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Load-Dependent Tribological Transition of PVD Coatings on Ti-6Al-4V in Wet and Dry Environments

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ABSTRACT

The tribological behavior of nitride coatings is highly influenced by the applied load, which dictates contact stress, micro-crack formation, and plastic deformation. This study examines the load-dependent performance of TiN- and TiCN-coated Ti-6Al-4V in both dry and wet sliding conditions. We did ball-on-disk tests at 1, 2, and 5 N for 3000 cycles with 6 mm alumina counterfaces. The friction coefficient (μ), wear morphology, and counterface scars were characterized systematically. At 1 N, both TiN and TiCN showed an unstable COF because of the formation of adhesive junctions. At 2 N, TiCN partially stabilized at ~0.45 through hardness and strain hardening, but TiN stayed at ~0.5. At 5 N, TiCN had a stable COF of about 0.4, but it also had brittle micro-cracks. TiN, on the other hand, had plowing grooves with a COF of about 0.45. Wet sliding lowered the COF in all cases, but brittle cracking and plowing stayed the same. Wear tracks showed that TiCN had mechanisms that controlled fractures, and TiN had wear that was mostly caused by abrasion. Counterface analysis corroborated abrasive debris transfer instead of self-lubrication. These findings indicate that load dictates the shift among adhesion, strain hardening, and brittle/plowing mechanisms in nitride coatings, with TiCN providing superior hardness-controlled protection yet diminished fracture resistance.

Keywords: Ti-6Al-4V; Tribology; Load dependence; PVD coatings

1. Introduction

Ti-6Al-4V is a titanium alloy that is commonly used for structural and biomedical parts, but it doesn't work well in tribological applications because it has a high COF, severe adhesive wear, and material transfer [1]. To reduce this, PVD coatings like TiN and TiCN have been used a lot to change the surface [2]. TiN coatings are good for cutting tools and biomedical devices because they are chemically stable, moderately hard (about 20 GPa), and resistant to wear. TiCN, a carbonitride, has an even higher hardness (about 29 GPa), better toughness, and better resistance to wear from rough surfaces [3].

But the performance of these nitride coatings depends a lot on the load that is applied while sliding [4]. At low loads, adhesive micro-junctions take over, which makes friction unstable. At moderate loads, strain hardening and stopping plastic deformation make things more stable. Ceramic-like coatings may break or peel off when they are under a lot of stress [5]. So, load controls the change from adhesion-controlled, hardness-controlled, and fracture-controlled mechanisms. Prior research has documented these behaviors separately; however, a comprehensive comparison of TiN and TiCN during both dry and wet sliding across various loads is still insufficient.

This research fills this void by assessing TiN- and TiCN-coated Ti-6Al-4V under 1, 2, and 5 N in both dry and wet environments. The analysis of COF evolution, wear track morphology, and counterface scars elucidates the mechanistic transitions. The interaction of hardness, toughness, and fracture resistance in determining tribological response is given special attention.

2. Materials and Methods

Ti-6Al-4V disks with a diameter of 40 mm and a thickness of 3 mm were prepared and polished to a mirror finish with a surface roughness of Ra < 0.05 µm. TiN and TiCN coatings were deposited using a physical vapor deposition (PVD) process, achieving coating thicknesses of approximately 0.8–1.0 µm. The hardness results are summarized in Table 1.

Tribological tests were conducted on a ball-on-disk tribometer using 6 mm alumina balls as counterfaces. Normal loads of 1, 2, and 5 N were applied, with a sliding speed of 3.14 cm/s and a total of 3000 cycles. Tests were carried out in two environments: (i) dry sliding in ambient laboratory air and (ii) wet sliding in 0.9% NaCl aqueous solution. The schematic of the ball-on-disk tribometer is presented in Fig. 1.

Table 1: Elemental composition and hardness of TiN and TiCN coating films.

