EUROPEAN MECHANICAL SCIENCE

Research Article

e-ISSN: 2587-1110

Investigation of the effects of nanoparticle additive lubricants on the adhesive wear properties of ST37 steel and AISI304

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Abstract: In this study, the adhesive wear behavior of different metals lubricated with nanoparticle-modified oils was investigated. Two different metal samples, namely St37 steel and AISI304, were used. As the lubricant, the widely used industrial 10W-40 motor oil was selected and titanium carbide (TiC) and titanium nitride (TiN) nanoparticles were added at concentrations of 1%, 3%, and 5% by weight to improve the tribological properties. The lubricants were homogeneously mixed with the nanoparticles, and the prepared samples were subjected to wear tests using the pin-on-disk method. Tests were conducted under fixed parameters, and subsequently, the worn surfaces were analyzed in detail using SEM, EDS, FTIR, UV spectroscopy and Optical Microscopy techniques. The results demonstrated that the addition of nanoparticles reduced the coefficient of friction and increased wear resistance. Particularly, the addition of 3% TiN and TiC nanoparticles provided lower wear tracks and more homogeneous surface deformation on all metal surfaces. This study presents important findings supporting the potential of nanoparticle-reinforced lubricants to extend the service life and improve the performance of machines in industrial applications.

Keywords: Tribology, AISI304, St37 Steel, TiC, TiN

1. Introduction

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 development of nanotechnology has led to the idea of improving tribological properties by incorporating nanoparticles into lubricants. Nano-sized reinforcements have the potential to reduce friction, provide resistance to wear and extend system life. In the literature, many nanoparticles such as Nanodiamond, Carbon Nanotube (CNT), Molybdenum Disulfide (MoS_2), Silicon Dioxide (SiO_2), Alumina (Al_2O_3), Zinc Oxide (ZnO), Titanium Dioxide (TiO_2), Titanium Nitride (TiN) and Titanium (IV) Carbide (TiC) have been used as lubricant additives.

In this study, the effects of TiN and TiC nanoparticles on adhesive wear will be specifically examined. TiN reduces friction due to its high hardness and oxidation resistance [3], while TiC offers high-temperature stability and wear resistance [4]. Both nanoparticles aim to provide lower wear and longer life in contact between metal surfaces.

Lubricants can be either natural (vegetable, mineral, animal-based) or synthetic (PAO, ester, glycol-based) [5]. It is known that both types improve machine efficiency by reducing friction and wear. Tribology is the science that studies friction, wear, and lubrication phenomena, and it plays a critical role in reducing energy loss and surface damage in machines [6].

Adhesive wear occurs when contacting surfaces stick together and break apart, resulting in material loss. In

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Cite this article as:
Urhan, E.U, *et.al.* (2025). Investigation of the effects of nanoparticle additive lubricants on the adhesive wear properties of ST37 steel and AISI304. *European Mechanical Science*, 9(2): 177-188. https://doi.org/10.26701/ems.1698103

History dates:
Received: 12.05.2025, ***Revision Request***: 24.05.2025, ***Last Revision Received***: 29.05.2025, ***Accepted***: 04.06.2025

abrasive wear, hard particles wear down a softer surface. Fatigue wear develops through crack formation caused by repeated stress on the surface. Erosive wear occurs due to the impact of moving abrasive particles, while corrosive wear is caused by a combination of friction and chemical reactions [7].

Previous studies have shown that nanoparticle-enhanced lubricants significantly improve tribological performance. Wu et al. [2] reported that lubricants containing CuO, TiO_2 and nanodiamond additives considerably reduced both friction coefficient and wear. Similarly, Birleanu et al. [8] demonstrated that adding TiO_2 nanoparticles at concentrations of 0.01–0.075% improved load-carrying capacity and reduced friction. In another study conducted by Choi et al. [9], it was found that Cu nanoparticle-added lubricants reduced the coefficient of friction by up to 44% under high loads. Zhu and colleagues [10] reported that the addition of 8% Fe_3O_4 nanoparticles improved surface quality in rolling processes and significantly reduced rolling force. Padgurskas et al. [11] also showed that lubricants reinforced with Fe, Cu and Co nanoparticles decreased both the friction coefficient and wear by up to 1.5 times. Moreover, Yu et al. [12] demonstrated that MoS_2 nanoparticles reduced surface roughness and helped prevent adhesive wear. Wu and colleagues [13] developed ZnO@SiO_2 nanocomposites, which, when added to grease, reduced the coefficient of friction by 11.5% and wear by 25%. These studies strongly support that adding nanoparticles to lubricants can significantly reduce friction and wear in tribological systems. Ma et al. [14] reported that a water-based nanolubricant containing 3.0 wt.% TiO_2 nanoparticles reduced the coefficient of friction by 82.9% and wear by 42.7% compared to dry conditions, demonstrating significant improvements in tribological performance. Martin et al. [15] demonstrated that adding TiO_2 and SiO_2 nanoparticles to PVE lubricant reduced the coefficient of friction, with optimal performance observed at concentrations below 0.010% for TiO_2 and 0.005% for SiO_2, achieving lower COF and wear scar diameter compared to pure PVE lubricant. Liñeira del Río et al. [16] reported that adding 0.1 wt% MoS_2 nanoparticles to PAO4 lubricant led to a 64% reduction in friction, a 62% decrease in wear width and a 97% reduction in worn area, confirming the formation of protective tribofilms and highlighting the effectiveness of MoS_2 under boundary lubrication conditions. Bordo et al. [17] demonstrated that while Cu nanoparticles at 0.3% and 3.0%wt were ineffective in synthetic ester oils, their addition to mineral oil significantly reduced the coefficient of friction and enhanced antiwear performance, with optimal results observed at 0.3%wt concentration under varying contact pressures and temperatures.

2. Materials and Method

In this study, based on the information gathered from the literature, the adhesive wear behavior of lubricants modified with different nanoparticles on various metal surfaces was investigated. The experiments were conducted using specially prepared lubricants with specific metal and nanoparticle combinations and the wear performance was evaluated through tribological tests.

