



Tetrahedral amorphous carbon (Ta-C:Ti) nanocomposite coating application on selector carrier for friction reduction in double diaphragm pump

Mashitah Mohamad Zahir ¹, Muhammad Hafiz Hassan ^{1*}, Ryan Teh ²

¹ School of Mechanical Engineering, Universiti Sains Malaysia, Nibong Tebal, 14300, Nibong Tebal, Pulau Pinang, MALAYSIA.

² M Pump & Engineering Sdn Bhd, 8, Lorong Perusahaan Ringan Juru 3, Kawasan Perusa, 14100, Simpang Ampat, Pulau Pinang, MALAYSIA.

*Corresponding author: mhafizhassan@usm.my

KEYWORDS	ABSTRACT
Diamond-like carbon Tetrahedral amorphous carbon Coefficient of friction Wear and tear	The tribological applications as a range of model tests and destructive characterization techniques are frequently used to assess the tribological behavior of thin films. In contrast to the intricate sliding scenario found in most practical applications, these tests are often based on significantly simplified mechanical test circumstances. Therefore, each sample may be examined using sliding wear, nano indentation and scanning electron microscopy analysis. In the study, three coatings were introduced: anodized (AN), anodized with Teflon (AN-T) and Tetrahedral Amorphous Carbon (Ta-C:Ti), and compared to an uncoated carrier. The tribological properties and coefficient of friction of these coatings were analysed and evaluated. The results showed that the Ta-C:Ti coating outperformed the other coatings in terms of durability and wear resistance, making it the most suitable choice for the carrier material used in double diaphragm pumps. Therefore, the Ta-C:Ti coating can be recommended as an excellent option for enhancing the performance and longevity of these pumps.

Received 11 May 2025; received in revised form 30 October 2025; accepted 11 November 2025.

To cite this article: Mohamad Zahir et al. (2026). Tetrahedral amorphous carbon (Ta-C:Ti) nanocomposite coating application on selector carrier for friction reduction in double diaphragm pump. Jurnal Tribologi 49, pp.14-26.

1.0 INTRODUCTION

Tetrahedral amorphous carbon (Ta-C) coatings, characterized by a high content of sp^3 hybridized carbon atoms, exhibit exceptional hardness, chemical stability, and low friction coefficients. These properties have led to their widespread application in tools, molds, and precision engineering components (Xie et al., 2024). The incorporation of titanium (Ti) into Ta-C coatings results in Ta-C:Ti nanocomposites, which further enhance mechanical and tribological properties, making them highly suitable for demanding industrial applications (Kamis et al., 2020; Zheng et al., 2024).

Double diaphragm pumps are crucial across various industries such as chemical processing, pharmaceuticals, and food production, primarily due to their high efficiency and reliability in fluid handling especially those that are abrasive or corrosive (Carl Glauber, 2013). Despite their advantages, the carrier materials in these pumps are prone to significant wear, particularly in sliding wear applications where diaphragms repetitively move across the carrier's surface. This wear can lead to decreased efficiency, increased maintenance demands, and ultimately higher operational costs (Schork et al., 2010).

Enhancing the durability and lifespan of carrier materials is thus vital. This research focuses on identifying a suitable coating that can improve the carrier's lifespan by incorporating tribological properties such as hardness and a low coefficient of friction. By applying an appropriate coating, we aim to create a coated carrier that enhances the overall efficiency of double diaphragm pumps and reduces maintenance needs (Xiang li et al., 2018; Curtis Dietzsch, 2011).

The application of Ta-C:Ti nanocomposite coatings on selector carriers presents a promising approach to address these challenges (Ding et al., 2023). The unique combination of Ta-C's hardness and Ti's ability to improve adhesion and toughness results in a coating that can withstand the rigorous operational conditions of double diaphragm pumps (Jang et al., 2021). Studies have demonstrated that Ti-doped Ta-C coatings exhibit improved mechanical and tribological properties compared to undoped Ta-C coatings, making them ideal for components subjected to high friction and wear (Ding et al., 2023). Implementing Ta-C:Ti nanocomposite coatings on selector carriers is anticipated to significantly reduce friction, leading to enhanced pump performance and energy efficiency. The low friction coefficient of Ta-C minimizes energy losses due to friction, while the enhanced wear resistance ensures prolonged component lifespan (D. Zhao et al., 2014). This combination not only improves the reliability of double diaphragm pumps but also contributes to cost savings by reducing downtime and maintenance expenses (Majdoub et al., 2013). Therefore, the development of ways to enhance the durability and longevity of the carrier material is critical (LI et al., 2021).

In this research, the aim is to identify a suitable coating that can improve the lifespan of the carrier by introducing tribological properties such as hardness and coefficient of friction. The results of this study will introduce a coated carrier that can be used in the application of double diaphragm pumps, improving the overall efficiency and reducing maintenance requirements. The use of an appropriate coating can significantly enhance the wear resistance of the carrier material, improving its durability and longevity (Li et al., 2005; Kumar et al., 2024). The selection of the suitable coating will be based on various tribological properties, including hardness and coefficient of friction. By introducing a highly durable and

wear-resistant coating, it is possible to significantly reduce the wear and tear of the carrier material, ultimately improving the efficiency of the pump and reducing maintenance requirements.