Coating Type	N (at.%)	Ti (at.%)	C (at.%)	O (at.%)	Cr (at.%)	Hardness (HV)
TiN	26.56	73.44	–	–	–	2,300
TiCN	13.22	75.41	11.37	–	–	3,000

Fig. 1: Schematic of the ball-on-disk tribometer used in this experiment

3. Results and Discussion

3.1 Element Compositions

The elemental composition and hardness values of the TiN and TiCN coating films are presented in Table 1. The TiN film is mostly made up of titanium (73.44 at.%) and nitrogen (26.56 at.%), and there are no detectable amounts of carbon, oxygen, or chromium. The TiCN film, on the other hand, has a lot of carbon (11.37 at.%), titanium (75.41 at.%), and nitrogen (13.22 at.%) in it. The TiN coating was found to be 2,300 HV hard, but the TiCN film was found to be much harder, at 3,000 HV. These variations in elemental composition and mechanical properties signify the unique attributes and prospective performance benefits of each coating in tribological contexts.

3.2 Friction Behavior at Different Loads

The evolution of COF under dry sliding is presented in Fig. 2-4. TiN had an average COF of about 0.64 at 1 N, which is much higher than TiCN's average COF of about 0.25. At 2 N, TiN rose to about 0.66, which meant that the load was causing plowing and the start of micro-cracks. TiCN stayed the same at about 0.25 because its high hardness kept it from bending. At 5 N, TiN had a high COF of about 0.65, which was caused by abrasive wear and crack coalescence. TiCN, on the other hand, dropped slightly to about 0.22, showing that it can handle high contact stress better. When sliding on wet surfaces (Fig. 5), COF values dropped by about 15–20%. TiCN dropped to about 0.20, while TiN stayed high at about 0.55. This shows that lubrication lowers adhesion but doesn't change the main ways that wear happens.