Two different metals commonly used in industry were selected for the experiments: St37 steel and AISI304 stainless steel. The chemical composition data of these metals were obtained from the literature and are presented in ▶**Table 1**.

Table 1. Chemical Composition of St37 Steel and AISI304 Stainless Steel (by weight %) [18]

Element	C	Si	Mn	P	S	Cr	Ni
St37	0.11	0.03	0.56	0.007	0.005	0.07	0.03
AISI304	0.034	0.55	1.33	0.03	0.01	18.50	8.44

The TiC and TiN nanoparticles used in this study had a particle size below approximately 44 microns and were supplied in -325 mesh form (completely passing through the sieve) (▶**Table 2**). This was intended to ensure better interaction with the surface and achieve homogeneous dispersion within the lubricant.

Table 2. Material Properties of TiC and TiN Nanoparticles Used in the Study

Nanoparticle	Purity	Size	Molecular Weight (g/mol)	CAS Number
TiC	%98	-325 mesh	59.88	12070-08-5
TiN	%99.5	-325 mesh	61.91	25583-20-4

The base lubricant used in this study was a motor oil with a 10W40 viscosity grade. The fundamental properties of this oil are presented in ▶**Table 3**.

Table 3. Technical Specifications of 10W40 Lubricants

	Viscosity (40 °C) mm²/s	Viscosity (100 °C) mm²/s	Viscosity Index	Density (15 °C) g/ml	Flash Point °C	Pour Point
10W40	90	13.4	150	0.882	210	-39

TiC and TiN nanoparticles were added to the base oils at different weight ratios and the ratios were given in ▶**Table 4**. Special dispersion techniques were applied to ensure the homogeneous distribution of the nanoparticles within the oil. The lubricant formulations were prepared as follows.

The prepared lubricants, both with and without additives, were applied to different metal specimens and subjected to wear tests. Tribological performance evaluations were carried out using the pin-on-disk method [19]. In this study, a steel ball (52100 SAE Bearing Steel) with a hardness range of 58–66 HRC was used as the counter surface in the pin-on-disk wear test. The tests were conducted under constant parameters to en-

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Table 4. 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

sure repeatability, and the test conditions used given ▶**Table 5**.

Each metal specimen was individually tested under standard Hz (unmodified) oil and nanoparticle-enhanced lubricants. After the wear tests, surface analyses were performed using Scanning Electron Microscopy (SEM), Energy-Dispersive X-ray Spectroscopy (EDX), Optical Microscopy, Fourier Transform Infrared Spectroscopy (FTIR) and Ultra-Violet (UV) spectroscopy. These techniques allowed for a detailed investigation of surface morphology, chemical composition changes and wear mechanisms.

3. Results and Discussion

In this study, the effects of 10W40 engine oil and the addition of TiC and TiN nanoparticles on the tribological performance of AISI304 and St37 steel specimens were investigated through pin-on-disk wear tests. The experimental results were evaluated based on both the coefficient of friction and weight loss parameters, and the interactions between material, oil and additive were thoroughly analyzed. Coefficient of Friction results are plotted in ▶**Figure 1**.

For the AISI304 sample, the average coefficient of friction in its pure (unlubricated) form was measured as 1.06. This value indicates that there is a significant level of friction between the surfaces when no lubricant is applied. When 10W40 motor oil was used, a notable reduction in the coefficient of friction was observed, decreasing to 0.84. This reduction demonstrates that the 10W40 lubricant effectively reduced direct metal-to-metal contact and improved the tribological performance.

However, when TiC nanoparticles were added to the

Table 5. 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)	Data Acquisition Frequency (Hz)	Test Ambient Temperature (°C)
Value	600	12	377	1326	500000	6.4	50	30

Table 6. Average Friction Coefficient Results of AISI304 with 10W40 + TiC Additives

	Pure	10W40	10W40 + TiC %1	10W40 + TiC %3	10W40 + TiC %5
Average Coefficient of Friction (μ)	1.06	0.84	1.55	2.00	1.98

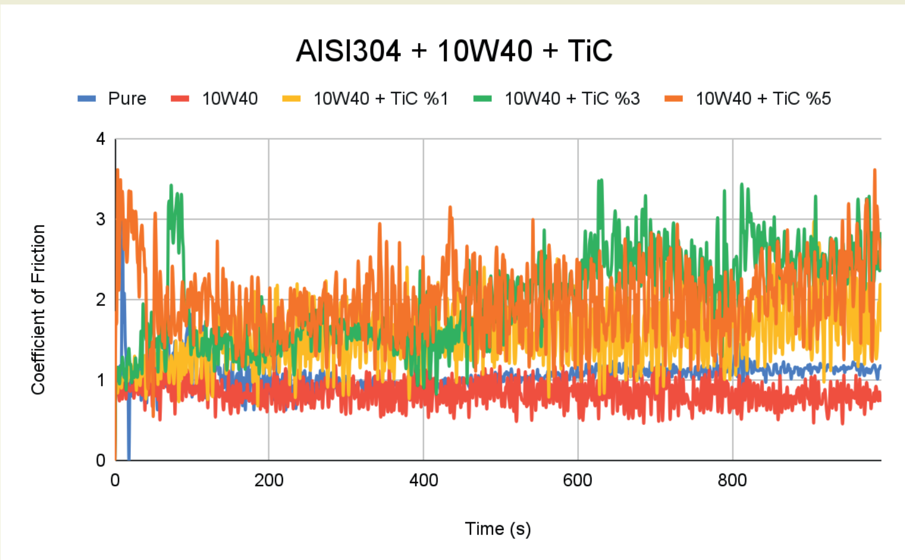

Figure 1. Coefficient of Friction Results for AISI304 with 10W40 + TiC Additives

10W40 oil, the following changes in friction coefficient were observed: with 1% TiC, the coefficient increased to 1.55; with 3% TiC, it reached 2.00; and with 5% TiC, it slightly decreased to 1.98. These results indicate that the addition of TiC nanoparticles to 10W40 oil increased the coefficient of friction on the AISI304 surface and negatively affected the tribological performance. Notably, at 3% and 5% addition rates, the coefficient of friction increased significantly compared to the use of base oil alone.