2.0 EXPERIMENTAL PROCEDURE

In this experiment, Aluminium 6061 manufactured by M Pump and Engineering Sdn. Bhd. was selected as the carrier material. Four types of carriers were fabricated for comparison of their coefficients of friction. The first was an uncoated aluminium carrier that served as the reference substrate. The second was an anodized aluminium carrier, produced by Chemlite Industries Sdn. Bhd. through an electrochemical anodizing process that formed a protective aluminium oxide (Al_2O_3) layer with carbon-filled Teflon. The third was an anodized carrier coated with Teflon lubricant oil, procured from Ingenious Solutions and Quality (ISQ) Holdings Sdn. Bhd., consisting of a proprietary blend of mineral and vegetable oils, additives and Micpol®. The fourth was a Ta-C:Ti coated aluminium carrier fabricated by Surtreat Solution Sdn. Bhd. using a physical vapor deposition (PVD) method with coating parameters provided by the company. These four carriers, namely uncoated aluminium, aluminum coated with black anodized, aluminum coated with black anodized + Teflon, and aluminum coated with Tetrahedral amorphous carbon (Ta-C:Ti) are shown in Figure 1.



Figure 1: (a) Aluminum carrier, (b) Aluminum coated with Black anodized carrier, (c) Aluminum coated with Black anodized + Teflon carrier, and (d) Aluminum coated with Tetrahedral amorphous carbon (Ta-C:Ti) carrier.

The coefficient of friction was determined using two parameters: weight loss and surface roughness of the carrier material. The frictional wear test was performed using a ball-on-flat contact setup on a DUCOM TR-20 friction tester at room temperature. Prior to conducting the frictional test, the samples were weighed to obtain the initial weight (W_b). To compare the results, the samples were weighed again after the test to obtain the final weight (W_a). The diagram of pin-on-flat frictional wear test is shown in Figure 2 The coefficient of friction for each coating was determined following the guidelines outlined in ASTM G133-05.

The testing procedure for the sliding wear test was carried out following a specific set of parameters. Firstly, the normal force applied during the test was set at 25.0 N, which determined the level of load exerted on the sample. The stroke length, representing the distance of back-and-forth movement, was set to 60.0 mm. This defined the extent of the sliding motion between the surfaces. To control the speed of the sliding motion, an oscillating frequency of 1.667 Hz was selected. This frequency regulated the rate at which the surfaces moved back and forth, ensuring a consistent and controlled testing environment. Additionally, an angular frequency of 100 rev/min (rotations per minute) was chosen to specify the rotational speed of the testing apparatus. The test duration for the sliding wear test was set at 16 minutes and 40 seconds,

providing sufficient time to observe and evaluate the wear behavior of the samples under the specified testing conditions. Nanoindentation measurements were conducted using a Nano Test system (Micro Materials, UK). Before testing, the sample surface was thoroughly cleaned to remove any contaminants. The specimen was then securely mounted on the nanoindenter stage to ensure stability during loading. A Berkovich indenter, selected for its sharp geometry and symmetrical design, was used to obtain precise indentation profiles. Tests were performed with a maximum load of 500 mN, a loading and unloading rate of 50 mN/s, and a dwell time of 6 s at peak load.

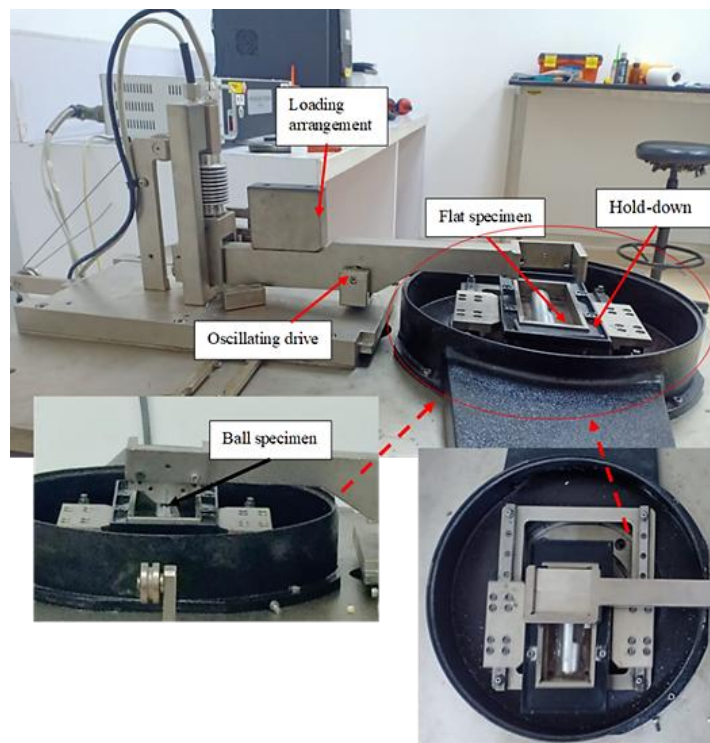


Figure 2: Sliding wear test machine.

