both titanium nitride and silicon nitride are very hard materials, the micro-bulge in the lower rough disk could be deformed under high pressure. This resulted in the bigger real contact area, which means the friction force of among all the micro-bulge with upper ball increased. It is confirmed that the real-time friction coefficient raised during the later stage of the friction tests.

The surface morphology of wear track in TiN film and wear scar in upper zirconia ball are shown in **Figure 8**. It is also seen that there is not obvious wear and more smooth pits in the wear track of TiN film, which is similar with the wear track of TiN film sliding against silicon nitride ball. There is a wear scar with the diameter of 0.32 mm in the upper zirconia ball. Very small pores can be found in the wear scar of upper ball. These pores could absorb the lubricating oils on the surface of lower disk. During the sliding process, the absorbed oils in the pores can improve tribological properties by avoiding the direct contact of rubbing surface. So, the friction coefficient of TiN film against ZrO_2 was steady.

The surface morphology of wear track of TiN film and wear scar in upper alumina ball is shown in **Figure 9**. Compared with the negligible wear of other different ball, there is obvious wear trace from the low-resolution figure and bigger smooth contact area from the high-resolution figure in the TiN film. The bigger the contact area is, the bigger the friction force between the contact interface. So, the friction coefficient increases during the sliding process. There is a very small wear scar in the alumina ball as compared to the wear scars in the other different upper balls. It means that the material in the smooth contact area is from the lower disk and lubricating oil, not upper ball.

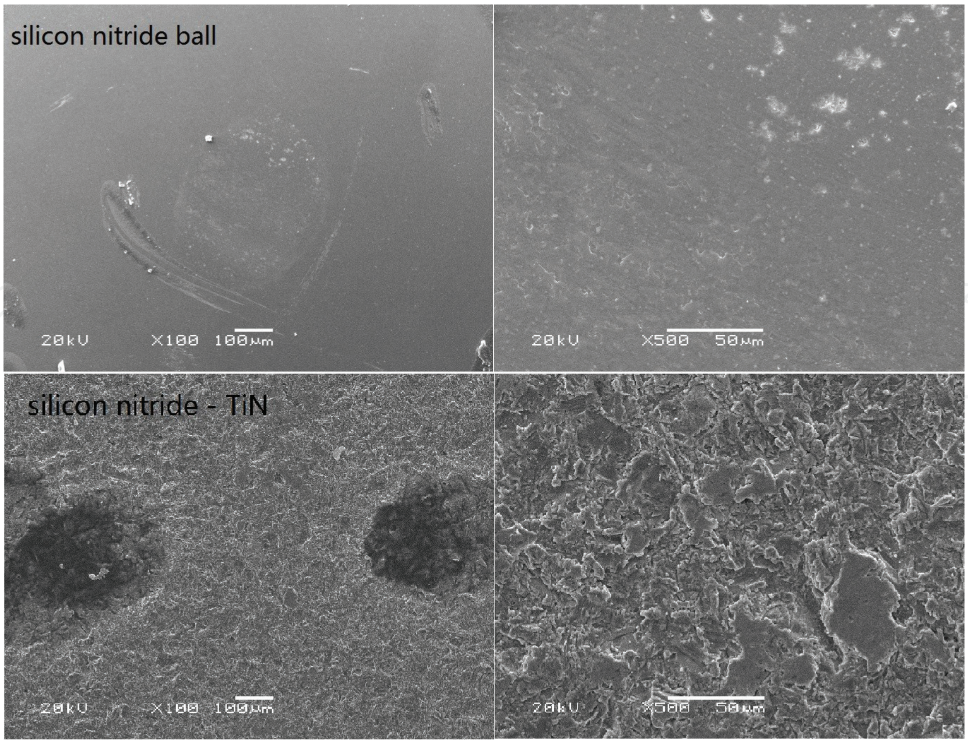

Figure 7. Morphology of wear track in TiN film and wear scar in upper silicon nitride ball after friction tests under the starve lubrication regime.

