

Article

Lubricating Properties of Oil-Based Solutions Containing Graphene as Additive

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Abstract

Graphene, a 2D carbon allotrope with a hexagonal atomic structure, exhibits an exceptionally low friction coefficient of approximately 0.004, making it a superior alternative to traditional lubricants. This research investigates the performance of graphene as an additive in oil-based lubricants. Experimental trials will be conducted using a block-on-ring (B-o-R) setup involving a steel rod pressed against a rotating steel ring under a fixed load. By varying the sliding velocities, the study will map the Stribeck curve across the boundary (BL), mixed (ML), and hydrodynamic (HL) lubrication regimes. Furthermore, the lubricant's durability under extreme pressure will be assessed via Timken testing. The study identified 0.08 wt.% as the optimal concentration for PAO8, achieving a 21.25% friction reduction in the boundary regime. Furthermore, graphene as an additive mitigated wear volume by up to 90% under extreme pressure conditions (1.3 GPa), whereas epoxidized soybean oil proved to be highly effective as a base lubricant without additional nano-additives.

Keywords: friction; wear; graphene additive; Timken test; block-on-ring; Stribeck curve

1. Introduction

Growing environmental concerns and increasingly stringent regulations on petroleum-based lubricants have accelerated the search for sustainable, high-performance alternatives. In this context, biobased lubricants derived from renewable resources have emerged as viable candidates due to their reduced environmental footprint and favorable tribological properties. Among the various biobased base stocks, vegetable oils represent one of the most promising options due to their intrinsic lubricity and chemical compatibility with sliding surfaces [1].

Vegetable oils are primarily composed of triglycerides, which consist of a glycerol backbone esterified with three fatty acid chains. This molecular architecture imparts several advantageous properties, including excellent lubricity, high viscosity index (typically exceeding 200), low volatility, high flash point, and strong affinity for metal surfaces due to the polar nature of the fatty acid chains. Additionally, vegetable oils are biodegradable, non-toxic, and exhibit good shear stability, making them attractive for environmentally sensitive lubrication applications. Among vegetable oils, soybean oil has received considerable attention due to its wide availability, low cost, and favorable physicochemical properties. Soybean oil demonstrates good solubility even in the absence of additives and provides



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effective lubricity, anti-wear protection, load-carrying capacity, corrosion resistance, and forming performance [2–4]. As a result, it has been explored for applications such as gear oils, chainsaw bar oils, compressor oils, and metalworking fluids [3,5].

Despite these advantages, the industrial application of soybean oil is constrained by its relatively poor thermal and oxidative stability. The high degree of unsaturation in its fatty acid chains introduces reactive sites that are susceptible to oxidation and thermal degradation under severe operating conditions. To mitigate these limitations, chemical modification and additive incorporation have been widely employed. One effective strategy involves reducing the degree of unsaturation to enhance oxidative stability. Epoxidation, which converts carbon–carbon double bonds into epoxide groups, has proven particularly effective, yielding epoxidized soybean oil with improved thermal and oxidative resistance.

In parallel, the incorporation of nanoparticles into liquid lubricants has attracted significant interest as an effective approach to reducing friction and wear. A variety of nanoparticle additives—including metals [6], metal oxides [7], and carbon-based nanomaterials such as carbon nanotubes, graphene, and graphite [8]—have demonstrated substantial tribological benefits. These improvements are commonly attributed to mechanisms such as surface smoothing, rolling or sliding effects, and the formation of protective tribofilms at the contact interface. For instance, Hernandez et al. [7] reported enhanced anti-wear performance in PAO6 oil containing CuO, ZnO, and ZrO₂ nanoparticles, with optimal friction and wear reduction observed at low concentrations. Similarly, Cizaire et al. [9] demonstrated that fullerene-like MoS₂ nanoparticles significantly reduced friction in PAO oil due to interlayer sliding and shear between MoS₂ sheets.

Among the carbon-based nanomaterials, graphene has emerged as a particularly promising lubricant additive due to its exceptional mechanical strength, chemical inertness, high thermal conductivity, and outstanding shear characteristics [10,11]. Graphene is a two-dimensional material consisting of a single atomic layer of carbon atoms arranged in a hexagonal honeycomb lattice, with a C–C bond length of approximately 0.14 nm and a thickness of about 0.34 nm. Its tribological behavior is strongly influenced by structural features, stacking order, defect density, and interfacial interactions with sliding surfaces. Experimental and theoretical studies have shown that friction at the nanoscale decreases with increasing graphene layers, whereas excessive stacking beyond a critical number of layers can lead to increased friction due to interlayer interactions [11].