3.0 RESULTS AND DISCUSSION

3.1 Scanning Electron Microscope (SEM) observation

After the 16 minutes and 40 seconds of sliding wear test, the surface reveals distinct wear tracks or grooves on the surface. These wear tracks are visible and indicate the material removal and deformation that occurred during the test. The surface appears to exhibit fracture or crack formations, displaying a textured appearance that is neither excessively rough nor exceptionally smooth. The wear tracks or grooves observed in the SEM image provide evidence of sliding contact and the resulting material loss from the aluminum surface. The presence of fractures or cracks due to the applied load or sliding conditions may have induced localized stress concentrations, leading to the formation of these surface features. Characteristics that are neither

excessively rough, indicating severe abrasive wear, nor overly smooth, because of minimal material removal (Holmberg et al., 1998). This intermediate surface texture indicates a moderate level of wear and deformation during the sliding wear test.

Figure 3 (a) shows uncoated aluminium, which exhibits high surface roughness after the pin-on-disk test due to its low hardness and poor wear resistance. Aluminium surfaces are prone to plastic deformation, adhesion, and abrasion during sliding contact, leading to severe surface damage and material removal (Holmberg et al., 1998). In contrast, Figure 3(b), which features anodized aluminium, presents a relatively smoother surface. The anodizing process forms a hard aluminium oxide (Al_2O_3) layer that improves hardness and corrosion resistance. This layer helps reduce surface wear to some extent by acting as a protective barrier. However, anodized coatings can be brittle and porous, which makes them susceptible to microcracks and wear under prolonged mechanical loading. Despite these limitations, the anodized layer still reduces the extent of damage compared to bare aluminium (Keshavarz et al., 2025).

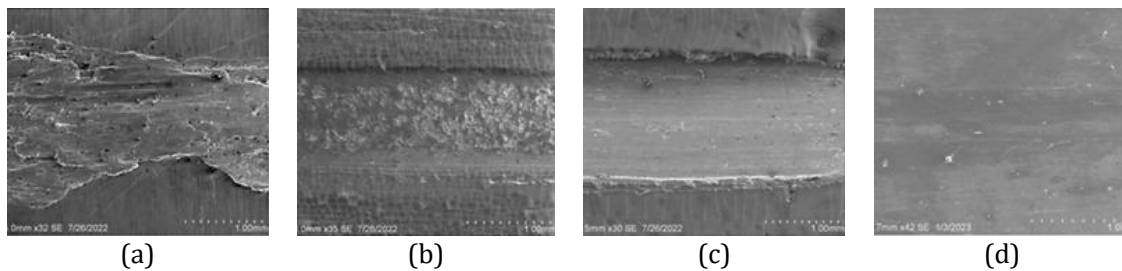


Figure 3: SEM observation (a) uncoated, (b) anodized, (c) anodized with Teflon, (d) Ta-C:Ti.

The surface shows clear tracks and grooves are visible, consistently exhibiting a particular width. The surface within the wear tracks appears noticeably rougher compared to the surrounding areas. These observations indicate that the coating has experienced failure, as evidenced by the peeling-off of the coating layer, exposing the substrate beneath (Okti J. P. Manalu et al., 2005). The presence of well-defined wear tracks and grooves due to the material removal and deformation have occurred during the sliding test. The consistent width of the tracks indicates a uniform wear pattern along the sliding path. The roughness observed within the wear tracks signifies significant surface damage and the removal of the protective oxide layer of anodized coating. The failure of the coating as the SEM images shows clear indications of coating delamination and peeling. The peeling-off of the coating layer exposes the underlying substrate material, which implies a loss of coating adhesion or inadequate coating integrity. This coating failure compromises the protective properties of the anodized coating and reduces its ability to prevent wear and damage to the substrate (Y. Zhao et al., 2024).

Figure 3(b) and Figure 3(c) both include anodized aluminium, but the surface in Figure 3(c) is additionally coated with Teflon (PTFE). While anodizing provides structural hardness, the addition of a Teflon layer significantly enhances the tribological performance by reducing friction (Rodiouchkina et al., 2021). PTFE has a very low coefficient of friction ($\sim 0.05-0.1$) and acts as a solid lubricant, minimizing direct contact and material removal during the sliding test. This dual-layered structure (hard anodized base with a lubricating top layer) results in lower surface damage and smoother morphology compared to the anodized-only surface in Figure 3(b). Teflon also aids in reducing the transfer of material and wear debris, further protecting the surface (Jacques et al., 2025).

The surface reveals prominent tracks and grooves. The surface within the wear tracks appears smoother compared to the surrounding anodized coating. This smoother appearance can be attributed to the presence of Teflon, which acts as a lubricant and fills the empty spaces between particles in the anodized carrier. This filling effect creates a more compact and dense surface texture within the wear tracks (Rodiouchkina et al., 2021). Despite the presence of the Teflon coating, the images also indicate that the coating has failed. Clear instances of coating layer peeling-off can be observed, reaching the substrate below. Moreover, the extent of peeling-off appears to be more significant compared to the anodized coating alone. This is attributed to the nature of Teflon, as once the Teflon layer peels off, it can also pull the underlying oxide layer along with it. Consequently, this leads to substantial surface damage and an increase in the severity of the carrier's surface condition.

