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Original scientific paper

Investigation of the Effects of Nanoparticle Additive Lubricants on the Adhesive Wear Properties of Al2024

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Abstract: The adhesive wear behaviour of Al2024 aluminium alloy lubricated with oils modified with nanoparticles was examined in this work. The popular industrial 10W40 motor oil was chosen as the lubricant, and titanium carbide (TiC) and titanium nitride (TiN) nanoparticles were added at weight concentrations of 1%, 3%, and 5% to enhance the tribological characteristics. The nanoparticles and lubricants were combined evenly, and the pin-on-disk method was used to test the samples' resistance to wear. Following tests with predetermined parameters, a detailed analysis of the worn surfaces was performed using techniques from SEM, FT-IR, and optical microscopy. The findings showed that adding nanoparticles improved wear resistance and decreased the coefficient of friction. On Al2024 specimens, the addition of 3% TiN and TiC nanoparticles in particular resulted in more uniform surface deformation and smaller wear tracks. Significant results from this study demonstrate the potential of lubricants reinforced with nanoparticles to increase machine performance and service life in industrial settings.

Keywords: Al2024; TiC; TiN; Tribology

1 INTRODUCTION

The increasing demand for high-performance and energy-efficient mechanical systems has intensified the need for advanced lubrication strategies to mitigate friction and wear. Traditional lubricants often fall short under extreme operating conditions, such as high loads and temperatures, leading to the exploration of novel additives to enhance their tribological properties [1].

Nanoparticles have emerged as promising additives due to their unique size-dependent properties and ability to form protective tribofilms on contact surfaces. Studies have demonstrated that incorporating nanoparticles like titanium carbide (TiC) and titanium nitride (TiN) into lubricants can significantly reduce the coefficient of friction and wear rates [2]. These enhancements are attributed to mechanisms such as the formation of self-assembled tribofilms, the mending effect where nanoparticles fill surface asperities, and the rolling effect that facilitates smoother motion between contact surfaces [3].

Specifically, TiC and TiN nanoparticles have shown effectiveness in improving the tribological performance of lubricants. Their high hardness and thermal stability contribute to the formation of durable tribofilms that protect surfaces under severe conditions [2]. Furthermore, the optimal concentration of these nanoparticles is crucial, as excessive amounts may cause agglomeration and adversely affect lubricant performance [3].

With the advancement of technology, while human labor in industry is decreasing, an increase in machine usage is being observed. Developing wear-prevention strategies to enhance the durability and performance of machines has become critical. Metal materials are generally preferred in production; however, lubricants are used to reduce friction and wear between surfaces [1]. Although conventional lubricants offer many advantages, their performance can be limited under harsh conditions such as high temperature, pressure, and contamination [2].

The use of titanium-based nanoparticles as lubricant additives has garnered significant attention due to their exceptional tribological properties, including high hardness, thermal stability, and chemical inertness. Titanium dioxide (TiO_2), titanium carbide (TiC), and titanium nitride (TiN) nanoparticles have been widely studied for their ability to reduce friction and wear in mechanical systems. These nanoparticles contribute to forming protective tribofilms on contact surfaces, minimizing direct metal-to-metal interaction and altering wear mechanisms from severe adhesive to mild oxidative or abrasive wear [4]. For instance, TiO_2 nanoparticles have demonstrated the ability to reduce the coefficient of friction and improve surface smoothness under varying loads and temperatures [5]. Similarly, TiN and TiC nanoparticles have shown promise in enhancing load-carrying capacity and wear resistance, particularly in high-temperature applications due to their superior mechanical integrity [6, 7]. These findings confirm the potential of titanium-based nanoparticles as effective solid additives for improving lubricant performance and extending the service life of tribological components.

Adhesive wear arises when two contacting surfaces bond at their asperities and subsequently separate, leading to the transfer and loss of material. In the case of abrasive wear, harder particles or asperities scratch or plow through a softer material, causing surface degradation. Fatigue wear is typically the result of cyclic loading, where repeated stresses induce crack initiation and propagation over time. Erosive wear happens when high-velocity particles strike a surface, gradually removing material through impact. Meanwhile, corrosive wear stems from a synergistic interaction between mechanical friction and chemical reactions, which together accelerate material deterioration [8].