Graphene has been successfully employed both as a solid lubricant and as an additive in liquid lubricants, with numerous studies reporting significant reductions in friction and wear. Zhang et al. [12] demonstrated that oleic-acid-modified graphene dispersed in PAO oil formed protective tribofilms on steel surfaces, leading to improved anti-wear performance at low concentrations. Similarly, Safiyah et al. [13] identified an optimal graphene nanoplatelet concentration in palm-oil-based ester blends that minimized friction and wear by promoting the formation of a protective boundary layer. Additional studies involving multilayer graphene, reduced graphene oxide, and crumpled graphene structures have further confirmed that graphene additives can markedly enhance lubrication performance when appropriately dispersed and used at optimal concentrations [14–17].

Lubricant viscosity plays a critical role in determining lubrication regimes, film thickness, and overall tribological performance. Variations in viscosity directly influence the transition between boundary, mixed, and hydrodynamic lubrication regimes, thereby affecting friction and wear behavior. Vilhena et al. [18–20] demonstrated that lubricant viscosity significantly impacts the effectiveness of surface texturing under different lubrication regimes. Similarly, Sadeghi et al. [21,22] reported that increasing lubricant viscosity through additive incorporation shifted the lubrication regime toward hydrodynamic conditions and increased film thickness. In the context of graphene-enhanced lubricants, several

studies have reported a viscosity increase upon graphene addition, which can facilitate the formation of a stable lubricating film and reduce direct asperity contact [23].

However, investigations involving graphene additives in vegetable oils have yielded mixed outcomes. While some studies reported substantial reductions in friction and wear at optimal graphene concentrations [24], others observed increased friction under low-load and low-speed conditions due to particle agglomeration and insufficient contact pressure [25,26]. These findings underscore the strong dependence of tribological performance on operating conditions, additive concentration, dispersion quality, and lubricant viscosity.

Overall, the existing literature suggests that graphene nanoparticles can significantly modify both the rheological and tribological behavior of oil-based lubricants. Nevertheless, most reported studies employ testing conditions that differ considerably from those proposed in the present work. Consequently, a systematic investigation under controlled and relevant operating conditions is required to elucidate the combined effects of graphene additives and lubricant viscosity on the tribological performance of soybean-based biolubricants.

2. Materials and Methods

2.1. Lubricants and Nanoparticles Additives

The test specimens used for the tribological testing were made from bearing steel 100Cr6 (AISI52100). The top specimen was a cylindrical roller bearing element while the rotating ring was the outer race of a single row tapered roller bearing with specification 32305A. Information about the test specimens is given below in Table 1.

Table 1. Geometrical dimensions and mechanical properties of the test specimens used for tribological tests.

	Top Cylindrical Roller	Rotating Ring
Type of material	Bearing steel (100Cr6)	Bearing steel (100Cr6)
Diameter (mm)	5	60
Length (mm)	16	-
Width (mm)	-	20
Young Modulus (GPa)	210	210
Poisson's ratio	0.3	0.3
Surface Roughness (μm)	0.02	0.04

The lubricating base oils employed in the present research work were epoxidized soybean oil (ESO) and polyalphaolefin oil 8 (PAO8). Epoxidized soybean oil was supplied by the Department of Chemical Engineering at the University of Coimbra, Portugal, and was originally purchased from Composit Company (Vila Chã de Ourique, Portugal). ESO was selected due to its biodegradability, renewable origin, and promising tribological properties, which make it a suitable candidate for environmentally friendly lubrication applications. In addition, a commercially available polyalphaolefin oil with a viscosity grade of 8 (PAO8) was procured from Kemat Company (Brussels, Belgium). PAO8 is a widely used synthetic lubricant base oil known for its excellent thermal stability, oxidation resistance, and favorable viscosity–temperature characteristics, making it an appropriate reference oil for comparative analysis.