Figure 3(c) shows a surface protected by anodizing and Teflon, while Figure 3(d) features a tetrahedral amorphous carbon (Ta-C) coating. The Ta-C coating significantly outperforms the PTFE coating in terms of hardness, durability, and wear resistance. While PTFE provides effective lubrication, it is relatively soft and can degrade over time under mechanical stress (Remešová et al., 2020). In contrast, Ta-C, a form of diamond-like carbon (DLC) characterized by a high fraction of sp^3 carbon bonds, exhibits exceptional hardness, low friction, and excellent chemical stability. The result is a much smoother surface in Figure 3(d), with minimal signs of wear or deformation. DLC coatings such as Ta-C are widely recognized for their superior tribological properties and long-term performance under harsh conditions (Fernandes et al., 2021).

The surface shows nearly imperceptible wear tracks, appearing almost invisible to visual inspection. The presence of small fractures or cracks is also observed, indicating minimal structural damage. The SEM images demonstrate that the Ta-C:Ti coating effectively resists wear and exhibits excellent durability under the applied sliding conditions. The nearly invisible wear tracks due to the coating successfully mitigate material loss and surface deformation, maintaining the integrity of the coating and substrate (Rajak et al., 2021a). The small fractures or cracks indicate that the coating is capable of absorbing localized stress without significant propagation of damage. Considering the absence of visible peeled-off sections in the coating, it can be concluded that the Ta-C:Ti coating passes the sliding wear test. The coating remains adhered to the substrate without significant delamination or detachment, indicating good coating adhesion and cohesive strength (Elam et al., 2021).

Among all the tested coatings, Figure 3(d) exhibits the best surface integrity and the lowest roughness after the pin-on-disk test. Compared to the bare aluminium in Figure 3(a), the Ta-C coated surface shows a dramatic improvement in wear resistance and elimination of surface deformation. Compared to Figure 3(b), Ta-C does not suffer from the brittleness and porosity of anodized layers. When compared to Figure 3(c), the Ta-C layer provides a more durable and harder surface than the soft Teflon coating, which may degrade during extended use. Overall, Ta-C combines hardness, low friction, and chemical inertness, making it the most effective coating for maintaining surface smoothness and resisting tribological wear among all the samples studied.

3.2 Coefficient of Friction (COF) Analysis

At the beginning of the graph representing the uncoated aluminium carrier as shown in Figure 4(a), the coefficient of friction (COF) starts at a relatively low value, below 0.2 in Region 1. This initial low COF is typically associated with the run-in phase, during which surface asperities are being flattened or deformed, and a thin natural oxide layer may still offer minimal resistance to

sliding. As sliding progresses, the COF begins to increase exponentially, indicating a rise in resistance to motion due to surface degradation (Qin et al., 2024). This upward trend continues through regions 2 and 3, ultimately reaching approximately 1.2 at region 4 (at around 200 seconds). The steady increase in friction reflects the progressive deterioration of the aluminium surface, characterized by wear mechanisms such as adhesive wear, abrasive wear, and surface roughening. These mechanisms contribute to increased frictional forces and make smooth sliding contact more difficult to maintain (Luo et al., 2024). This behavior is common in uncoated aluminium, which, due to its low hardness, high ductility, and strong adhesive tendencies, is highly susceptible to material transfer, ploughing, and severe wear under repeated sliding contact.

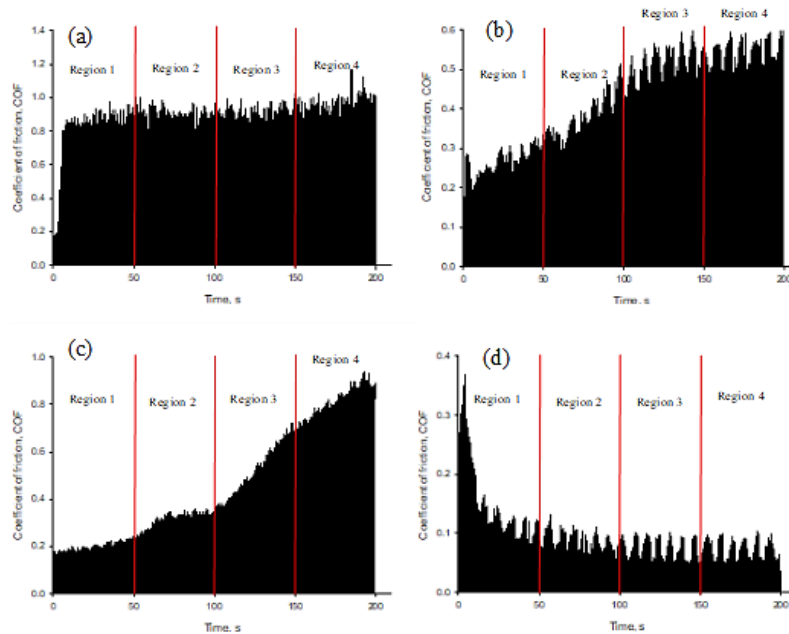


Figure 4: COF reading for (a) uncoated, (b) anodized (c) anodized + teflon, and (d) Ta-C:Ti

The graph for the aluminium carrier with an anodized coating, shown in Figure 4(b), exhibits a distinct trend in coefficient of friction (COF) behavior during the test. In Region 1, the COF begins below 0.3 and increases steadily as surface asperities interact and the coating adjusts to the sliding contact. As the test progresses into region 2, the rate of increase slows, forming a near plateau. In Region 3, the COF remains relatively stable, indicating the establishment of a steady frictional interface. This plateau extends into region 4, where the COF rises gradually to approximately 0.6 without sharp fluctuations.