This increase can be attributed to several mechanisms. Firstly, the high concentration of TiC nanoparticles may have caused the formation of an uneven film layer on the surface, leading to micro-abrasion. Additionally, the increased amount of solid particles could have produced abrasive effects on the sliding surface, thereby raising the friction coefficient. Moreover, the high particle concentration may have increased the viscosity of the oil, negatively affecting its flow properties and preventing the formation of a stable lubricating film between the surfaces. Considering all these mechanisms together, it is evident that excessive nanoparticle addition has a detrimental impact on tribological performance. Coefficient of friction results for AISI304 with 10W40 + TiN additives are given in ▶**Figure 2**.

The average coefficient of friction for the AISI304 specimen in its pure (unlubricated) state was measured as 1.06, indicating significant friction between the surfaces under dry conditions (Table 7). When 10W40 motor oil was used, the coefficient of friction decreased noticeably to 0.84, demonstrating that the oil formed a protective film layer between the surfaces, thereby reducing direct contact.

However, when TiN nanoparticles were added to the 10W40 oil, a significant increase in the coefficient of friction was observed: 1.82 for 1% TiN, 2.69 for 3% TiN and 2.70 for 5% TiN additions. These findings clearly show that the use of TiN nanoparticles in combination with 10W40 oil increased friction on AISI304 surfaces and negatively affected the tribological performance.

This increase can be attributed to several potential factors. Firstly, the higher concentration of nanoparticles may have led to particle accumulation and aggregation within the oil, resulting in the formation of uneven wear zones on the surface. Additionally, the dense presence of nanoparticles might have caused a micro-abrasive effect rather than acting as a protective film layer, thereby damaging the surface. Moreover, as the particle ratio increased, adverse changes in the oil's viscosity may have occurred, disrupting the lubricant's flowability, preventing sufficient film formation on the surface and ultimately leading to an increase in the coefficient of friction.

The average coefficient of friction measured for the pure AISI304 sample was found to be 1.06. In tests performed with 10W40 motor oil, the coefficient of friction decreased to 0.84, indicating that 10W40 oil provided significantly lower friction values compared to the dry condition. When TiC nanoparticles were added to the

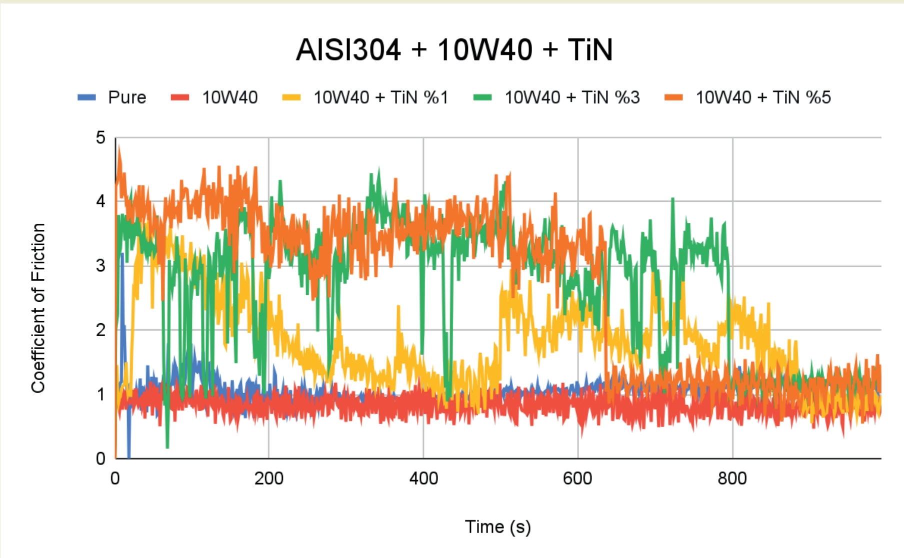

Figure 2. Coefficient of Friction Results for AISI304 with 10W40 + TiN Additives

Table 7. Average Friction Coefficient Results of AISI304 with 10W40 + TiN Additives

	Pure	10W40	10W40 + TiN %1	10W40 + TiN %3	10W40 + TiN %5
Average Coefficient of Friction (μ)	1.06	0.84	1.82	2.69	2.70

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10W40 motor oil, the coefficient of friction increased to 1.55 at 1% concentration, and reached 2.00 and 1.98 at 3% and 5% concentrations, respectively. In the case of TiN in addition to 10W40 oil, high coefficients of friction were obtained: 1.82 at 1% concentration, 2.69 at 3% and 2.70 at 5%.

The weight loss values obtained from the wear tests performed on the AISI304 specimen are presented in ▶Table 8. The measured weight loss for the pure (unlubricated) AISI304 sample was found to be 0.0059 g. When 10W40 motor oil was used, this value significantly decreased to 0.0001 g, indicating that 10W40 oil is highly effective in minimizing wear on the AISI304 surface.

Table 8. Weight Loss Results from Wear Tests of AISI304-Based Samples with TiC and TiN Additives

AISI304	Weight Loss (g)
Pure	0.0059
10w40	0.0051
10w40+TiC1	0.0057
10w40+TiC3	0.0054
10w40+TiC5	0.0050
10w40+TiN1	0.0034
10w40+TiN3	0.0031
10w40+TiN5	0.0027

When TiC and TiN nanoparticles were added to the oil, the following changes in weight loss were observed: For 10W40 + TiC additives, the weight loss ranged between 0.0050 and 0.0057 g, showing an increase compared to pure 10W40 oil. For 10W40 + TiN additives, the weight loss remained relatively low, between 0.0027 and 0.0034 g. These findings indicate that the effect of nanoparticle additives on tribological performance depends not only on the type of additive but also on its concentration, the type of base oil, and the surface properties of the material.