The nanoparticle additive used in this study was graphene nanoplatelets (GNPs), which were produced by Graphenest Company (Sever do Vouga, Portugal). The graphene nanoplatelets used were of high-performance quality and consisted of several stacked layers of graphene, with a reported density of 2270 kg/m^3 . According to technical information provided by Graphenest, the GNPs were synthesized from natural graphite through an exfoliation process assisted by ultrasonic cavitation combined with high-shear mixing. This

production method ensures the formation of thin graphene layers with enhanced surface area and excellent mechanical and thermal properties. The material characterization images of the graphene nanoplatelet powders are presented in Figure 1. Transmission electron microscopy and scanning electron microscopy were used to obtain the morphology of the graphene nanoplatelets. The characterization of the GNP was carried out by the supplying company, Graphenest. As seen in the images below (Figure 1), the GNP powder presented a flake-like morphology with layers of graphene sheets that are stacked.

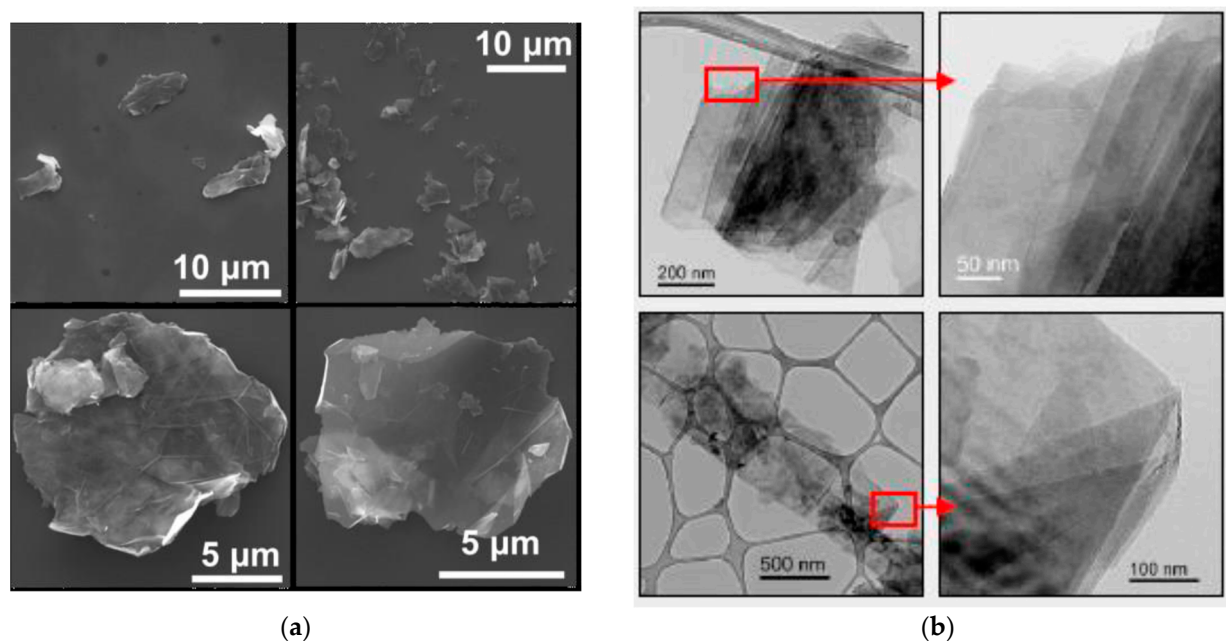


Figure 1. Micrographs of the GNP powder obtained by (a) SEM; (b) TEM [27].

To improve the dispersion stability of graphene nanoplatelets within the PAO8 base oil, Span-80 was used as a dispersant. Span-80 was obtained from Sigma-Aldrich (St. Louis, MO, USA) and was selected due to its effectiveness as a non-ionic surfactant in stabilizing nanoparticle suspensions in nonpolar media. The graphene nanoplatelet powders were incorporated into the PAO8 oil at various concentrations of 0.025, 0.05, 0.08, 0.10, and 0.15 wt.% to prepare different oil-based formulations. The required quantities of graphene nanoplatelets were accurately measured using a digital weighing scale to ensure precise concentration control. Span-80 ($C_{24}H_{44}O_6$) was added at a fixed concentration of 0.05 wt.% to each formulation to enhance the homogeneity and long-term stability of the graphene nanoplatelets dispersed in the PAO8 oil.