The initial rise in COF can be attributed to increasing contact area and surface interactions, while the subsequent stability indicates a balance between wear and frictional forces. The anodized layer, composed of aluminium oxide (Al_2O_3), provides moderate hardness and improved wear resistance, contributing to a lower initial COF compared to uncoated aluminium (Nabhan et al., 2015). However, this oxide layer is also porous and brittle, making it susceptible to microcracking or spallation under continuous sliding. Over time, wear debris may accumulate, gradually increasing friction. Despite this, the frictional rise is less severe than in the uncoated

case. The stability observed in regions 3 and 4 may result from the formation of a steady-state wear track, changes in surface roughness, or the development of a stable frictional interface between the contact surfaces (Xiong et al., 2024).

In region 1, the anodized aluminium carrier with a Teflon coating [Figure 4(c)] shows a low COF below 0.2, reflecting PTFE's excellent lubricating properties. This low initial value results from reduced contact stress and adhesive interactions during the early sliding phase (Rodiouchkina et al., 2021). As the test progresses into Region 2, the COF gradually rises to about 0.4, indicating that the Teflon layer continues to provide moderate lubrication. In Region 3, the COF increases more sharply, and by region 4 it reaches approximately 1.0, showing significant resistance to sliding. This sharp increase is attributed to wear and degradation of the Teflon layer, which exposes the underlying anodized aluminium. Although harder than bare aluminium, the exposed surface contributes to higher friction, causing the COF in the later stages to approach values similar to or slightly better than uncoated aluminium (Yadav et al., 2018).

For the Ta-C:Ti-coated aluminium carrier, the graph shows an initially high COF in region 1, beginning just below 0.4. This initial value may be attributed to surface roughness or the bedding-in process of the coating. As the test progresses, however, the COF steadily decreases, dropping below 0.2 in region 2 and eventually stabilizing at around 0.1 by region 4. This decreasing trend indicates that the Ta-C:Ti coating becomes more effective with continued sliding contact. This behavior is characteristic of Ta-C coatings, which are a form of diamond-like carbon (DLC) known for their high sp^3 bond content, imparting exceptional hardness, chemical stability, and low friction (Rabadzhiyska et al., 2022). The gradual reduction in COF suggests the formation of a self-lubricating tribofilm or transfer layer during the sliding process, which helps reduce shear forces between the surfaces. Unlike PTFE, the Ta-C coating remains intact under high loads, ensuring consistent low-friction performance throughout the test duration (Elam et al., 2021).

The Ta-C:Ti coating showed superior tribological performance, maintaining low and stable COF values below 0.2 throughout regions 2, 3, and 4. This consistent behavior highlights its excellent wear resistance and long-term effectiveness in reducing friction (Rajak et al., 2021b). In contrast, the anodized coating failed after about 50 seconds under load, while the anodized + Teflon coating, although initially effective, degraded after roughly 100 seconds due to wear of the Teflon layer. Compared with these coatings, the Ta-C:Ti layer provided durable protection, lower COF, and smoother sliding, making it the most suitable option for enhancing efficiency and extending the service life of carriers in pump applications.

3.3 Nanoindentation Analysis

The indentation graph for the uncoated aluminium carrier reveals the highest values for both maximum depth (~ 4000 nm) and plastic depth (~ 4500 nm) as shown in Figure 5(a). These results indicate substantial material displacement and a high degree of plastic deformation under applied load. Uncoated aluminium, due to its low hardness and ductility, lacks sufficient resistance to indentation, resulting in deep penetration and permanent deformation (Meng et al., 2025). In terms of mechanical properties, this condition shows the lowest hardness, signifying minimal resistance to localized deformation. Interestingly, the reduced modulus is relatively higher than those of the anodized and anodized+Teflon coatings, which may be attributed to the absence of softer coating layers that typically reduce stiffness. Additionally, the uncoated sample exhibits the lowest elastic work and the highest plastic work, confirming poor ability to recover elastically and a tendency to absorb energy through permanent structural changes during loading (Luo et al., 2024).