Overall, 10W40 motor oil was found to be effective in reducing the coefficient of friction. However, the addition of TiC nanoparticles increased the coefficient of friction for the AISI304 sample (▶Figure 3). In contrast, TiN nanoparticles improved friction performance only at a specific concentration (3%); increasing the concentration beyond this point had a negative effect on tribological performance.

In conclusion, the effectiveness of nanoparticle additives depends not only on the material and oil type but also significantly on the additive concentration. If the optimal concentration is not carefully determined, undesirable increases in friction may occur.

The average coefficients of friction obtained from the wear tests conducted on the St37 steel specimen using 10W40 motor oil and TiC (Titanium Carbide) nanoparticle additives are presented in ▶Table 9.

The average coefficient of friction for the pure St37 steel

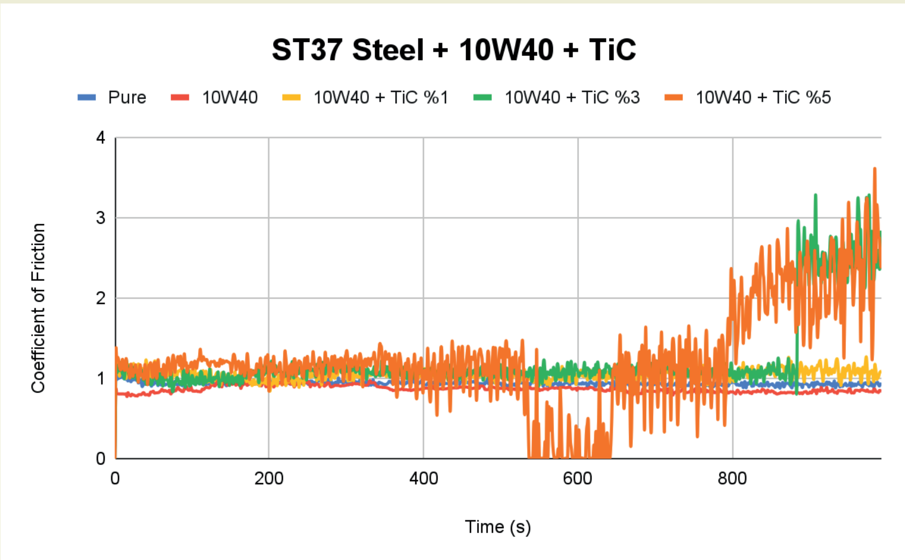

Figure 3. Coefficient of Friction Results for St37 Steel with 10W40 + TiC Additives

Table 9. Average Coefficient of Friction Results for the St37 Steel Specimen Under 10W40 + TiC Additive

	Pure	10W40	10W40 + TiC %1	10W40 + TiC %3	10W40 + TiC %5
Average Coefficient of Friction (μ)	0.94	0.87	1.05	1.23	1.23

specimen was measured as 0.94. When 10W40 motor oil was used, a decrease in the coefficient of friction was observed, with the value measured at 0.87. This result indicates that the 10W40 lubricant forms a more effective film layer between the surfaces, thereby reducing friction. However, when TiC nanoparticles were added to the 10W40 motor oil, an increase in the coefficient of friction was observed: with 1% TiC additive, the coefficient rose to 1.05 and for 3% and 5% TiC additives, it was measured as 1.23.

The increase in friction with higher additive ratios suggests that TiC nanoparticles may have created an abrasive effect on the St37 steel surface, rather than forming a friction-reducing film layer. Additionally, the high particle concentration may have negatively impacted the flow properties of the oil, leading to more contact points on the surface.

In general, it was determined that the use of 10W40 motor oil alone was effective in reducing friction on the St37 steel surface. However, the addition of TiC nanoparticles resulted in increased friction with higher concentrations, negatively affecting tribological performance. These findings indicate that nanoparticle additives may not produce the desired effect in every system and that the compatibility of the additive, material and lubricant must be carefully optimized.

The average coefficients of friction obtained from the wear tests conducted on the St37 steel specimen using 10W40 motor oil and TiN (Titanium Nitride) nanoparticle additives are presented in ▶**Table 10**.

The average coefficient of friction for the pure St37 steel specimen was determined to be 0.94. When 10W40 motor oil was used, the coefficient of friction decreased to 0.87, indicating that the lubricant effectively reduced direct surface contact and improved tribological performance. When TiN (Titanium Nitride) nanoparticles were added to the 10W40 motor oil, the following changes in the coefficient of friction were observed: 1.05 with 1% TiN, 1.29 with 3% TiN and 1.13 with 5% TiN.

The use of TiN additives at 1% and 3% resulted in an increase in the coefficient of friction compared to pure oil (▶**Figure 4**). At 5% TiN, a slight improvement was observed compared to lower concentrations, but the value still remained higher than that of the base oil alone. This trend suggests that TiN nanoparticles did not achieve the desired friction-reducing effect on St37 steel surfaces when dispersed in 10W40 oil. Factors such as particle agglomeration at higher concentrations or negative changes in lubricant flow characteristics may have negatively influenced the tribological behavior.