Numerous prior investigations have demonstrated that the incorporation of nanoparticles into lubricants leads to notable enhancements in tribological performance. In the study conducted by Birleanu et al., it was demonstrated that adding TiO_2 nanoparticles at concentrations of 0.01%, 0.025%, 0.050% and 0.075% to lubricants increased the load-carrying capacity and reduced friction [9]. Kumar et al. [10] conducted a study investigating the tribological and physicochemical properties of servo system lubricating oil enhanced with TiO_2 nanoparticles, prepared via sonication without surfactants. They found that at volume concentrations of 0.2%, 0.4%, 0.6%, and 0.8%, the addition of TiO_2 nanoparticles decreased the calorific value and flash point, while the wear scar diameter and coefficient of friction increased with higher nanoparticle content. Mohamed et al. [11] investigated the tribological behavior of nano-lubricants by incorporating Al_2O_3 and TiO_2 nanoparticles with average sizes of 8-12 nm and 10 nm, respectively, into engine oil at concentrations ranging from 0.05 to 0.5 wt%. Their findings demonstrated a noticeable reduction in friction coefficient, wear, and power losses in the piston ring assembly, indicating that such nano-lubricant additives can significantly improve fuel economy and energy efficiency in automotive applications. Padgurskas et al. [12] conducted tribological investigations using mineral oil enhanced with Fe, Cu, and Co nanoparticles (each at 0.5 wt% and in 0.25/0.25 wt% combinations), revealing that these additives significantly reduced the coefficient of friction and wear, by up to 1.5 times, primarily due to the formation of protective tribo-layers composed of nanoparticle elements on the contact surfaces.

Al2024 aluminum alloy was selected for this study due to its extensive use in aerospace and automotive industries, attributed to its high strength-to-weight ratio and good fatigue resistance [13]. However, its low surface hardness increases its vulnerability to wear, necessitating the enhancement of its tribological performance for prolonged service life [14].

This study investigates the influence of TiC and TiN nanoparticle additives on the tribological performance of Al2024 aluminum alloy, using 10W40 engine oil as the base lubricant. To date, no studies have been found in the literature that specifically examine the effects of TiC and TiN nanoparticles on the tribological behavior of Al2024 alloy within this lubrication context. Therefore, this research is expected to make a notable contribution to the existing body of knowledge on the application of nanoparticle-enhanced lubricants. Through pin-on-disc wear tests and advanced surface characterization techniques, the mechanisms by which these nanoparticles affect friction and wear will be explored, ultimately supporting the development of more effective lubricant formulations for industrial use.

2 MATERIALS AND METHOD

In this study, the adhesive wear behavior of lubricants modified with various nanoparticles was systematically investigated on selected metallic surfaces, guided by relevant findings in the literature. Lubricant formulations were prepared using specific combinations of nanoparticle additives and metal substrates, and their tribological performance was assessed through standardized wear testing methods. Among the selected materials, Al2024 was chosen due to its widespread use in industrial applications [13]. The chemical composition of this alloy was obtained from previously published sources and is presented in Tab. 1.

Table 1 Chemical composition of Al2024 alloy (by weight %) [15]

Element	Cu	Mg	Zn	Si	Zr	Mn	Cr	Al
Al2024	4.5	1.6	0.2	0.45	0.10	0.40	0.05	Remain

In this study, TiC and TiN nanoparticles with particle sizes under 44 microns were employed, provided in a -325 mesh grade, meaning they could fully pass through the corresponding sieve (Tab. 2). This fine size distribution was chosen to improve surface interaction and to support a more uniform dispersion of the particles within the lubricant formulation.

The titanium-based nanoparticles used in this study were titanium carbide (TiC) and titanium nitride (TiN), both selected for their superior tribological properties. The TiC nanoparticles had a purity of 98% and a particle size of -325 mesh, corresponding to particles smaller than 44 microns. Their molecular weight was 59.88 g/mol, and the Chemical Abstract Service (CAS) number was 12070-08-5. On the other hand, the TiN nanoparticles were of higher purity at 99.5%, also with a -325 mesh particle size. The molecular weight of TiN was 61.91 g/mol, and its CAS number was 25583-20-4. These characteristics ensured suitability for homogeneous dispersion in lubricants and effective interaction with metal surfaces during tribological testing.