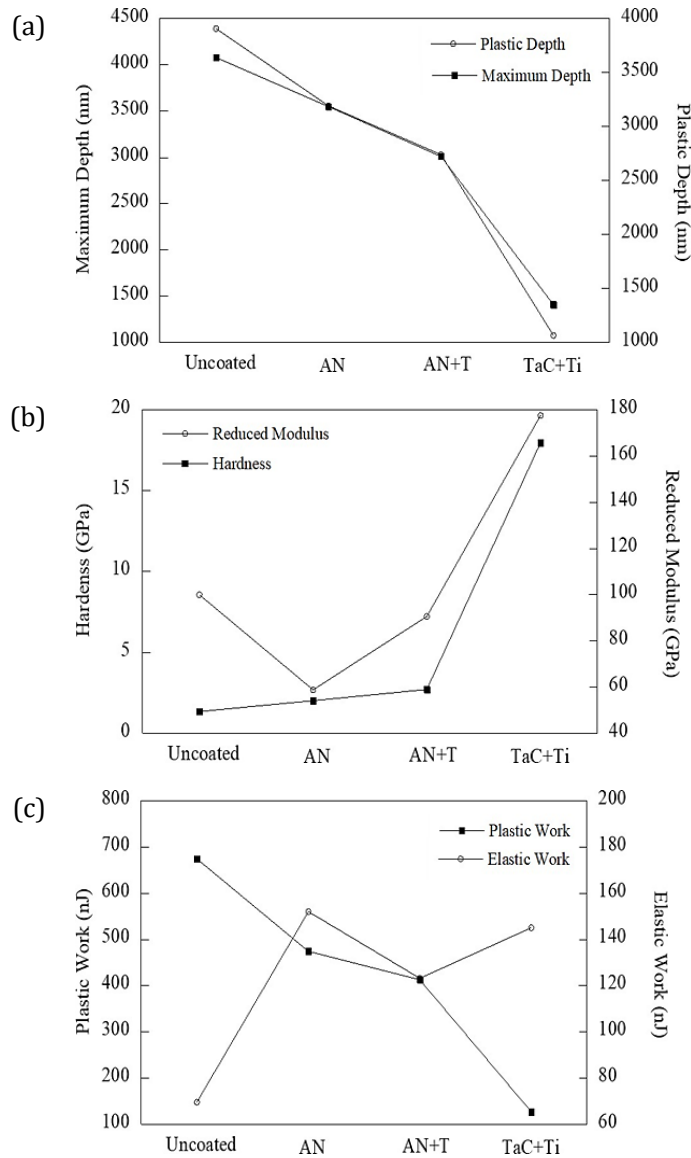


Figure 5: Nano-indentation test (a) relationship between the maximum depth and plastic depth, (b) hardness and reduce modulus value, (c) plastic work and elastic work.

Compared to the uncoated sample, the anodized aluminium shows a significant reduction in both maximum indentation depth and plastic depth, indicating improved surface hardness and reduced material plasticity (Masahashi et al., 2025). The anodizing process produces a hard aluminium oxide (Al_2O_3) layer that resists penetration and reduces permanent deformation. While the hardness value increases, the reduced modulus is comparatively lower, likely due to the porous and brittle nature of the anodic film, which affects the coating's ability to resist elastic deformation uniformly (Ye et al., 2025). In energy terms, the anodized carrier exhibits higher

elastic work and lower plastic work than the uncoated condition, suggesting a shift toward more recoverable deformation and better wear resistance overall.

The anodized + Teflon-coated carrier demonstrates further improvement in indentation resistance, showing even lower maximum and plastic depths than the anodized-only sample. This suggests that the PTFE (Teflon) top layer adds an extra barrier to indentation while also enhancing surface lubricity. Both hardness and reduced modulus are higher than in the anodized-only condition, indicating increased rigidity and resistance to localized deformation. However, both elastic and plastic work values decrease compared to anodized-only coatings. This suggests that while deformation resistance is higher, the structure becomes stiffer and less capable of absorbing deformation energy. The performance benefit of PTFE is largely tied to its tribological properties, where it acts to minimize friction and surface damage rather than elastic energy storage (Yang et al., 2025).

The Ta-C:Ti coating shows exceptional mechanical performance, with the lowest indentation depths recorded, below 1500 nm for maximum depth and around 1000 nm for plastic depth. These results reflect the superior hardness and elastic modulus provided by the tetrahedral amorphous carbon (Ta-C) content in the coating (Kim et al., 2010). The coating demonstrates a 12-fold increase in hardness and a 77% increase in reduced modulus compared to the uncoated sample, signifying excellent resistance to both surface penetration and elastic deformation. Additionally, the plastic work is reduced by approximately 80%, while elastic work increases by about 40%, confirming that this coating not only minimizes permanent deformation but also improves energy recovery during mechanical loading (Zia et al., 2022). These enhancements support the use of Ta-C:Ti as a protective coating in high-performance components such as diaphragm pumps.

4.0 CONCLUSION

This study evaluated the mechanical and tribological performance of four types of aluminium carriers, uncoated, anodized, anodized with Teflon, and Ta-C:Ti coated based on their behavior during indentation and pin-on-disk tests. Each carrier displayed distinct characteristics in terms of coefficient of friction (COF), hardness, deformation resistance, and energy dissipation. The uncoated aluminium carrier exhibited the poorest performance. It recorded the highest maximum indentation depth (~4000 nm) and plastic depth (~4500 nm), indicating severe material displacement and plastic deformation. Additionally, it had the lowest hardness and the highest plastic work, suggesting poor resistance to surface penetration and a high tendency for permanent deformation. Its COF increased sharply from an initial value below 0.2 to approximately 1.2 by region 4, confirming significant adhesive and abrasive wear under sliding conditions.

In comparison, the anodized aluminium carrier showed moderate improvements. The presence of a hard aluminium oxide layer reduced the indentation depths and improved surface hardness. The COF remained relatively stable, starting at approximately 0.3 and reaching around 0.6 by region 4, indicating improved but limited wear resistance. However, the anodized layer's brittleness and porosity led to microcracking over time. The anodized with Teflon coated carrier demonstrated further enhancement in hardness and reduced material deformation. The combination of a hard anodized base with a lubricating PTFE layer initially maintained a low COF (~0.2), but this value rose to approximately 1.0 by region 4 as the Teflon layer wore off. Despite

improved stiffness and hardness over the anodized-only coating, the durability of the Teflon layer under extended mechanical stress was limited.