In general, the use of pure 10W40 motor oil was effective in reducing friction on St37 steel surfaces. However, the addition of TiN nanoparticles led to an increase in friction depending on the concentration, negatively affecting overall tribological performance. These findings highlight that the effectiveness of nanoparticle additives depends not only on the type of additive but also

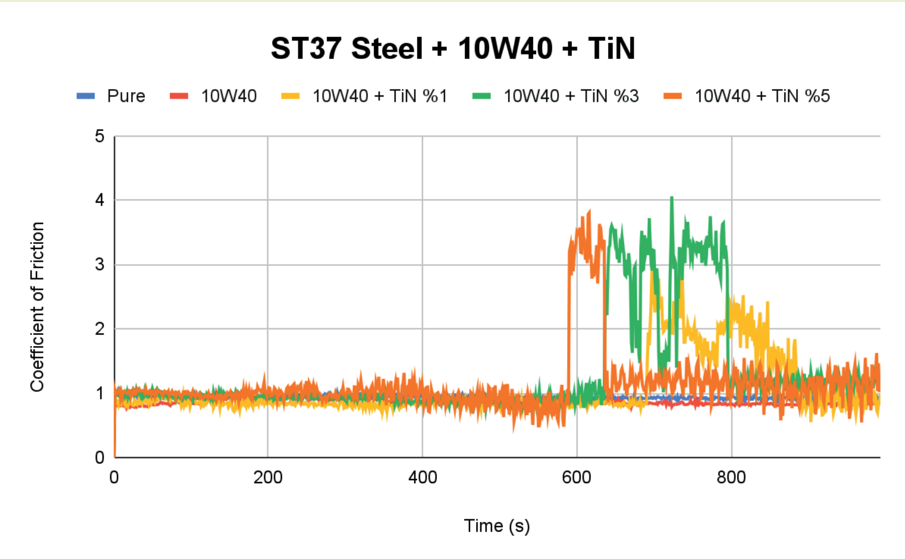

Figure 4. Coefficient of Friction Results for St37 Steel with 10W40 + TiN Additives

Table 10. Average Coefficient of Friction Results for St37 Steel Specimen Under 10W40 + TiN Additive Conditions

	Pure	10W40	10W40 + TiN %1	10W40 + TiN %3	10W40 + TiN %5
Average Coefficient of Friction (μ)	0.94	0.87	1.05	1.29	1.13

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on its interaction with the lubricant and the material properties. Therefore, careful optimization of additive type and concentration is essential for achieving desired performance.

The average coefficient of friction measured for the pure St37 steel specimen was 0.94. The use of motor oil improved tribological performance by reducing friction on the specimen surfaces. When 10W40 motor oil was applied, the coefficient of friction decreased to 0.87. Upon the addition of TiC and TiN nanoparticles to the 10W40 motor oil, different trends in the coefficient of friction were observed. For TiC additives, a clear increase in friction was noted with increasing nanoparticle concentration. In 10W40 + TiC samples, the coefficient of friction was measured as 1.05 at 1% concentration and 1.23 at both 3% and 5% concentrations. This rise suggests that TiC nanoparticles did not exhibit the expected friction-reducing effect on St37 steel surfaces and may have even induced an abrasive effect.

On the other hand, the influence of TiN additives followed a different pattern. In 10W40 + TiN samples, the coefficient of friction was 1.05 at 1% TiN, 1.29 at 3% and 1.13 at 5% concentration. These results indicate that TiN nanoparticles may provide a friction-reducing effect on St37 steel when used at an optimal concentration (3%), but this effect diminishes at both lower and higher concentrations.

The wear test results for the St37 steel specimen in terms of mass loss are presented in ▶**Table 11**.

Table 11. Wear Loss Results for St37 Steel Specimen

St37 Steel	Weight Loss (g)
Pure	0.0013
10w40	0.0052
10w40+TiC1	0.0012
10w40+TiC3	0.0091
10w40+TiC5	0.0024
10w40+TiN1	0.0017
10w40+TiN3	0.0059
10w40+TiN5	0.0027

The wear loss measured for the pure St37 steel specimen was 0.0013 g. When 10W40 motor oil was used, the wear increased to 0.0052 g. Upon the addition of TiC and TiN nanoparticles to the oil, the wear loss values showed the following variations: For 10W40 + TiC, a very low wear loss of 0.0012 g was observed at 1% concentration; however, at 3%, the wear increased sharply to 0.0091 g, and at 5%, it decreased again to 0.0024 g. For 10W40 + TiN, the wear values generally remained low, ranging between 0.0012–0.0059 g. Titanium is widely used in various industries, especially in aviation, due to its exceptional strength, corrosion resistance, low density and favorable biocompatibility and biomechanical properties. The results obtained in this study prove this [20].

These findings demonstrate that the effect of nanoparticle additives on wear behavior depends not only on the type of additive, but also on the concentration used, the base oil type and the properties of the material. It is observed that TiN nanoparticles at lower concentrations can enhance wear resistance, while their effectiveness diminishes at higher concentrations. In contrast, TiC additives may increase wear loss at certain concentrations, possibly due to their abrasive effects on the surface [21].

Based on the results of this study, it is concluded that for materials like AISI304, nanoparticle additives can improve tribological performance if the additive ratio is carefully optimized. For St37 steel, low-percentage TiN additives are recommended, while TiC additives should be avoided. In the selection of lubricating oils, both friction and wear parameters should be considered. Finally, it is recommended that more comprehensive wear tests under variable load and temperature conditions be conducted in future research to evaluate the long-term performance of nanoparticle-enriched lubricant systems [22].

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.

Abrasive wear typically occurs as a result of mechanical abrasion of the surface by hard particles. In the 3D microscope images, pronounced scratches, micro-pitting, and surface irregularities were observed, particularly on the pure St37 steel samples in ▶**Figure 5**. The images obtained for pure St37 steel revealed that the wear progressed in the form of directed and deep grooves. This type of wear mechanism is generally defined as two-body abrasive wear and tribological studies [23] have shown that this form of wear can be further intensified by the movement of abraded particles on the surface.

When reinforced lubricants were used, a significant reduction in surface wear was observed. In St37 steel specimens lubricated with oils containing 1%, 3% and 5% TiN additives, abrasive wear was found to be less pronounced. The depth of the scratches decreased and a more uniform wear pattern formed on the surface. TiN particles contributed to a more balanced wear behavior under frictional forces, leading to a more controlled wear mechanism. Lubricants with TiC additives, on the other hand, altered the wear mechanism more effectively, minimizing the impact of abrasive wear. The St37 steel specimen lubricated with 5% TiC-containing oil exhibited the least signs of abrasive wear, standing out as the sample with the best surface condition. Studies in the literature [24] have shown that TiC controls surface wear more effectively due to its high hardness and chemical stability. The high hardness prevents the

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formation of micro-cuts on the surface, leading to a smoother and more uniform wear pattern.