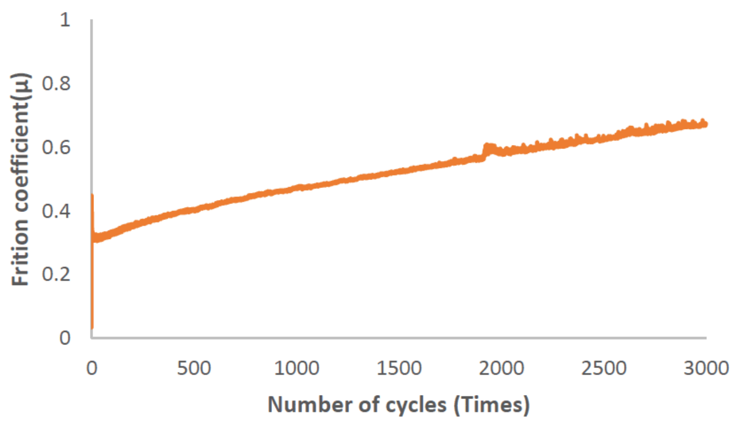

Fig. 2: Evolution of COF under dry sliding at 1 N of the TiCN-coated Ti-6Al-4V

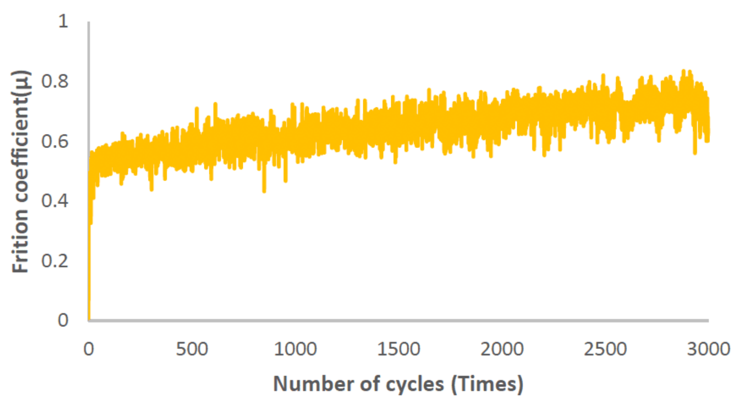

Fig. 3: COF evolution under dry sliding at 1 N of the uncoated Ti-6Al-4V surface

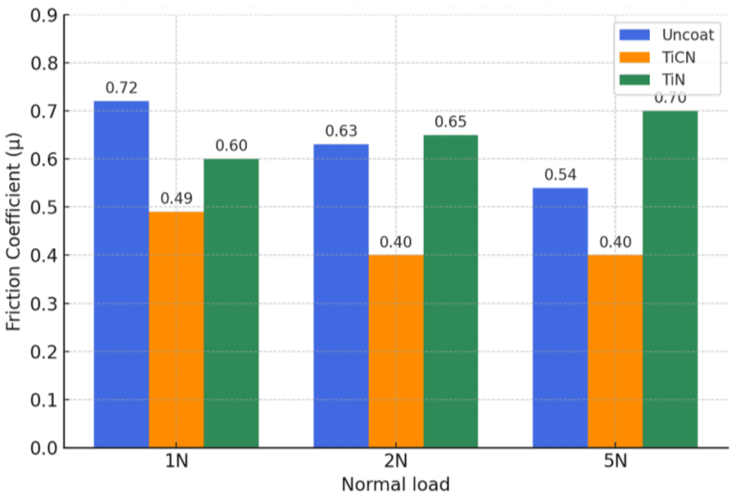

Fig. 4: Comparative COF values of TiN and TiCN coatings at 1 N, 2 N, and 5 N under dry sliding

COF evolution under wet sliding is presented in Fig. 5. Both coatings were helped by lubrication, which lowered the COF by about 15% to 20%. TiCN had a lower COF than TiN. At 5 N of wet sliding, TiCN stabilized at about 0.22, while TiN stayed at about 0.65. This shows that plowing wear was still going on.

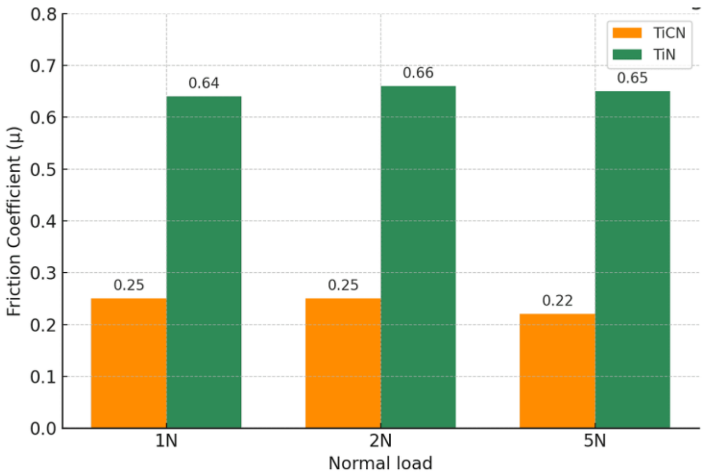

Fig. 5: Average COF values versus load under wet sliding (0.9% NaCl solution)

3.3 Wear Track Morphology

The morphology of wear is shown in Fig. 6. The results show that optical analysis showed that TiN mostly had abrasive grooves that looked like plowing. TiCN had narrower tracks, but the edges were brittle and cracked, especially at 5 N. The number of cracks grew with the load, which shows that brittle fractures are a cause of wear. Wet sliding made the grooves shallower and the cracks less dense, but it didn't get rid of them completely. These observations demonstrate TiCN's hardness advantage, while also revealing its vulnerability to brittle fracture under elevated stress.

Research on TiN/TiCN multilayers indicates that oxygen-assisted tribo-oxides and carbon-rich tribofilms can develop based on microstructure and load, as evidenced by XPS/Raman analysis [6]. This backs up what we saw: wet tests lower the average COF but don't stop plowing or edge cracking. Confirmatory XPS/Raman analysis on our tracks/balls would ascertain the formation of a protective tribolayer in 0.9% NaCl [6,9].