The Ta-C:Ti coated carrier delivered the best overall performance. It exhibited the lowest maximum (~1500 nm) and plastic depth (~1000 nm), confirming superior resistance to deformation. The coating showed a 12-fold increase in hardness and a 77% increase in reduced modulus compared to the uncoated sample. Additionally, it achieved an 80% reduction in plastic work and a 40% increase in elastic work, indicating excellent energy absorption and elastic recovery. Tribologically, it performed exceptionally, with the COF starting slightly below 0.4 and decreasing to just 0.1 by region 4, making it the lowest COF among all tested coatings. This performance is attributed to the high sp³ content in the Ta-C layer and the formation of a stable tribofilm during sliding.

In conclusion, the Ta-C:Ti coating significantly outperforms the other coatings in both friction reduction and mechanical strength. Its ability to maintain low COF and high hardness under mechanical stress makes it an ideal candidate for use in high-performance applications, such as carriers in double diaphragm pumps, where long-term durability and low friction are essential.

ACKNOWLEDGMENTS

The authors are grateful for the financial support provided by the Ministry of Higher Education Malaysia for Fundamental Research Grant Scheme with Project Code: FRGS/1/2022/TK10/USM/03/5. We are also grateful for the financial participation of M Pump and Engineering Sdn. Bhd. Technical support from the School of Mechanical Engineering at USM is also greatly acknowledged.

REFERENCES

- Carl Glauber. (2013). Born to be Wilden – alter your view of AODD pumps.
- Dietzsch, C. (2011). AODD technology: AODD efficiency improvements.
- Ding, J. C., Cheng, Y., Zhang, S., Wang, Q., & Zhang, T. F. (2023). Microstructure, mechanical and tribological properties of Ti doped Ta-C films deposited by a hybrid coating system. *Diamond and Related Materials*, 131.
- Elam, F. M., Hsia, F. C., van Vliet, S., Bliem, R., Yang, L., Weber, B., & Franklin, S. E. (2021). The influence of corrosion on diamond-like carbon topography and friction at the nanoscale. *Carbon*, 179, 590–599.
- Fernandes, G. H. N., Lopes, G. H. F., Barbosa, L. M. Q., Martins, P. S., & Machado, Á. R. (2021). Wear mechanisms of diamond-like carbon coated tools in tapping of AA6351 T6 aluminium alloy. *Procedia Manufacturing*, 53, 293–298.
- Holmberg, K., Matthews, A., & Ronkainen, H. (1998). Coatings tribology-contact mechanisms and surface design. *Tribology*, 31.
- Jacques, R., Jourani, A., Bouvier, S., Chen, Y. M., & Kebir, H. (2025). Analysis of wear mechanisms and microstructure modifications of thrust ball bearing under fretting contact, false brinelling and greases lubrication. *Results in Engineering*, 25.
- Jang, Y. J., Kim, J. Il, Lee, W. Y., & Kim, J. (2021). Tribological properties of multilayer tetrahedral amorphous carbon coatings deposited by filtered cathodic vacuum arc deposition. *Friction*, 9(5), 1292–1302.

- Kamis, S. L., Yee, T. M., Akasaka, H., & Ohtake, N. (2020). Wear behavior of non-hydrogenated and hydrogenated DLC films under protein lubricated conditions. *Jurnal Tribologi*, 25, 136–145.
- Keshavarz, S., Asgharzadeh, H., & Farvizi, M. (2025). Microstructure, mechanical properties, and wear behavior of Al5083/GNPs nanocomposites prepared by powder metallurgy method. *Materials Science and Engineering: A*, 929.
- Kim, S. G., Kim, S. W., Saito, N., & Takai, O. (2010). Effect of increasing hardness on Si-containing diamond-like carbon film during tribo-test. *Diamond and Related Materials*, 19(7–9), 1017–1020.
- Kumar, V., Tewari, R. P., & Rawat, A. (2024). Tribological evolution of ultra-high molecular weight polyethylene and its composites for hip and knee replacement implants. *Jurnal Tribologi*, 42, 161–197.
- Li, S. Z., Fang, Q. F., Liu, Q., Li, Z. S., Gao, J., Nesladek, P., Prochazka, J., Veprek-Heijman, M. G. J., & Veprek, S. (2005). Thermally activated relaxation processes in superhard nc-TiN/a-Si₃N₄ and nc-(Ti_{1-x}Al_x)N/a-Si₃N₄ nanocomposites studied by means of internal friction measurements. *Composites Science and Technology*, 65(5), 735–740.
- Li, X., Murashima, M., & Umehara, N. (2018). Effect of nanoparticles as lubricant additives on friction and wear behavior of tetrahedral amorphous carbon (Ta-C) coating. *Jurnal Tribologi*, 16, 15–29.
- Li, Z. X., Bao, Y. T., Wu, L. K., & Cao, F. H. (2021). Oxidation and tribological properties of anodized Ti₄₅Al_{8.5}Nb alloy. *Transactions of Nonferrous Metals Society of China*, 31(11), 3439–3451.
- Luo, Y., Xue, S., Mei, H., Wang, H., Weng, H., Mao, Y., Leng, X., Wang, X., & Cao, J. (2024). Investigation of tribology and life prediction of polymer coatings on 7N21 aluminum alloy under dry sliding wear. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 703.
- Majdoub, F., Belin, M., Martin, J. M., Perret-Liaudet, J., Kano, M., & Yoshida, K. (2013). Exploring low friction of lubricated DLC coatings in no-wear conditions with a new relaxation tribometer. *Tribology International*, 65, 278–285.
- Manalu, O. J. P., Astrawinata, R., Sharif, N. M., Basuki, E. A., & Maruyama, T. (2005). The effect of aluminium content on properties of TiAl based binary alloys.
- Masahashi, N., Kubota, M., Inoue, H., Mori, Y., & Ohmura, K. (2025). Microstructures and mechanical properties of anodic oxides on TiNbSn implant alloys. *Thin Solid Films*, 820.
- Meng, L., Li, D., Fu, X., Jin, Y., Liu, Z., Li, Z., Zhang, T., Du, R., & Zhang, X. (2025). Experimental study on the influence of shale content in fault zone on fault friction coefficient based on circular shear test. *Ain Shams Engineering Journal*, 16(4).
- Nabhan, D., Kapusta, B., Billaud, P., Colas, K., Hamon, D., & Dacheux, N. (2015). Effects of pH, surface finish and thermal treatment on the corrosion of AlFeNi aluminum alloy: Characterization of oxide layers. *Journal of Nuclear Materials*, 457, 196–204.
- Qin, Z., Gatea, S., & Ou, H. (2024). Friction and heat partition coefficients in incremental sheet forming process. *Journal of Manufacturing Processes*, 124, 503–523.
- Rabadzhiyska, S., Kotlarski, G., Valkov, S., Ormanova, M., Shipochka, M., Rafailov, P., & Petrov, P. (2022). Characterization of diamond-like carbon films produced by electron-beam physical vapor deposition. *Materials Today: Proceedings*, 67, 995–1000.
- Rajak, D. K., Kumar, A., Behera, A., & Menezes, P. L. (2021). Diamond-like carbon (DLC) coatings: Classification, properties, and applications. *Applied Sciences*, 11(10).
- Remešová, M., Tkachenko, S., Kvarda, D., Ročňáková, I., Gollas, B., Menelaou, M., Čelko, L., & Kaiser, J. (2020). Effects of anodizing conditions and the addition of Al₂O₃/PTFE particles on the

