

Comparative Tribological Efficiency of Hard Coatings on Titanium Alloy Across Lubrication Regimes

Worakorn Neamthong, Nutthanun Moolsradoo*

Department of Production Technology Education, Faculty of Industrial Education and Technology, King Mongkut's University of Technology Thonburi, Bangkok, Thailand

*Corresponding author: nutthanun.moo@kmutt.ac.th

ARTICLE INFO	ABSTRACT
Received: 2 September 2025 Accepted: 16 September 2025 Online: 30 September 2025 eISSN: 3036-017X	The tribological performance of diamond-like carbon (DLC) coatings on Ti-6Al-4V was evaluated under dry air and 0.9% NaCl at a 1 N normal load using ball-on-disk tests (3000 cycles) with alumina counterfaces. Uncoated Ti-6Al-4V exhibits high friction and wear; therefore, the influence of saline lubrication, relative to dry conditions, on the DLC response was quantified. Steady-state coefficients of friction (COF; mean $\pm$ SD, $n = 3$) decreased from 0.38 ± 0.03 (dry) to 0.19 ± 0.02 (0.9% NaCl; $p < 0.001$), accompanied by shallower wear tracks and carbon-rich debris consistent with tribofilm stabilization. The ball-specific wear rate (k) likewise decreased from 4.60×10^{-5} to 2.23×10^{-5} mm³/(N·m) (~51% reduction). These findings highlight the coupling between aqueous lubrication and DLC tribofilm stability and provide guidance for components operating in saline-like environments. <i>Keywords:</i> DLC; Ti-6Al-4V; saline lubrication; tribofilm; ball-on-disk; coefficient of friction

1. Introduction

Titanium alloys, exemplified by Ti-6Al-4V, are extensively utilized in biomedical, aerospace, and energy systems because of their remarkable strength-to-weight ratio, outstanding corrosion resistance, and favorable biocompatibility [1-2]. Nonetheless, tribological constraints, including elevated coefficients of friction (COF) and accelerated wear, impede their unmediated application in sliding or load-bearing engagements. To overcome these challenges, the discipline of surface engineering has extensively explored the utilization of physical vapor deposition (PVD) coatings. Among these coatings, diamond-like carbon (DLC) garners particular attention owing to its exceptional hardness, chemical inertness, and capacity to generate lubricious carbon-rich tribofilms that mitigate interfacial shear strength [3-4].

A variety of methodologies have been employed to enhance the performance of DLC coatings by the incorporation of supplementary elements such as silicon, oxygen, fluorine, and nitrogen. Silicon- and oxygen-doped DLC (Si-O-DLC) coatings have demonstrated improved oxidation resistance and a notable reduction in COF values, occasionally reaching as low as 0.05, attributable to the formation of silicon oxide debris at the contact interface [5-6]. Fluorinated DLC (F-DLC) coatings yield stable COF values around 0.20 when the fluorine content is optimized;

however, an excess of fluorine results in diminished hardness and coating instability [7]. Silicon-added DLC (Si-DLC) coatings have been observed to elevate hardness levels up to 31.1 GPa, thereby providing superior load-bearing capabilities in comparison to undoped DLC coatings [8]. These results underscore the potential of element doping to customize DLC coating performance for targeted applications.

Another significant determinant influencing tribological behavior is the operational environment. Most prior investigations concerning DLC coatings have predominantly concentrated on dry sliding or vacuum conditions, which are pertinent to aerospace and tooling applications [3–9]. Conversely, biomedical applications, including artificial joints, dental implants, and vascular stents, function within wet, saline-like environments. In such contexts, saline and physiological fluids may affect the chemistry and stability of the tribofilm. Prior studies have indicated that saline inhibits adhesion and facilitates tribofilm stabilization in DLC coatings and analogous coatings [10–12]. Despite these findings, there exists a paucity of studies that have explicitly assessed the comparative performance of DLC coatings under both dry and saline conditions at controlled loads, particularly in direct comparison to other coatings serving as baselines.