Adhesive wear occurs as a result of the adhesion and subsequent detachment of metal surfaces. In the images, material transfer was observed particularly in certain regions of the AISI304 samples in ▶**Figure 6**. Although AISI304 is known for its higher resistance to adhesive wear due to its natural oxide layer, localized material accumulation and deformation were detected in the samples lubricated with non-reinforced oils.

Adhesive wear is not solely a result of mechanical damage but is also influenced by chemical and physical interactions at the contact interface [25]. The incorporation of TiN and TiC additives into lubricants alters these interactions, significantly reducing metal transfer between contacting surfaces. In this study, AISI304 samples lubricated with 5% TiN and 5% TiC additives exhibited minimal adhesive wear. This observation aligns with findings from previous research, which demonstrated that TiN and TiC coatings effectively lower the coefficient of friction, thereby minimizing direct metal-to-metal contact and reducing adhesive wear. Especially for AISI304, the lubricant containing 5% TiC almost completely suppressed adhesive wear. This indicates that TiC particles act as a barrier preventing metal transfer between contact surfaces.

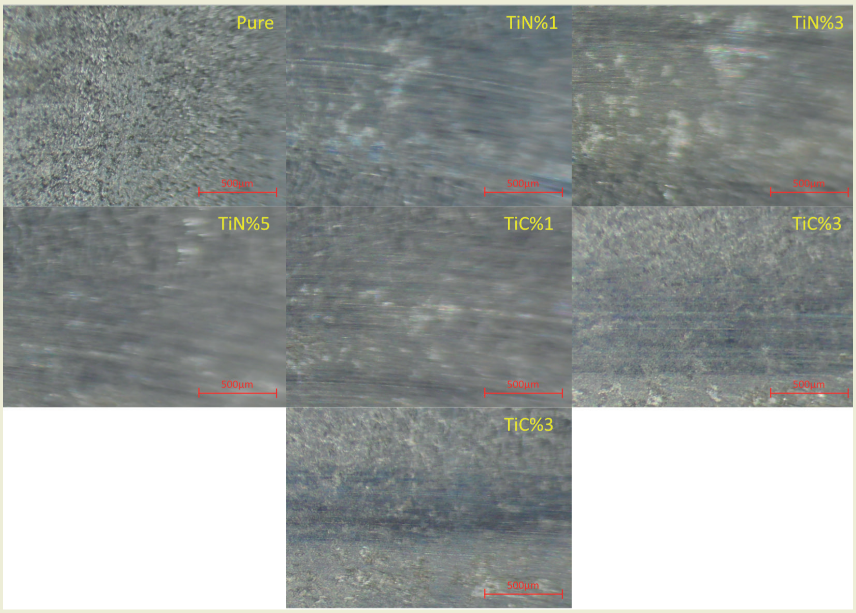

Figure 5. St37 Sample Surface Wear Analysis under 10W40 Oil with TiC and TiN Additives (3D Optical Microscopy Images)

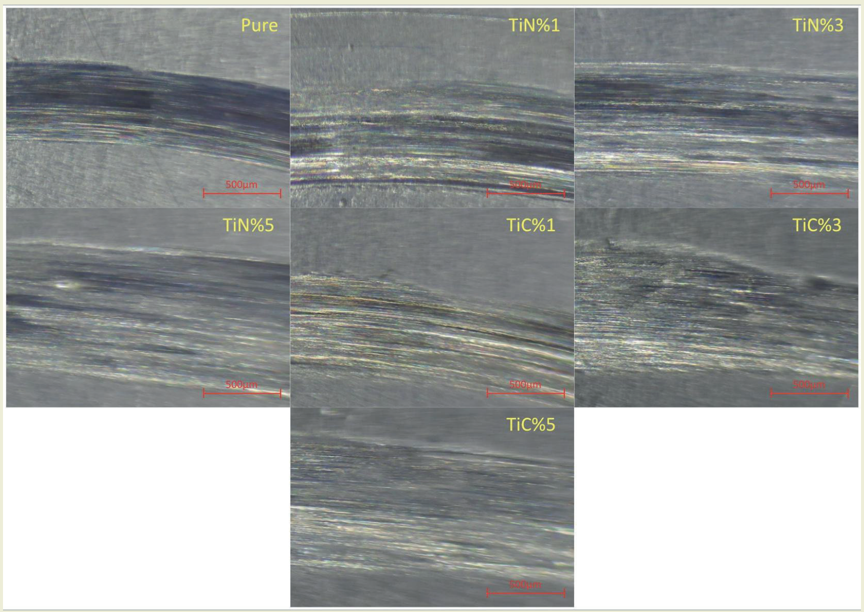

Figure 6. AISI304 Sample Surface Wear Analysis under 10W40 Oil with TiC and TiN Additives (3D Optical Microscopy Images)

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SEM images of St37 and AISI304 samples at 1000X scale are given in ▶**Figure 6**. When the SEM image of the St37 steel plate is examined, its grains are clearly visible. Very distinct and sharply bounded grains of various sizes are observed on the St37 surface. The surface of St37 steel showed a typical low carbon steel morphology consisting of white colored ferrite and black colored pearlite phases. The microstructure of these steels mainly consists of equiaxed ferrite grains ranging from 14 μm to 18 μm and pearlite phase in varying proportions. The proportion of pearlite phase in the microstructure is around 9% in St37 [23, 26]. The morphology of the AISI304 sample has a smoother surface appearance. There are some scratches and defects on the surface. There is a second phase consisting of small particles that appear to be homogeneously distributed on the AISI304 surface.