The lubricant selected as the base fluid in this study was a commercially available motor oil classified under the 10W40 viscosity grade. The base lubricant used in this study was a 10W40 engine oil, characterized by a kinematic viscosity of 90 mm²/s at 40 °C and 13.4 mm²/s at 100 °C. It has a viscosity index of 150, indicating stable viscosity behavior across temperature changes. The oil's density at 15 °C is 0.882 g/ml, with a flash point of 210 °C, demonstrates its thermal stability. Additionally, it maintains fluidity at low temperatures, with a pour point of −39 °C. These properties make it a suitable candidate for evaluating the influence of nanoparticle additives on tribological performance.

TiC and TiN nanoparticles were incorporated into the base lubricants at varying weight percentages, as detailed in Tab. 2. To achieve uniform distribution of the nanoparticles within the oil medium, advanced dispersion methods were employed. The formulation of the lubricant samples was conducted in accordance with the following procedure.

Table 2 Composition of test samples with nanoparticle additives

Nano-Lubricant Name	Nanoparticle	Metal Content (g/100 ml of oil)
10W40	-	-
10W40 + TiC1	TiC	0.1
10W40 + TiC3	TiC	0.3
10W40 + TiC5	TiC	0.5
10W40 + TiN1	TiN	0.1
10W40 + TiN3	TiN	0.3
10W40 + TiN5	TiN	0.5

Table 3 Parameters used during the Pin-on-Disk wear test

Parameter	Rotational Speed / rpm	Track Diameter / mm	Sliding Speed / mm/s	Duration / s	Total Sliding Distance / mm	Normal Load / N	Sampling Frequency / Hz	Test Ambient Temperature / °C
Value	600	12	377	1326	500000	6.4	50	30

The formulated lubricants, containing both pure and nanoparticle-enhanced compositions, were applied to distinct metal specimens and subjected to wear testing. Tribological assessments were conducted using the pin on disk method, in which a 52100 SAE bearing steel ball with a hardness between 58 and 66 HRC served as the counter surface. To ensure repeatability and reliability, all tests were performed under consistent conditions. The detailed parameters of the wear tests are presented in Tab. 3. The Al2024 specimens were tested individually using both the standard base oil and lubricants enhanced with nanoparticles. Following the wear tests, comprehensive surface analyses were conducted utilizing Scanning Electron Microscopy (SEM), Optical Microscopy, and Fourier Transform Infrared Spectroscopy (FT-IR). These analytical techniques enabled a thorough examination of the surface morphology, chemical alterations, and the dominant wear mechanisms observed on the Al2024 samples.

3 RESULTS AND DISCUSSION

In this study, the effects of adding different ratios (0.1, 0.3, and 0.5 g/100 ml of oil) of TiC and TiN nanoparticles into 10W40 engine oil on the tribological performance of Al2024 alloy samples were investigated. FT-IR analysis of the prepared nanoparticle oils were performed.

The aim of FT-IR analysis is to observe the spatial oscillations of TiC nanoparticles added at 1, 3 and 5% in 10W40 oil. We can see that there are four sharp peaks in the wavenumber range of 400-4000 cm^{-1} for all TiC ratios (Fig. 1). The first peak corresponding to the wavenumber value of 650 cm^{-1} in the sample is consistent with the Ti-C bond. The peak observed at the wavenumber of 650 cm^{-1} clearly characterizes the vibration between Ti and C atoms. The peak corresponding to the wavenumber of 1450 cm^{-1} is formed by the C atoms on the surface of TiC nanoparticles with respect to the surrounding oxygen and characterizes the C-O bonds. Normally, the peaks observed at 2350 cm^{-1} and 2690 cm^{-1} wavenumbers belong to Ti-OH or Ti-O bonds formed as a result of the interaction of Ti atoms on the surface with water molecules or ambient oxygen, but when TiC was added into 10W40, it was observed that the peaks shifted to the left [16, 17].