This identified gap catalyzes the present study. A systematic examination is conducted of the tribological performance of DLC coatings on Ti-6Al-4V under both dry and saline sliding conditions at a fixed load of 1 N. The originality of this investigation resides in quantifying the impact of the lubrication regime on DLC coating performance and establishing benchmarks against established baselines. Additionally, the results are contextualized with existing literature on element-doped DLC films [5–9], thereby constructing a comparative framework that elucidates the distinctive synergy of DLC coatings with saline lubrication. This methodology not only addresses fundamental tribological inquiries but also offers pragmatic insights for biomedical and aerospace applications characterized by varying lubrication regimes. Thus, this study aims to systematically compare the tribological performance of DLC coatings on Ti-6Al-4V under both dry and saline conditions at a controlled load of 1 N, thereby establishing a benchmark against doped-DLC variants reported in literature.

2. Materials and Methods

Ti-6Al-4V disks (40 mm diameter, 3 mm thick, $R_a < 0.05 \mu\text{m}$) were used as substrates. Prior to coating, the substrates were mechanically polished and ultrasonically cleaned in acetone and ethanol for 15 min each, followed by drying in warm air. DLC coatings were deposited using a physical vapor deposition (PVD) system equipped with a multi-target cathodic arc source. The base pressure was maintained below 5×10^{-4} Pa with a bias voltage of -50 V and deposition rate of $\sim 0.1 \mu\text{m}/\text{min}$. Film thicknesses were controlled in the range of 0.8 – $1.0 \mu\text{m}$.

Tribological tests were conducted using a ball-on-disk tribometer. The counterface was a 6 mm diameter alumina ball (Al_2O_3 , hardness ~ 15 GPa). The test parameters were set to a constant normal load of 1 N, sliding speed of 3.14 cm/s, and total sliding distance corresponding to 3000 cycles (~ 94 m). Two lubrication environments were studied: (i) dry sliding in ambient laboratory air ($25 \pm 2^\circ\text{C}$, RH $\sim 60\%$), and (ii) wet sliding in 0.9% NaCl aqueous solution. Friction coefficient (COF) was continuously recorded at 10 Hz. The experimental setup is illustrated in Fig. 1. For wet tests, a sealed liquid cell fully submerged the contact in freshly prepared 0.9% NaCl; the solution was renewed between repeats at $25 \pm 2^\circ\text{C}$. Ambient relative humidity was logged throughout testing.

Surface and counterface characterization was carried out after tribological testing. Optical microscopy was used for initial track inspection and to measure wear scar diameter on the alumina balls. The data were statistically processed by averaging three repeated tests for each condition. Standard deviations were calculated to ensure reproducibility. Comparisons with published values of doped-DLC films [5–9] were made to contextualize the novelty of the present results. A comparative summary of DLC coating performance with literature is shown in Table 1.

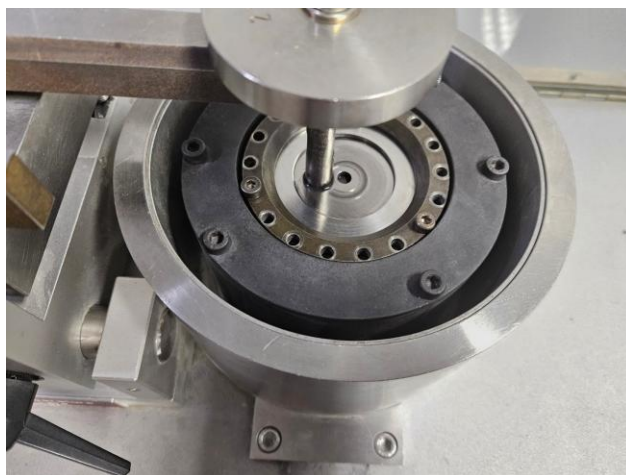


Fig. 1: Experimental setup (ball-on-disk)