When the EDX analysis of the AISI304 sample and the presence of the elements in it as a weight percentage

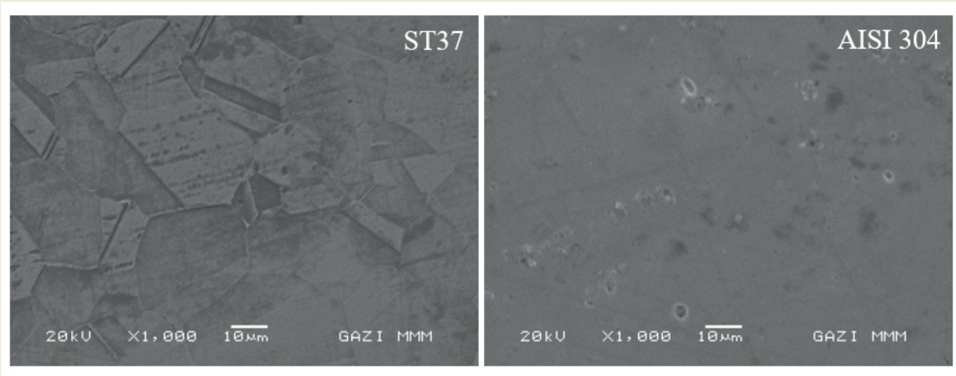

Figure 7. SEM images of St37 and AISI304 at 1000X scale

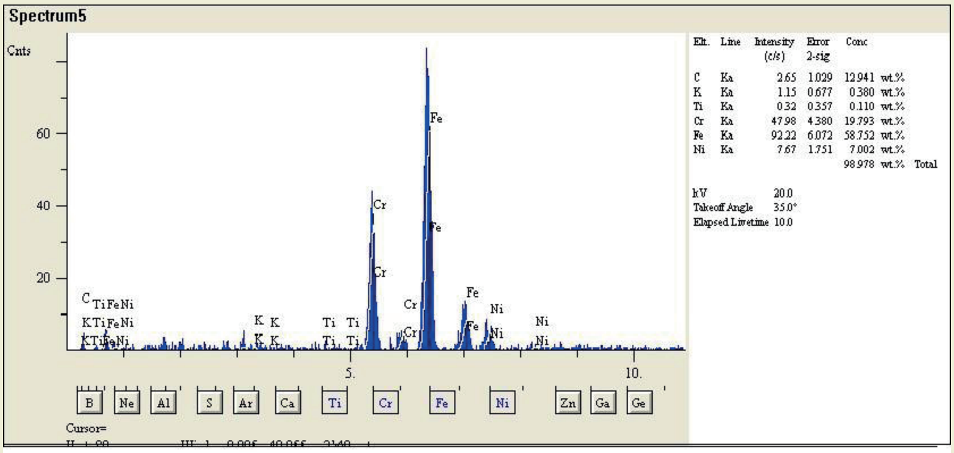

Figure 8. EDX spectrum of AISI304

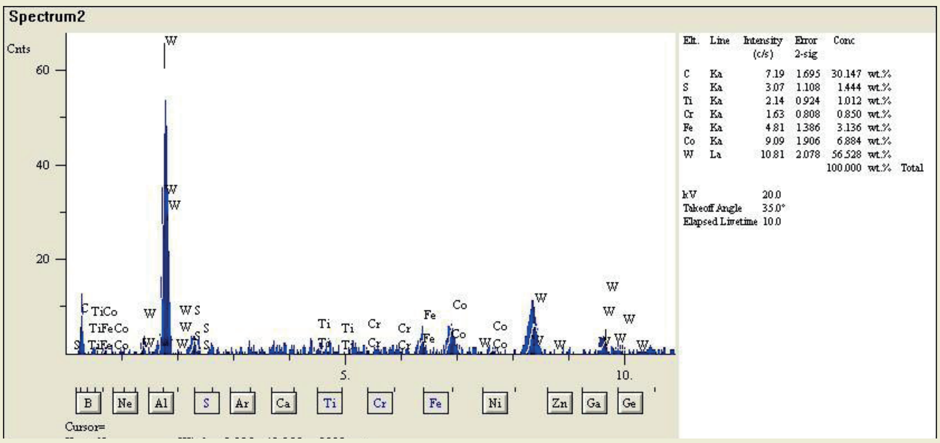

Figure 9. EDX spectrum of St37

were examined, it was observed that elements such as C, Cr, Fe and Ni were found in large amounts in the sample. Besides, the sample contains 58.752% Fe, 19.793% Cr, 12.941% C, 7.002% Ni, 0.380% K, 0.110% Ti.

The EDX elemental analysis results of the St37 sample in ▶Figure 9 show the presence of C, S, Ti, Cr, Fe, Co, W elements in the sample. The EDX spectrum showed that the chemical composition of St37 consists of 56.528% W, 30.147% C, 6.884% Co, 3.136% Fe, 0.850% Cr, 1.012% Ti and 1.444% S elements.

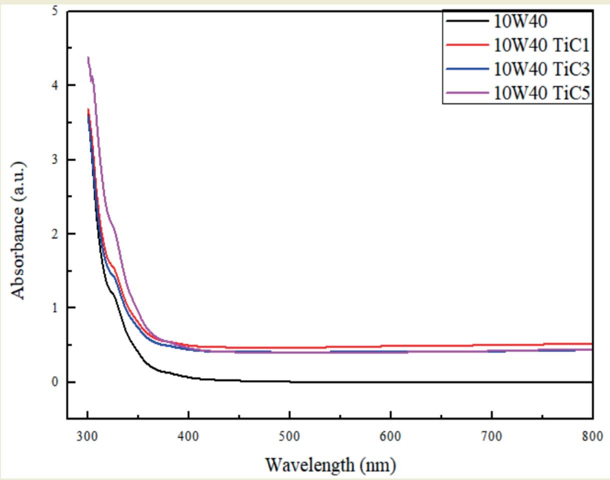

Figure 10. UV absorbance graphs of 10W40 oil including different amounts of TiC.