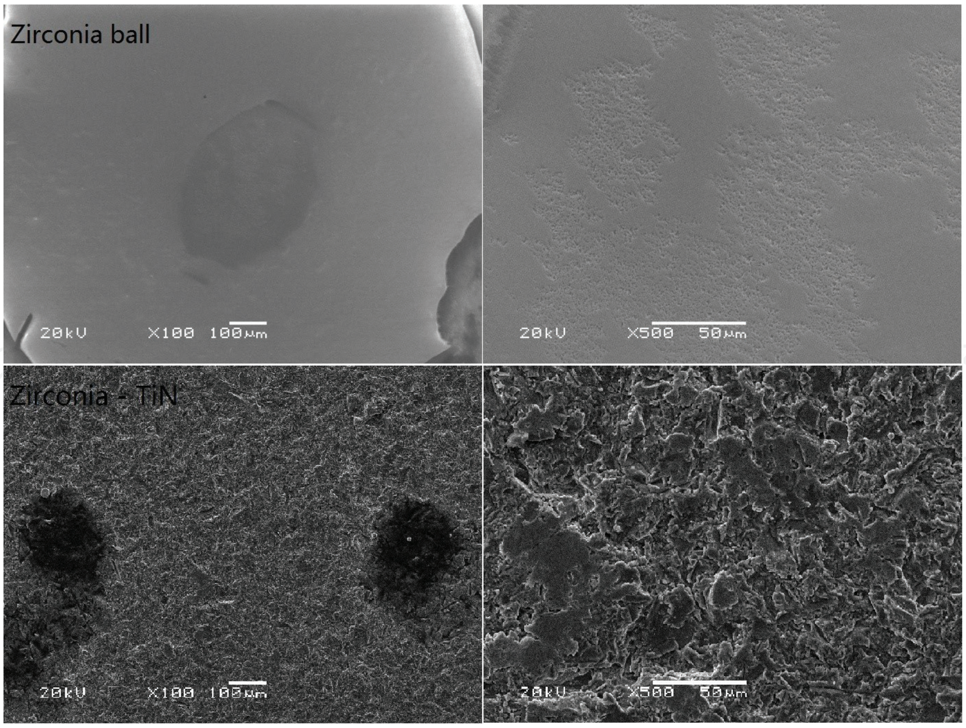

Figure 8. The morphology of wear track in TiN film and wear scar in upper zirconia ball after friction tests under the starve lubrication regime.

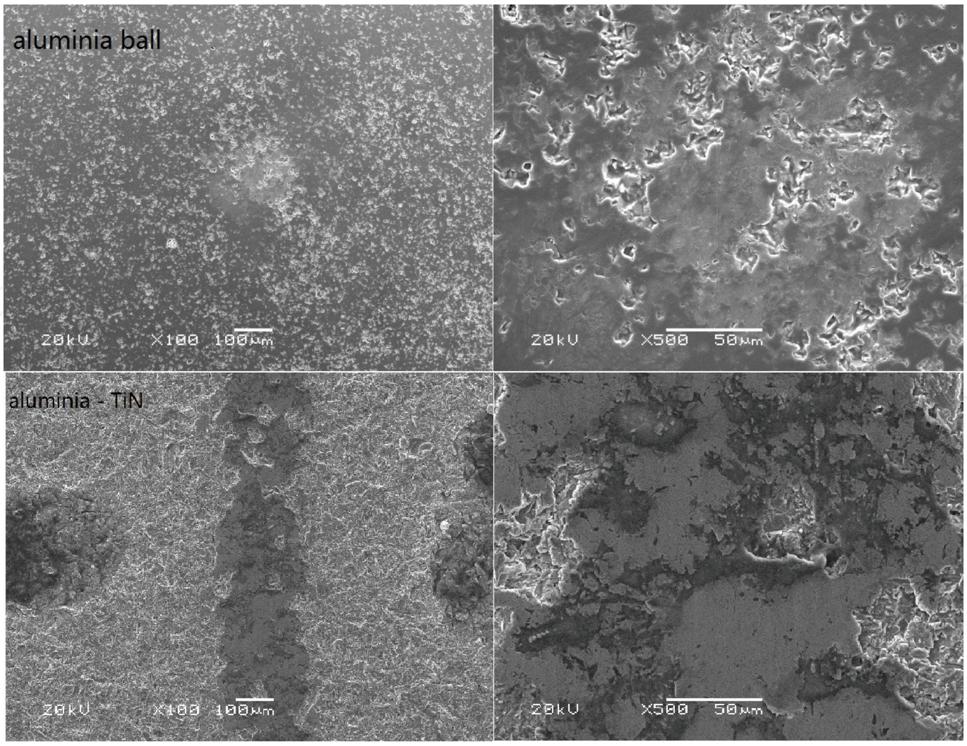

Figure 9. The morphology of wear track in TiN film and wear scar in upper aluminia ball after friction tests under the starve lubrication regime.

The tribological performance of friction pairs is attributed to many factors, such as the natural lubricating characteristic, the physic-chemical properties of different materials, the content of lubricating oil, experiment conditions, and so on. In this paper, however, the average oil thickness is 3 μm before the test, the real oil content about the contact area is more as compared to before the test because of the aggregation effect of lubricating oil caused by the surface free energies of different materials.

For the four kinds of upper balls, the lubricating abilities are different. Both zirconia and silicon nitride could exhibit better self-lubricating performance than alumina and steel. So, the friction durations of zirconia and silicon nitride are longer than alumina when they slid with TiN film under starved lubrication conditions. For one steel ball, its hardness is much smallest in all of the test balls. And the steel ball was worn in the sliding process.

4. Conclusion

One thick TiN film was prepared by ion-plated technology on the grit-blasted steel substrate. The tribological performance was evaluated with four upper balls made up of different materials under the starved lubrication regime. Compared with their higher friction coefficients for grit-blasting steel against different balls, the friction coefficients for TiN films on the grit-blasting steel were lower and steady. It was due to the hardness of TiN film and small contact area in the contact zone. During the sliding process, the strong load capacity of TiN films ensures the negligible wear rate, and the small contact area between of the friction pairs plays an important role in the steady friction coefficient.

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