The FT-IR spectrum of 10W40 oil containing 1, 3 and 5% TiN is given in Fig. 2. The FT-IR spectrum shows the presence of compounds containing Ti, N, C and O single bonds. While the stretching vibrations of the Ti-C bond are normally observed at 550 cm^{-1} [18, 19] and the Ti-N stretching mode at 600 cm^{-1} [20, 21], it was observed that in 10W40 these peaks shifted to the left by approximately 100 cm^{-1}, similar to the 10W40 including TiC nanoparticles FT-IR as results. For TiC-enhanced lubricants, these prominent Ti-C stretching vibrations confirmed the presence of ceramic phases capable of forming protective tribofilms. The peak around 1445 cm^{-1} is attributed to C-O bond [17, 22], while the stretching band of –N = C = N- was observed in the sample containing 0.3 g TiN with a very small peak at 2050 cm^{-1} wavenumber, the peak at around 2914 cm^{-1} belongs to C-H [18, 19]. These peaks confirm the presence of organic-inorganic hybrid structures. These chemical features imply that TiN nanoparticles participate in tribochemical reactions, forming low-shear-strength films that reduce friction and wear. Besides, the C-O bonds peaks were likely formed due to surface oxidation of TiC particles. Additional peaks at ~ 2350 and ~ 2690 cm^{-1}, associated with Ti-OH and Ti-O bonds, suggest interaction with ambient moisture and oxygen, facilitating tribofilm formation. Notably, these peaks exhibited a leftward shift upon nanoparticle addition, indicating altered chemical environments and possible bonding with oil constituents.

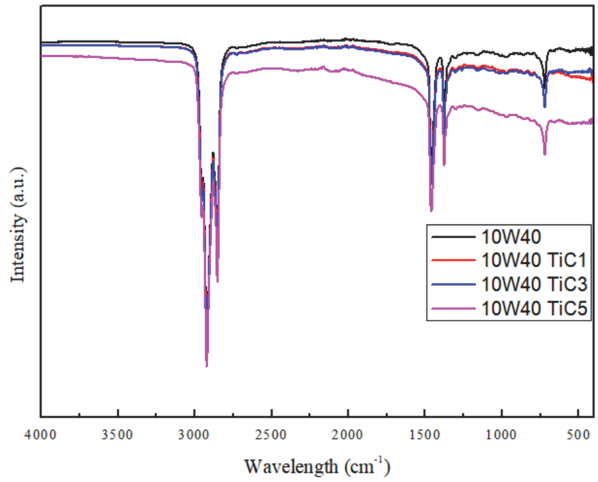

Figure 1 FT-IR graphs of 10W40 oil including different amounts of TiC

In summary, the spectra revealed distinct vibrational bands corresponding to Ti-C, Ti-N, C-O, Ti-O, and Ti-OH bonds, which provide insight into the formation of tribochemical films and surface interactions.

In this study, the effects of 10W40 engine oil and the incorporation of TiC and TiN nanoparticles on the tribological performance of Al2024 alloy specimens were investigated using pin-on-disk wear tests. The experimental findings were assessed based on both the coefficient of friction and weight loss measurements, and the interactions between the Al2024 material, lubricant, and nanoparticle additives were comprehensively analyzed. Coefficient of Friction results are for Al2024 plotted in Fig. 3.

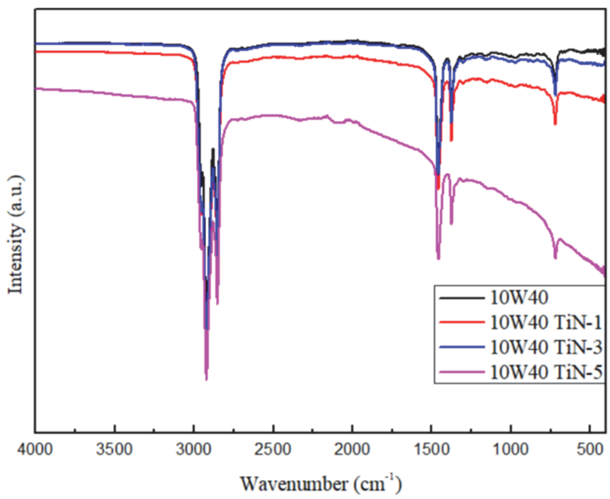

Figure 2 FT-IR graphs of 10W40 oil including different amounts of TiNi

Based on the tribological test results obtained for the Al2024 alloy, the average coefficient of friction in the unlubricated (pure) condition was measured as 2.72, indicating a high level of surface interaction and friction in the absence of lubrication (Tab. 4). Upon the application of 10W40 engine oil, a substantial reduction was observed, with the coefficient dropping to 0.83. This demonstrates the lubricant's ability to form a protective film layer between surfaces, significantly minimizing direct metal-to-metal contact.