Type **Load 2N** **Load 5N**

TiN

TiCN

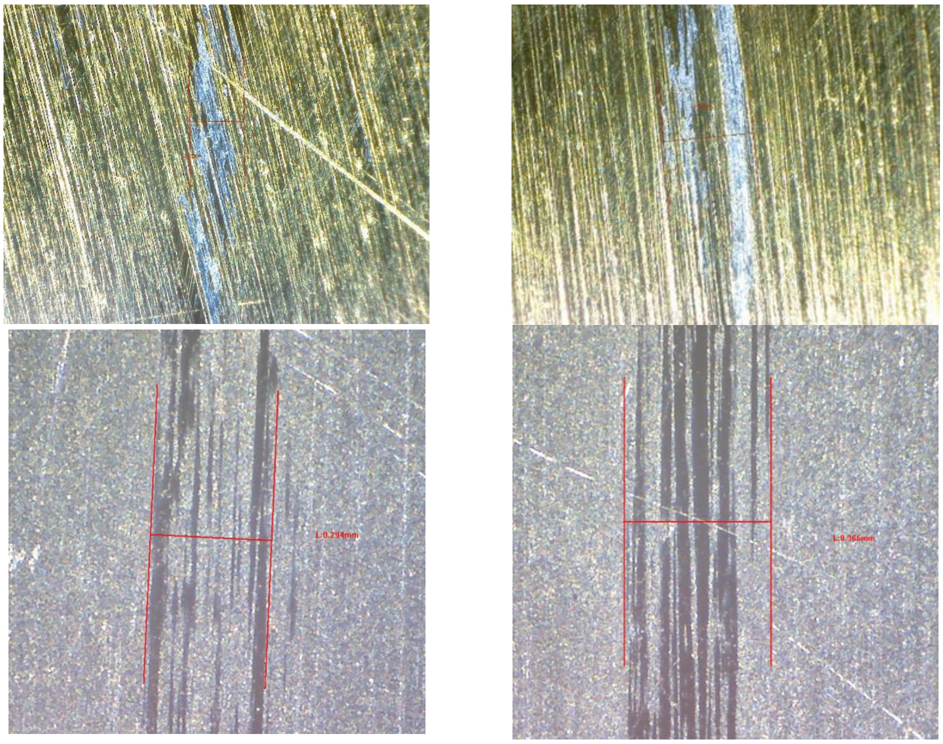

Fig. 6: Images of wear tracks for TiN and TiCN under wet sliding at 2 and 5 N.

3.4 Counterface Wear

The scars left by alumina balls are shown in Fig. 7. Instead of making lubricious transfer layers, both coatings made abrasive scratches. TiN made scars that were medium-sized and had plowing debris in them, while TiCN made scars that were smaller but had brittle particles stuck in them. Wet lubrication made scars smaller, which is what you'd expect when adhesion is lower. Table 1 shows the average scar diameters for TiN and TiCN at all loads.

In the context of tribocorrosion under wet conditions (0.9% NaCl), electrochemical activity influences friction and wear. Research on TiN/TiCN in 3.5% NaCl demonstrates OCP transients, coating-dependent Icorr, and wear-rate trends [8, 9]. Our wet results (COF reduction of about 15–20%) support the idea that solution chemistry reduces adhesion but may not change the way things wear down.

3.5 Mechanistic Interpretation

The tribological behavior of TiN and TiCN is controlled by a balance of hardness, plasticity, and toughness against breaking. Adhesion is the most important factor at 1 N, which makes the COF unstable. At 2 N, TiCN is harder, which lowers COF, but TiN is still prone to plowing. At 5 N, TiCN gets a stable COF, but it also starts to break easily. TiN, on the other hand, keeps wear that is mostly caused by plowing. Wet lubrication lowers adhesion and friction, but it doesn't change the main ways that wear happens.

Load-dependent transitions (adhesion at 1 N, hardness-stabilized at 2 N, brittle/plowing at 5 N) can be characterized using (i) H/E and H^3/E^2 indices and (ii) adhesion strength through scratch-test critical loads. Studies on TiN/TiCN multilayers indicate that optimizing the layer ratio enhances adhesion and reduces wear [6,7]. Cyclic micro-impact fatigue on TiN shows how increasing load speeds up interfacial fatigue, which is what we found [10].

Although TiCN consistently demonstrated superior hardness-controlled behavior and low COF, its inherent brittleness under high loads is a significant limitation. At 5 N, optical analysis revealed micro-crack initiation and propagation, which may lead to spallation under cyclic or impact-loaded conditions. This trade-off suggests that TiCN is reliable under moderate loads but susceptible to premature failure when fracture stresses accumulate. Future strategies, such as multilayer architectures (TiN/TiCN alternations) or elemental doping (Cr, Al), could enhance fracture toughness and delay crack coalescence.