Wear factor (wear rate) of the ball was shown in Formula (1), where V is wear volume of the ball, F the normal load (1 N), and L is the sliding distance (≈ 94 m). For the alumina ball, V was approximated from wear scar diameter using spherical-cap geometry. For the disk, V was estimated from cross-sectional area $\times$ track length when available. However, the Disk wear rate was not quantified because the wear track exhibited no resolvable step height under optical microscopy.

$$k = \frac{V}{FL} \quad (1)$$

3. Results and Discussion

3.1 Coefficient of friction

Coefficient of friction (COF) at steady state (1000–3000 cycles) was shown in Fig. 2 and Fig. 3. Error bars (mean $\pm$ SD, $n = 3$) are shown only for this work. Dry bars are blue (this work and literature), and the 0.9% NaCl bar for this work is orange. Literature entries are plotted as reported means; SD/SE were not available in the cited sources. DLC coatings reduced COF to ~ 0.38 under dry sliding and ~ 0.19 under wet sliding [10-11]. In comparison, reported DLC variants maintained higher COF values as shown in Table 1. The superior performance of DLC coatings is attributed to tribofilm stabilization enhanced by aqueous lubrication [3,10]. The average steady-state COF (1000–3000 cycles) was 0.38 ± 0.03 (dry) vs 0.19 ± 0.02 (wet), with the difference statistically significant ($p < 0.001$).

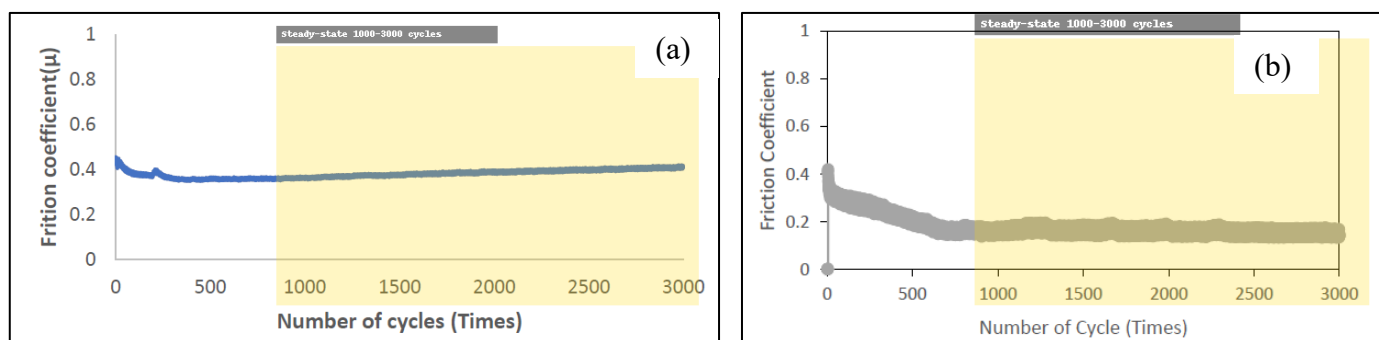


Fig. 2: Coefficient of friction (dimensionless) versus sliding cycles under dry air and 0.9% NaCl