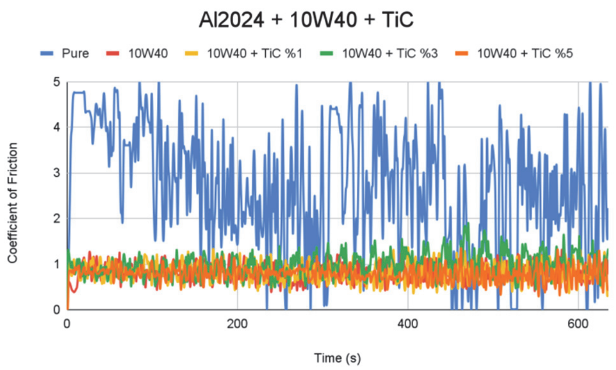

Figure 3 Coefficient of friction results for Al2024 with 10W40 + TiC additives

The addition of TiC nanoparticles to the lubricant led to noticeable changes in friction behavior. At a 1% TiC concentration, a slight increase in the coefficient to 0.84 was observed, possibly due to micro-abrasive effects introduced by the dispersed particles. When the TiC content was raised to 3%, the coefficient further increased to 0.98, suggesting that higher particle density may have disrupted the continuity of the lubricant film and intensified localized contact stresses. Interestingly, at 5% TiC concentration, the coefficient of friction decreased again to 0.78. This could indicate that, at higher concentrations, the nanoparticles were more uniformly distributed, resulting in a more stable tribo-film that reduced friction more effectively.

Table 4 Average friction coefficient results of Al2024 with 10W40 + TiC additives

	Pure	10W40	10W40 + TiC %1	10W40 + TiC %3	10W40 + TiC %5
Average Coefficient of Friction (μ)	2.72	0.83	0.84	0.98	0.78

The unexpected decrease in tribological performance observed with 3% TiC addition may be due to the agglomeration of nanoparticles and the disruption of oil film integrity. At moderate concentrations, particles may aggregate due to insufficient dispersion energy or inappropriate surface modification [23]. These aggregates can act as hard abrasives that cause localized stress increases on the surface, increasing both abrasive and adhesive wear. Optimizing concentration is crucial in nanoparticle-added oil formulations. Additive levels that are too low or too high can negatively impact performance through various mechanisms.

Overall, the impact of TiC nanoparticles on tribological performance was found to be non-linear and highly dependent on the concentration. The 5% TiC addition yielded the lowest friction value among the modified lubricants, highlighting that an optimal particle concentration can enhance the tribological properties of Al2024 alloy. These findings emphasize the importance of carefully optimizing nanoparticle content to achieve desirable performance in nano-lubricant systems. Coefficient of friction results for Al2024 with 10W40 + TiN additives were given in Fig. 4.

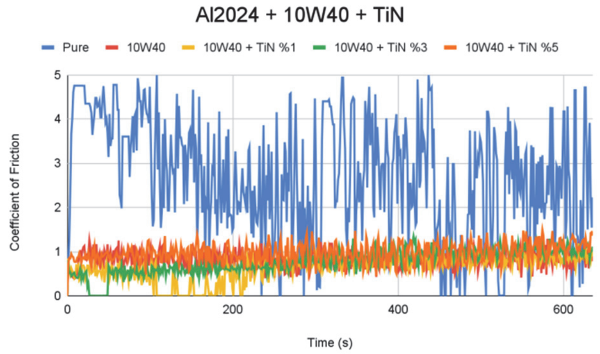

Figure 4 Coefficient of friction results for Al2024 with 10W40 + TiN additives

The results indicate a substantial reduction in the average coefficient of friction (μ) for Al2024 alloy upon the addition of TiN nanoparticles to 10W40 engine oil. The pure Al2024 sample, tested without any lubricant, exhibited a significantly high friction coefficient of 2.72, highlighting the inherently poor tribological performance of untreated aluminum surfaces (Tab. 5). The use of base oil alone reduced this value drastically to 0.83, confirming the lubricant's essential role in forming a protective boundary layer.