- microstructure and the mechanical properties of porous anodic coatings on the AA1050 aluminium alloy. *Applied Surface Science*, 513.
- Rodiouchkina, M., Lind, J., Pelcastre, L., Berglund, K., Rudolphi, Å. K., & Hardell, J. (2021). Tribological behaviour and transfer layer development of self-lubricating polymer composite bearing materials under long duration dry sliding against stainless steel. *Wear*, 484–485.
- Schork, W., Schultrich, B., & Weihnacht, V. (2010). A new kind of oscillating dynamic load test for tribological coatings. *Wear*, 268(7–8), 955–959.
- Xie, Z. J., Li, J. L., Gong, L., Zhong, X. L., Song, H. J., & Wang, J. B. (2024). Thickness and sp³ bond modulation of (Ti/tetrahedral amorphous carbon) multilayer coatings. *Tungsten*.
- Xiong, Z., Zhang, W., Jin, S., Wu, R., Ma, F., Wang, X., & Wang, G. (2024). One-step hydrothermal fabrication of Co-MOFs/LDH superhydrophobic composite coating with corrosion resistance and wear resistance on anodic aluminum oxide. *Applied Surface Science*, 677.
- Yadav, G., Tiwari, S., & Jain, M. L. (2018). Tribological analysis of extreme pressure and anti-wear properties of engine lubricating oil using four ball tester. *Materials Today: Proceedings*, 5.
- Yang, S., Liu, Z., Zhang, S., Wang, W., Huang, G., Lu, L., & Xie, Y. (2025). Self-lubricating film formation and ultra-low wear of PTFE/aluminum through anodization induced nano-microtextures. *Tribology International*, 208.
- Ye, Z., Yan, T., Shi, J., Yang, R., Zhang, Y., Shi, X., Chen, Z., Rong, H., Bai, B., Liu, K., Hu, Y., & Yue, X. (2025). Construction of wear-resistant and anti-corrosion composite coatings on uranium surface by laser surface nitriding and texture coupled with solid lubrication. *Journal of Nuclear Materials*, 607.
- Zhao, D., Wang, M., Xu, Y., Zhang, Z., & Ge, X. (2014). The fabrication and corrosion resistance of benzotriazole-loaded raspberry-like hollow polymeric microspheres. *Surface and Coatings Technology*, 238, 15–26.
- Zhao, Y., Shabani, M., Wang, L., & Xiong, W. (2024). Investigation on high cycle fatigue performance of additively manufactured alloys: Synergistic effects of surface finishing and post-heat treatment. *International Journal of Fatigue*, 185.
- Zheng, J., Shang, J., Zhuang, W., Ding, J. C., Mei, H., Yang, Y., & Ran, S. (2024). Structural and tribomechanical properties of Cr-DLC films deposited by reactive high power impulse magnetron sputtering. *Vacuum*, 230.
- Zia, A. W., Hussain, S. A., & Baig, M. M. F. A. (2022). Optimizing diamond-like carbon coatings: From experimental era to artificial intelligence. *Ceramics International*, 48(24), 36000–36011.