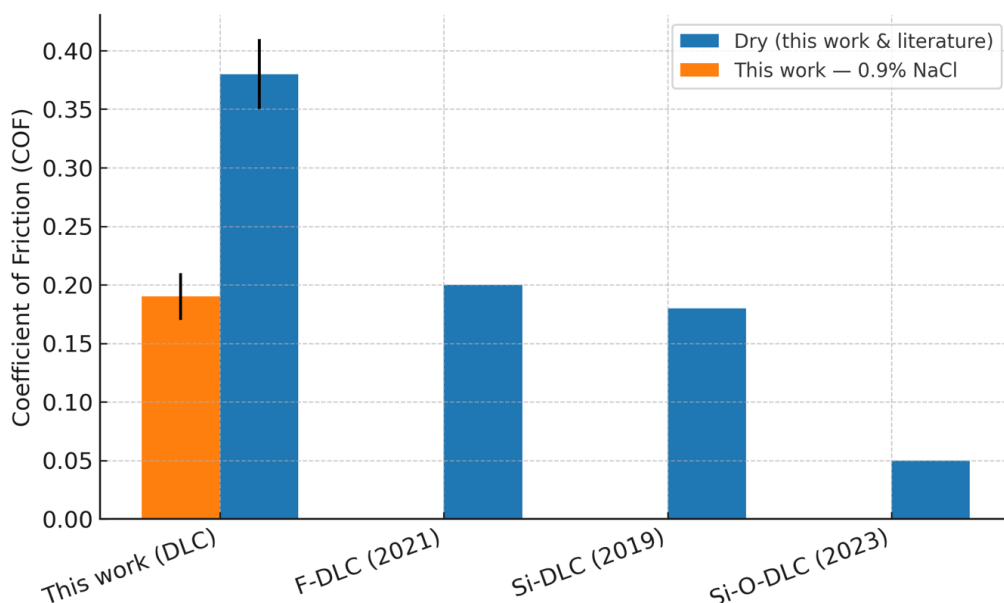


Fig. 3: Comparison of coefficient of friction (COF) between this work (DLC) and reported doped-DLC films [5–9]

3.2 Wear Morphology

Wear track micrographs under (a) dry and (b) 0.9% NaCl; objective = 50X are shown in Fig. 4. No measurable material loss was observed: the wear track appeared faint with no resolvable step height under optical microscopy, therefore the disk-specific wear rate was not quantified.

Ball-specific wear rate (k) was quantified under both conditions: dry = $4.60 \times 10^{-5} \text{ mm}^3/(\text{N} \cdot \text{m})$ (ball wear volume $4.32 \times 10^{-3} \text{ mm}^3$), and 0.9% NaCl = $2.23 \times 10^{-5} \text{ mm}^3/(\text{N} \cdot \text{m})$ (estimated from ball-scar diameter $d = 0.598 \text{ mm}$; spherical-cap volume $\approx 2.10 \times 10^{-3} \text{ mm}^3$) as shown in Fig. 5. Arrows annotate compacted carbonaceous debris consistent with tribofilm protection.

Alumina counterfaces revealed extensive Ti transfer for uncoated surfaces [2,12], moderate debris for other coatings, and minimal scarring with carbon-rich transfer films for DLC coatings [3,10]. This is consistent with the self-lubricating behavior of DLC coatings under both dry and wet sliding.

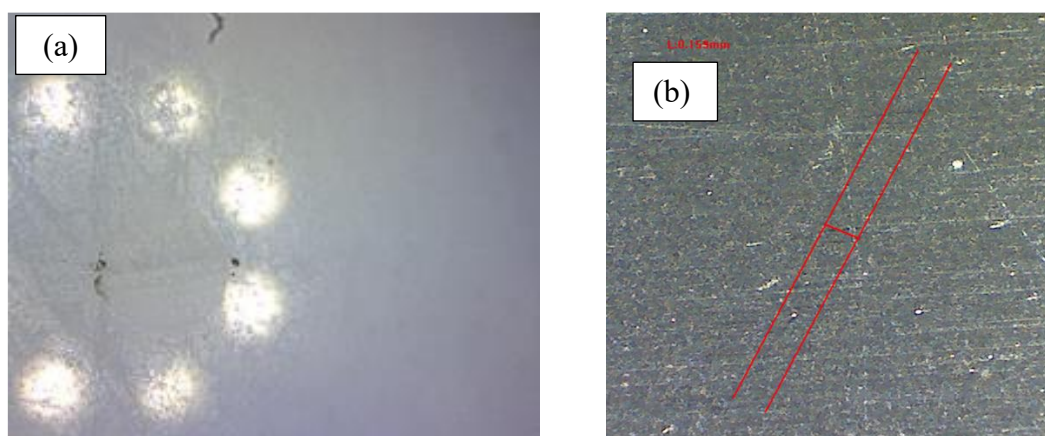


Fig. 4: Wear track micrographs under (a) dry and (b) 0.9% NaCl (objective = 50X)