Table 5 Average friction coefficient results of Al2024 with 10W40 + TiN additives

	Pure	10W40	10W40 + TiN %1	10W40 + TiN %3	10W40 + TiN %5
Average Coefficient of Friction (μ)	2.72	0.83	0.64	0.77	0.98

The incorporation of TiN nanoparticles further improved performance, especially at 1% and 3% concentrations. The lowest friction value was obtained at 1% TiN (μ = 0.64), suggesting that at this concentration, the TiN particles were optimally dispersed within the oil matrix and contributed to the formation of a stable tribo-film on the aluminum surface. At 3% TiN, the friction coefficient increased slightly to 0.77, yet it remained lower than the base oil alone. This may be attributed to slight agglomeration or changes in oil viscosity. However, at 5% TiN concentration, the coefficient of friction rose to 0.98, possibly due to particle clustering or a disruption in lubricant film stability, which may have introduced mild abrasive effects.

In summary, TiN additives were found to significantly enhance the tribological performance of Al2024 at optimal concentrations, with diminishing benefits or even adverse effects observed at higher loadings. This underlines the necessity of concentration optimization when formulating nanoparticle-reinforced lubricants for aluminum-based components.

Based on the wear test results, the weight loss data obtained from experiments on the Al2024 alloy demonstrate that the addition of nanoparticles has a significant impact on tribological performance (Tab. 6).

Table 6 Weight loss results from wear tests of Al2024-based samples with TiC and TiN additives

Al2024	Weight Loss / g
Pure	0.0458
10W40	0.0004
10W40 + TiC1	0.0003
10W40 + TiC3	0.0005
10W40 + TiC5	0.0066
10W40 + TiN1	0.0003
10W40 + TiN3	0.0003
10W40 + TiN5	0.0003

The pure (unlubricated) Al2024 sample exhibited the highest wear, with a measured weight loss of 0.0458 g. When 10W40 motor oil was used, this value was dramatically reduced to 0.0004 g, indicating the effectiveness of the lubricant in minimizing wear. With the addition of TiC nanoparticles, the lowest wear loss was observed at 1 wt%, with a value of 0.0003 g. However, at 5 wt% TiC, the weight loss sharply increased to 0.0066 g, suggesting that high concentrations of TiC may induce abrasive effects on the surface and compromise the protective nature of the lubricant film.

In contrast, all concentrations of TiN nanoparticles (1%, 3%, and 5%) resulted in consistently low wear values of 0.0003 g, indicating a stable wear resistance on the Al2024 surface. These results imply that TiN provides reliable surface protection and does not disrupt the lubricant's film-forming ability, even at higher concentrations.

In this study, the tribological performance of the Al2024 alloy was investigated using 10W40 synthetic lubricants containing TiN and TiC nanoparticle additives. The aim was to evaluate how these additives affect surface wear and assess their potential to extend material life. 3D Optic microscope images were used to examine the wear mechanisms, and the surface deformations were analyzed in detail in terms of abrasive and adhesive wear. In Fig. 5, 3D microscope images revealed the wear mechanisms in detail and demonstrated how surface deformations varied in terms of abrasive and adhesive wear.

3D optical microscopy revealed significant differences in surface topography across the tested samples, directly correlating with the type and concentration of nanoparticle additives. The unlubricated Al2024 surface exhibited deep, irregular grooves and micro-pits, which are indicative of severe adhesive and abrasive wear. These features reflect uncontrolled surface damage due to direct metal-to-metal contact.