For the preparation of graphene-enhanced epoxidized soybean oil, the soybean oil was first diluted with a small quantity of ethanol to reduce its viscosity and facilitate better dispersion of the graphene nanoplatelets. Subsequently, graphene nanoplatelet powders were added to the epoxidized soybean oil at a concentration of 0.05 wt.% to produce a single oil-based nanolubricant formulation. The selected concentration levels for both PAO8- and ESO-based nanolubricants were determined based on the findings reported in previous literature studies [28,29], which indicated optimal tribological performance within similar concentration ranges.

All prepared lubricant mixtures were subjected to ultrasonic dispersion using an ultrasonic probe sonicator (QSonica Sonicator, Newtown, CT 06470, USA) for an average duration of 1 min. Compared to conventional ultrasonic cleaner baths commonly used for nanoparticle dispersion, probe sonicators deliver significantly higher energy intensity, resulting in more effective deagglomeration and uniform distribution of nanoparticles within

the base oil [30]. The ultrasonic treatment ensured improved stability and homogeneity of the nanolubricant suspensions.

Dispersion stability was optimized in subsequent studies conducted by the Department of Chemical Engineering at the University of Coimbra. This optimization was beyond the scope of the present paper, which focused primarily on the tribological behavior of different graphene concentrations.

2.2. Tribotesting

2.2.1. Block-on-Ring Testing

To analyze the friction behavior of the different lubricants at different lubrication regimes, the tribotests were conducted at different sliding speeds so that the Stribeck curve could cover BL, ML and HL regimes.

An in-house block-on-ring sliding test tribometer (Figure 2) with a linear contact geometry, typical from parallel cylinders configuration (Figure 2a) was used for tribotesting. The schematic of the tribometer can be seen in Figure 2b. The laboratory setup for the tribometer included a power source, oil reservoir, counter body, two force sensors (each for the normal and tangential force).

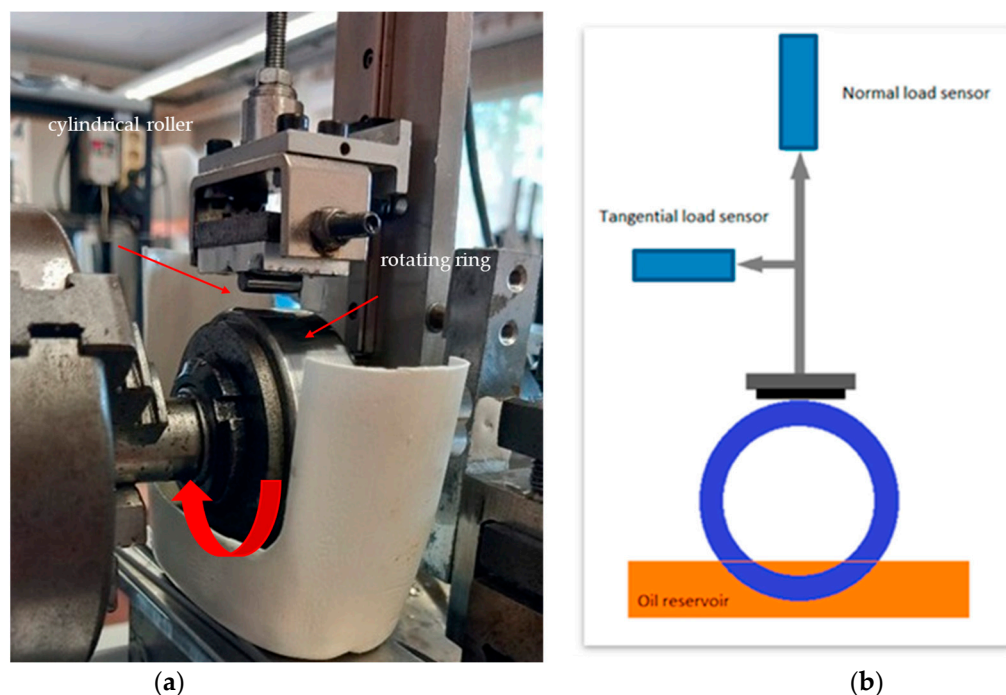


Figure 2. (a) Block-on-ring sliding test tribometer. (b) Schematics of Block-on-ring.