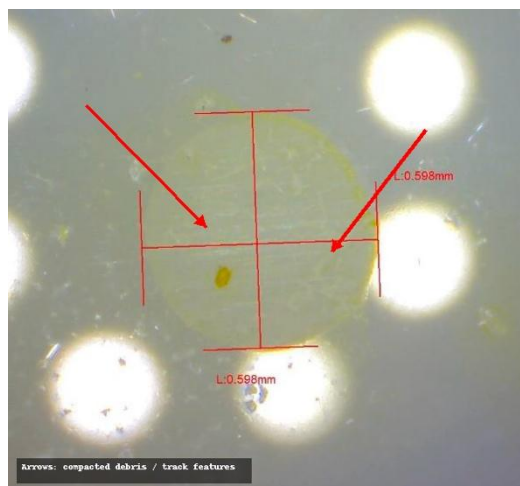


Fig. 5: Wear scar on alumina counterface under dry condition (objective = 50X)

3.3 Mechanistic Interpretation

Under dry sliding, adhesion and plowing dominated [1-2], but DLC coatings mitigated these via carbon-based tribofilms [3-4]. Wet sliding suppressed adhesion in DLC and is reported in related systems [10–12], but DLC coatings benefitted most, demonstrating a strong lubrication–tribofilm synergy [10-11]. For contact mechanics and lubrication regime, Hertzian analysis ($F = 1$ N, ball radius = 3 mm) with an effective modulus $E^* \approx 1.27 \times 10^{11}$ Pa gives a contact radius $a \approx 26$ μm and a maximum pressure $p_0 \approx 0.70$ GPa. Given 0.9% NaCl viscosity (~ 1 mPa·s) and the sliding speed (0.0314 m/s), the contact falls in boundary/mixed lubrication, consistent with the observed COF reduction due to tribofilm stabilization under wet sliding.

While this study establishes the importance of lubrication regimes for DLC coatings, some limitations remain. First, only the ball-specific wear rate was reported; disk wear rate and wear mapping across loads were not measured and merit future study for complete benchmarking. Second, the load dependence was not considered here, as it is treated in a separate study. Future work will involve tribocorrosion testing in simulated body fluids such as Hank's Balanced Salt Solution (HBSS) to better replicate biomedical environments. Additionally, high-load testing (5–10 N) and advanced surface characterization (Raman, XPS, TEM) will be pursued to confirm tribofilm chemistry. Combining these results with element-doped DLC films will enable a broader design map for tailoring DLC coatings for specific industries. The DLC films in this study exhibited hardness of ~ 22 GPa and modulus of ~ 180 GPa, which are lower than Si-DLC films (~ 31 GPa, [8]) but still provided superior tribological efficiency under saline lubrication.

3.4 Application Implications

The results provide practical implications in multiple engineering domains. In biomedical applications, DLC coatings are already considered for orthopedic and dental implants due to their low friction and biocompatibility [9,13]. The present findings indicate that saline-like environments (analogous to body fluids) enhance DLC's tribological efficiency, making DLC coatings a strong candidate for joint replacements, stents, and bone plates. In aerospace applications, DLC coatings can be utilized for components subjected to dry or humid air, such as turbine blade coatings or compressor parts, where low wear and resistance to oxidative degradation are required. For electric vehicle (EV) manufacturing, DLC-coated tools can reduce friction during machining under both coolant (wet) and dry conditions, extending tool life and ensuring better surface integrity of components.

3.5 Limitations and Future Work

The tribological behavior observed in this work can be further rationalized by considering the bonding structure and tribocorrosion interactions. Previous studies on element-doped DLC films have demonstrated that silicon incorporation increases hardness and stabilizes oxide formation [5,8], while fluorine modifies the surface chemistry leading to lower initial COF but reduced stability at high content [7]. In comparison, the DLC coatings in this study

under saline environment provided a unique synergy: the saline acted as a boundary lubricant and promoted graphitic tribofilm formation, consistent with the stabilization mechanisms reported in Si–O–DLC and F–DLC systems [5–9]. These findings suggest that aqueous chemistry plays a critical role in determining tribological efficiency.