In contrast, smoother and more uniform wear tracks were consistently produced by TiN-enhanced lubricants. At 1 wt%, TiN reduced groove depth and improved surface homogeneity. At 3 wt%, the wear tracks became shallower. They also became more evenly distributed. This suggests the formation of a stable tribofilm. The 5 wt% TiN sample exhibited the least surface damage. It had nearly imperceptible wear features. This confirms its superior tribological performance. This behaviour is attributed to TiN's excellent dispersion and thermal stability, which promote consistent tribofilm formation and suppress both adhesive and abrasive wear.

TiC-enhanced lubricants showed a more concentration-dependent response. At 1 wt%, we observed moderate improvement, with partial suppression of adhesive wear. The 3 wt% sample revealed mixed wear behavior. This included localized micro-abrasion. This was likely caused by particle clustering. Interestingly, the 5 wt% TiC sample exhibited the lowest wear depth among TiC variants, with smoother surface morphology and minimal groove formation. This suggests that at optimal concentration, TiC nanoparticles contribute to tribological protection through mending and rolling effects. However, if dispersion is not well-controlled, abrasive interactions may be risked by excessive TiC.

In general, TiN additives showed consistent improvements in tribology at all concentrations, while TiC needed precise optimisation to strike a balance between its protective and abrasive properties. These findings confirm that nanoparticle-enhanced lubricants significantly alter wear behaviour and that 3D optical microscopy is a valuable tool for studying this phenomenon.

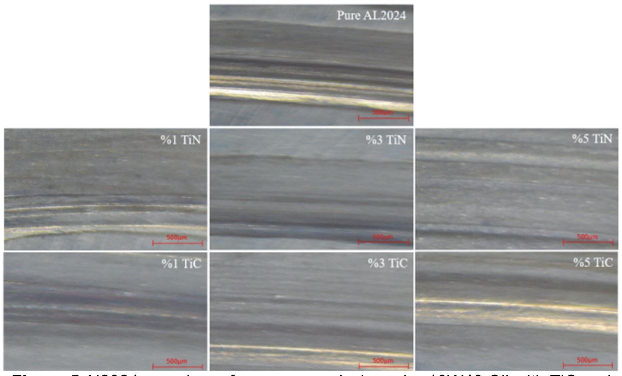

Figure 5 Al2024 sample surface wear analysis under 10W40 Oil with TiC and TiN Additives (3D optical microscopy images)

Abrasive wear occurs as a result of mechanical abrasion caused by hard particles on the surface. Using pure Al2024 as the reference, the influence of nanoparticle additives on surface deformation was analyzed. On the surface of the pure Al2024 specimen, pronounced scratches and irregular micro-pitting were observed. The wear tracks appeared to be directionally aligned but varied in depth across different regions. The addition of TiN nanoparticles at concentrations of 1%, 3%, and 5% resulted in a more controlled surface wear behavior. The depth of wear tracks decreased, and the surface exhibited a more homogeneous wear pattern. Notably, the lubricant containing 5% TiN produced the lowest wear marks, indicating its effectiveness in minimizing surface deformation. The addition of TiC at concentrations of 1%, 3%, and 5% demonstrated a more effective suppression of wear-induced deformation due to the inherent hardness of the particles. The surface lubricated with oil containing 5% TiC exhibited the lowest depth of scratches and effectively minimized abrasive wear, indicating superior surface protection.

Adhesive wear is a form of mechanical damage that occurs when surfaces stick to each other and material is transferred between them. In this study, the effectiveness of TiN and TiC nanoparticle additives in preventing metal transfer on Al2024 alloy surfaces was evaluated. For the pure Al2024 surface, noticeable signs of metal transfer were observed in the images, along with local deformations and material accumulation in certain regions. The addition of TiN nanoparticles significantly reduced surface adhesiveness, with the 5% TiN-containing lubricant effectively suppressing adhesive wear marks and minimizing metal transfer. Similarly, the use of TiC additives demonstrated a strong ability to control adhesive wear. Notably, the surface lubricated with 5% TiC exhibited almost no signs of metal transfer, indicating that the TiC particles acted as an effective barrier at the contact interface. Previous studies [24-26] have shown that the addition of TiN and TiC significantly enhances tribological performance by effectively controlling abrasive wear.