Another method used to characterize TiC nanoparticles dispersed in 10W40 oil is UV spectrometry. ▶Figure 10 shows the UV absorption spectra of 10W40 oils containing 1, 3 and 5% TiC nanoparticles. The absorption of TiC nanoparticles was observed below 350 nm, similar to the literature [27]. With the increase in the TiC nanoparticle ratio in the oil, the absorption in the UV wavelength region also increased. The reason for the increased light extinction with the increased TiC amount may be due to both UV absorption of the nanoparticles and light scattering. The results showed that TiC particles are good UV absorbers.

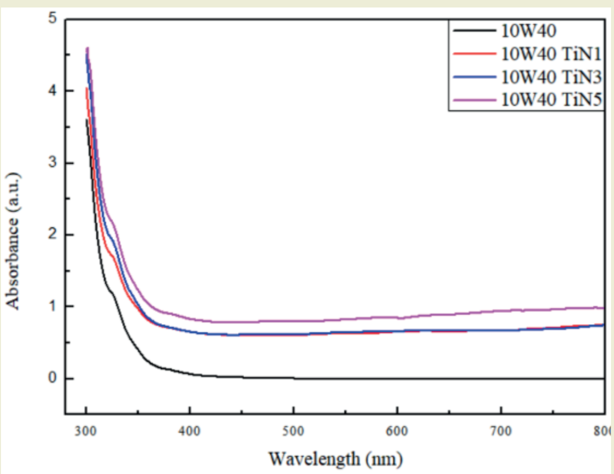

Figure 11. UV absorbance graphs of 10W40 oil including different amounts of TiN.

UV–vis absorption spectra were used to characterize the deoxygenation of GO and the formation of TiN–rGO nanohybrids. ▶Figure 11 shows the absorption spectra of 10W40 oil containing 1, 3 and 5 wt% TiN. In the UV spectrum, TiN showed a broad absorption band at between 300-350 nm, which was in agreement with the literature [28, 29]. As the TiN ratio in the oil increased, the peak shifted towards 350 nm.

4. Conclusions

This study systematically investigated the tribological performance of AISI304 and St37 steel specimens lubricated with 10W40 engine oil, both with and without TiC and TiN nanoparticle additives. The findings revealed that while the base oil alone effectively reduced friction and wear, the incorporation of nanoparticles led to varying outcomes depending on their type and concentration.

Specifically, the addition of TiC nanoparticles resulted in an increased coefficient of friction for both steel types, suggesting that at higher concentrations, TiC may induce abrasive effects rather than providing lubrication. Especially, TiN nanoparticles demonstrated a concentration-dependent behavior. At optimal concentrations, they improved wear resistance, particularly in St37 steel specimens. However, at higher concentrations, the benefits diminished, likely due to nanoparticle agglomeration and increased lubricant viscosity, which hindered effective lubrication.

Surface analyses further revealed that the wear mechanisms transitioned from predominantly adhesive in dry conditions to a combination of abrasive and adhesive when nanoparticle-enhanced lubricants were applied. Notably, TiC additives were more effective in mitigating adhesive wear in AISI304 specimens, while TiN additives provided smoother wear patterns in St37 specimens at optimal concentrations. These results indicated that nanoparticle additives can alter wear mechanisms based on their interaction with the base oil and the material surface.

Lubricants reinforced with TiN and TiC have modified the wear mechanism, effectively controlling both abrasive and adhesive wear. 3D microscope images clearly illustrate the wear mechanisms and support the contribution of reinforced lubricants to tribological performance. Weight loss data and friction coefficient results clearly demonstrate the surface protection effect provided by the additives.

As a result, in abrasive wear tests, it was observed that wear occurred in the form of deep channels and distinct scratches in pure ST37 steel samples. When a lubricant without nanoparticle reinforcement was used, wear was more severe and uncontrolled. In adhesive wear tests, the non-reinforced lubricant could not completely prevent adhesive wear. For abrasive wear, the ST37 steel sample lubricated with 5% TiC-reinforced lubricant showed the lowest abrasive wear marks and the high hardness and chemical stability of the TiC particles prevented the formation of microcuts on the surface and minimized wear. Adhesive wear results showed that adhesive wear was almost completely suppressed in the 304 stainless steel sample lubricated with 5% TiC-reinforced lubricant. In summary, TiC particles acted as an effective barrier preventing metal transfer. 5% TiN and 5% TiC reinforcements minimized adhesive wear by reducing metal-to-metal contact.

Acknowledgments

This article is derived from the master's thesis of Cemile Eylem Urhan, conducted in 2025 at the Graduate School of Uşak University, Department of Materials Science and Nanotechnology Engineering. The thesis was supervised by Dr. Kadir Gündoğan as the primary advisor and Dr. Atike İnce Yardımcı as the co-advisor. The authors would like to express their gratitude to Uşak University for its support.

Research ethics

Not applicable.

Author contributions

Conceptualization: [Kadir Gündoğan, Atike İnce Yardımcı, Cemile Eylem Urhan], Methodology: [Kadir Gündoğan, Atike İnce Yardımcı, Cemile Eylem Urhan], Formal Analysis: [Cemile Eylem Urhan, Kadir Gündoğan], Investigation: [Cemile Eylem Urhan, Atike İnce Yardımcı], Resources: [Kadir Gündoğan, Atike İnce Yardımcı], Data Curation: [Cemile Eylem Urhan, Kadir Gündoğan], Writing - Original Draft Preparation: [Cemile Eylem Urhan], Writing - Review & Editing: [Kadir Gündoğan, Atike İnce Yardımcı], Visualization: [Cemile Eylem Urhan, Kadir Gündoğan], Supervision: [Kadir Gündoğan, Atike İnce Yardımcı]

Competing interests

The author(s) state(s) no conflict of interest.

Research funding

None declared.

Data availability

The raw data can be obtained on request from the corresponding author.

Peer-review

Externally peer-reviewed.

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