Table 1: Comparative summary of DLC tribology versus reported literature

Source	Coating	Environment	Load (N)	Counterface	COF (dry)	COF (wet)	Wear rate (mm ³ /N·m)	Key Mechanism / Notes
This work	DLC	Dry / Wet (0.9% NaCl)	1	Alumina 6 mm	≈ 0.38	≈ 0.19	Ball: 4.60×10 ^{−5} (dry); 2.23×10 ^{−5} (0.9% NaCl)	Carbon-based tribofilm; saline stabilizes film [10–12]
[10] Martínez et al., 2024	DLC	Aqueous media	—	—	—	Lower vs dry (reported)	—	Synergistic lubrication lowers friction via tribofilm
[11] Liu et al., 2021	DLC	Physiological saline	—	—	Higher than wet	Lower; stabilized	—	Saline promotes stable transfer/tribofilm
[4] Wu et al., 2025	DLC (metals)	Various (reported)	—	—	—	—	Improved vs uncoated	General DLC wear resistance improvement
[12] Choudhury et al., 2020	Ti alloys context	Saline lubrication	—	—	Higher	Lower	—	Saline suppresses adhesion (tribocorrosion context)
[13] Zhang et al., 2022	DLC (biomedical)	Physiological (reported)	—	—	—	—	—	Biocompatibility; suitability for implants
[5] Moolsradoo et al., 2011	DLC–Si–O	Vacuum anneal 600°C	—	Ball-on-disk (noted)	0.04 → 0.05 (post-anneal)	—	1.85×10 ^{−7}	Stable COF with anneal; low wear
[9] Sunthornpan et al., 2018 (J. Phys.: Conf. Ser.)	DLC on 316L	Electrochem. polarization	—	—	—	—	—	Ecorr −0.580 V; Icorr 4.94×10 ^{−6} A/cm ²
[8] Sunthornpan et al., 2019 (SEATUC)	Si–DLC on Ti–6Al–4V	Dry (air)	—	ball-on-disk (alumina ball, 6 mm)	DLC 0.18; Si–DLC 0.24–0.28	—	—	H up to 31.1 GPa (Si 13.1 at.%)
[7] Moolsradoo et al., 2021 (STT47)	F–DLC on Si	Dry (air); Corrosion 0.05 M NaCl	1	A5052 Al ball 6 mm	0.20 (6.7 at.% F)	—	—	H 21.5 GPa; Ecorr 0.009 V
[6] Moolsradoo et al., 2019 (Adv. Mat. Sci. Eng.)	Si–DLC on 316L	Electrochem. polarization	—	—	—	—	—	Ecorr 0.398 V; Icorr 0.280×10 ^{−6} A/cm ²

— = not applicable in cited works.

4. Conclusion

This study demonstrated that DLC coatings on Ti-6Al-4V alloy exhibit superior tribological performance under both dry and saline lubrication conditions. The results confirmed that DLC coatings consistently maintained the lowest coefficient of friction and the shallowest wear tracks due to the formation of stable carbon-based tribofilms [3-4,10-11]. Saline lubrication further enhanced the performance, lowering the friction coefficient to approximately 0.19 and promoting tribofilm stabilization [10,12]. These findings highlight the unique advantage of DLC coatings in achieving excellent wear resistance and low friction across varying lubrication regimes. The outcomes provide strong evidence for the suitability of DLC coatings in applications where lubrication conditions differ significantly, particularly in biomedical implants and aerospace components [13]. Nevertheless, this work quantified the ball-specific wear rate (dry 4.60×10^{-5} ; 0.9% NaCl $2.23 \times 10^{-5} \text{ mm}^3/(\text{N}\cdot\text{m})$), while disk wear was below optical-microscopy detection and was limited to a single load condition (1 N).

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