The morphology of the Al2024 sample showed a smooth surface appearance. The visible dark areas represent pores or voids left behind by the removal of particles broken off from the surface during the pin-on-disk test. This uniform distribution of the second phase within the matrix alloy is a characteristic of the in situ powder metallurgy method [27]. There is a second phase consisting of small particles that appear to be homogeneously distributed on the Al2024 surface. The sizes of these particles found on the studied Al 2024 are in the range of 0.5 µm to 3 µm (Fig. 6).

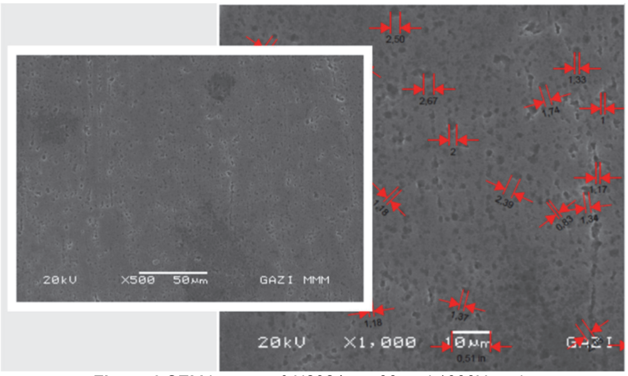

Figure 6 SEM images of Al2024 at 500 and 1000X scale

The tribological performance data obtained in this study indicate that the addition of TiN and TiC nanoparticles to 10W40 engine oil as an additive has significant effects, particularly on the Al2024 alloy. The results indicate that TiN and TiC nanoparticle-added 10W40 oils have significant potential for use in various industrial areas. One of the most suitable sectors for such advanced lubrication solutions is the automotive sector. Minimizing surface wear and extending component life are critical in high-friction components such as engine parts, gears, and piston-cylinder surfaces. The study observed that the coefficient of friction decreased from 0.83 to 0.64 with 1% TiN addition, representing approximately a 23% decrease compared to the base oil. Furthermore, the wear rate remained constant and low (0.0003 g) in all TiN-added samples. These data indicate that TiN-added oils can be used effectively in the automotive sector, particularly in internal combustion engine systems and powertrains. Similarly, the aerospace industry is another area that could directly benefit from such nano-additive lubricants due to the widespread use of Al2024 alloy. Reducing surface deformation and improving tribological performance in structural and moving parts used in aviation is crucial for safety and longevity. Literature reports indicate that TiN additives effectively control abrasive and adhesive wear mechanisms. Therefore, nanoparticle-added oils have a high potential for use in aviation applications such as landing gear, flap systems, and moving linkages. Furthermore, in general engineering applications, TiN additives stand out with their stable and low-wear performance, particularly in equipment where friction and wear directly affect performance, such as bearings, chain systems, and gearboxes. Therefore, 10W40 oil with TiC and TiN additives is expected to be suitable for long-term use in heavy-duty machines or automation systems.

4 CONCLUSIONS

The results obtained from the wear tests conducted on Al2024 samples reveal that the addition of TiC and TiN nanoparticles to 10W40 engine oil has a notable influence on tribological behavior. While the use of base oil alone significantly reduced both the coefficient of friction and weight loss compared to the dry condition, the integration of nanoparticles further modified these outcomes. TiC additives showed a non-linear effect: although 1 wt% TiC provided a slight reduction in wear, increasing the concentration to 5 wt% led to a considerable rise in material loss, indicating abrasive behavior at higher loadings. In contrast, TiN-enhanced lubricants consistently exhibited low wear values across all concentrations tested, suggesting superior surface protection and better compatibility with Al2024. These findings demonstrate that TiN is a more effective additive for improving the wear resistance of Al2024 alloy under lubricated conditions, whereas the application of TiC should be carefully optimized to avoid negative effects at higher concentrations.

While this study demonstrates the potential of TiC and TiN nanoparticle additives to improve the tribological performance of 10W40 lubricants, all experiments were conducted under controlled laboratory conditions using a pin-on-disc setup. This test setup does not fully reflect the complex and variable operating conditions encountered in real-world applications, such as temperature fluctuations, environmental contaminants, and load changes. Furthermore, the long-term stability of nanoparticle-added oils, including particle precipitation, oxidation, thermal degradation, and overall oil stability, should be investigated in future studies.

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