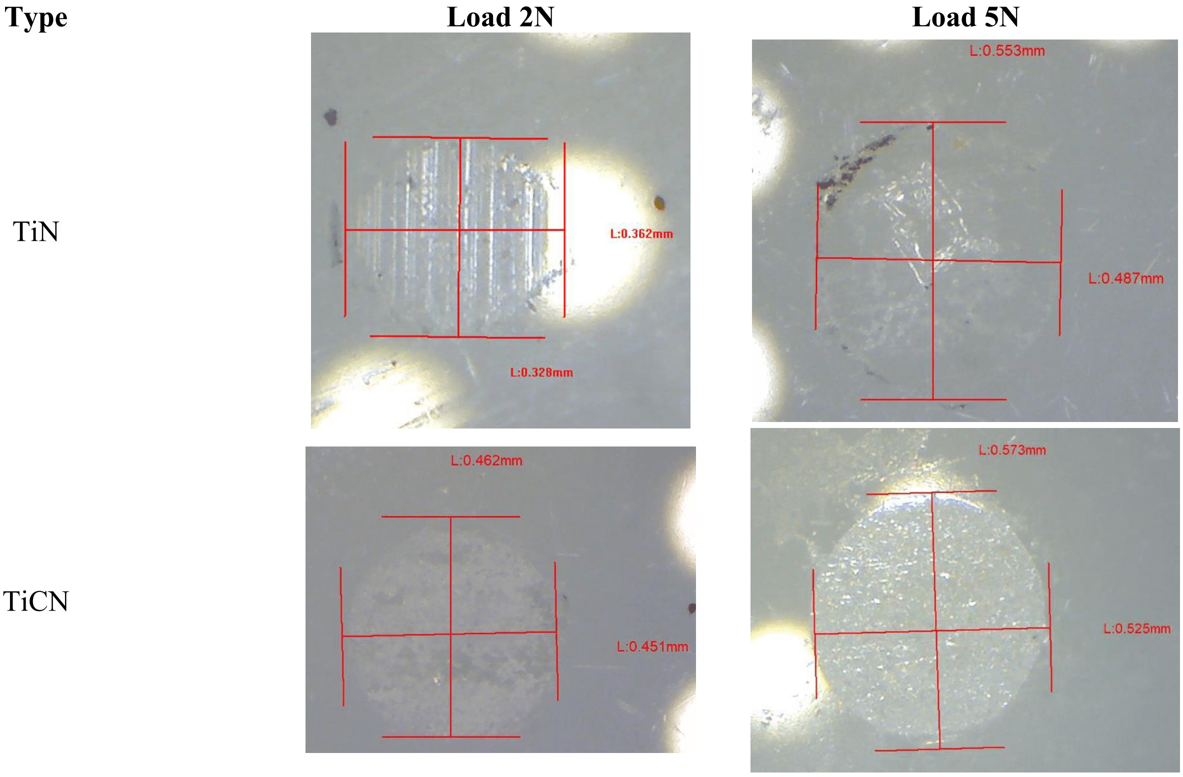

Fig. 7: Images of wear ball scars for TiN and TiCN under wet sliding conditions at loads of 2 and 5 N.

4. Conclusion

This study systematically investigated the load-dependent tribological performance of TiN and TiCN coatings on Ti-6Al-4V during dry and wet sliding conditions. We can come to the following conclusions: TiN had a high COF of about 0.64 to 0.66 across all loads. This was mostly due to plowing, oxidative wear, and brittle fracture. - TiCN always had a much lower COF (about 0.22–0.25) and a stable hardness-controlled behavior. - Wet sliding decreased the COF by about 15–20% for both coatings, but it did not change the main ways they wear. - EDS showed that TiN surfaces had more Ti and O, while TiCN surfaces had more Ti and C and less oxygen, which cut down on material transfer. - TiCN was much better than TiN in all loads and environments. It had stable, low-friction performance and smaller wear scars, making it the best choice for tribological applications with changing loads.

Limitation: Despite TiCN's superior tribological performance, its brittleness at high loads remains a weakness, which could restrict its long-term application in dynamic or impact-prone environments. Addressing this limitation will require balancing hardness with fracture resistance through multilayer or doped coating architectures.

In addition to COF trends, research shows that combining H/E, H^3/E^2, and scratch Lc with XPS/Raman and wear-rate quantification makes it easier to figure out how mechanisms work [6–8]. Future research ought to encompass nanoindentation modulus, scratch Lc, tribocorrosion metrics, and 3D wear-rate data for predictive design principles.

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