During testing, the stationary top cylindrical roller of diameter 5 mm (100Cr6/AISI 52100 bearing steel) was pressed with a constant load against a rotating ring (100Cr6/AISI52100 bearing steel) with a diameter of 60 mm. A constant normal load of 30 N was applied for eight different linear speeds (0.04, 0.1, 0.25, 0.5, 0.7, 1, 1.2, and 1.49 m/s). This applied load corresponds to a nominal contact pressure of 0.17 GPa according to Hertzian stress theory. During the test, the ratio between the friction force (tangential force) between the sliding surfaces of the block and the ring and the normal load was monitored so that the coefficient of friction can be computed. The lubricating conditions were set in such a way that the contact can be fully flooded. A uniform lubricant film of several thicknesses formed at the ring's surface when the ring rotated inside the lubricant. The oil, which is picked up by the rotating disc, is supplied to the contact and returns to the housing. Before each test, the specimens were ultrasonically cleaned with ethanol and then allowed to dry in

air. The tests were conducted at a room temperature of 22 ± 3 °C. The tests were repeated three times and then standard deviations were determined. The test parameters for the unidirectional sliding friction test are shown in the table below (Table 2).

Table 2. Contact conditions used during the tribotests.

Test	Load (N)	Frequency (Hz)	Sliding Distance (m)	Sliding Speed (m/s)	Sliding Time (s)
1	30	60	188	1.49	127
2	30	48.4	188	1.2	157
3	30	40.4	188	1	188
4	30	28.4	188	0.7	269
5	30	20.4	188	0.5	377
6	30	10.4	188	0.25	754
7	30	4.4	188	0.1	1885
8	30	2	188	0.04	4712

As demonstrated in previous studies [18–20], Hamrock and Dowson’s equation was used for calculating the minimum film thickness, as shown in Equation (1):

$$\frac{h_0}{R'} = 3.63 \left(\frac{U \eta_0}{E' R'} \right)^{0.68} (\alpha E')^{0.49} \left(\frac{W}{E' R'^2} \right)^{-0.0073} \left(1 - e^{-0.068K} \right) \quad (1)$$

where

h_0 is the minimum film thickness (m);

R' is the reduced radius of curvature (m);

U is the entraining surface velocity (m/s), i.e., $U = (U_A + U_B)/2$, where the subscripts ‘A’ and ‘B’ refers to the velocities of bodies A & B respectively;

W is the contact load (N);

E' is the reduced Young’s modulus (Pa);

α is the pressure viscosity coefficient (m^2/N);

η_0 is the viscosity at atmospheric pressure and temperature (Pa·s);

k = elliptical parameter defined as $k = (a/b)$, where ‘a’ is the semiaxis in the transverse direction and ‘b’ is the semi-axis in the direction of motion. For line contact, $k = \infty$.

After calculating the minimum film thickness, the formula below, proposed by Talian [31], was used to calculate the lambda ratio.

$$\lambda = \frac{h_0}{\sqrt{\sigma_A^2 + \sigma_B^2}} \quad (2)$$

where

h_0 is the minimum film thickness (m);

σ_A is the root mean square surface roughness of body A (m);

σ_B is the root mean square surface roughness of body B (m);

λ = lambda ratio (ratio of minimum film thickness to composite surface roughness).

Using the lambda ratio values, the lubrication regimes were classified into boundary, mixed, elastohydrodynamic and hydrodynamic regimes ($\lambda < 1$, Boundary Lubrication; $1 < \lambda < 3$, Mixed Lubrication; $3 < \lambda < 5$, Elastohydrodynamic lubrication; $\lambda > 5$, Hydrodynamic lubrication).

2.2.2. Reichert Wear Test Testing

The Reichert test method covers the procedure for evaluating the wear properties of a lubricant and their additives. The test rig is made up of fixed mounted test cylindrical

roller pressed against a friction wheel that is in a cross-cylinder contact configuration, as shown in Figure 3 below. The friction wheel (rotating ring) was placed in the lubricant bath during the test and loading was applied through dead weights. The lubricant without the extreme pressure additive was tested first to know how long it would take for adhesion to occur between the test roller and the rotating friction wheel. The wear scar on the test roller surface was observed after the test. The lubricant with the extreme pressure additive was also tested and the time taken for adhesion to occur was also noted. The wear scars on the test roller surface containing the extreme pressure additive were compared to the wear scar on the test roller surface without any extreme pressure additive. For this experiment, the test time was set at a maximum of one minute, while the contact load was varied. The parameters used for the Reichert test are given below in Table 3.

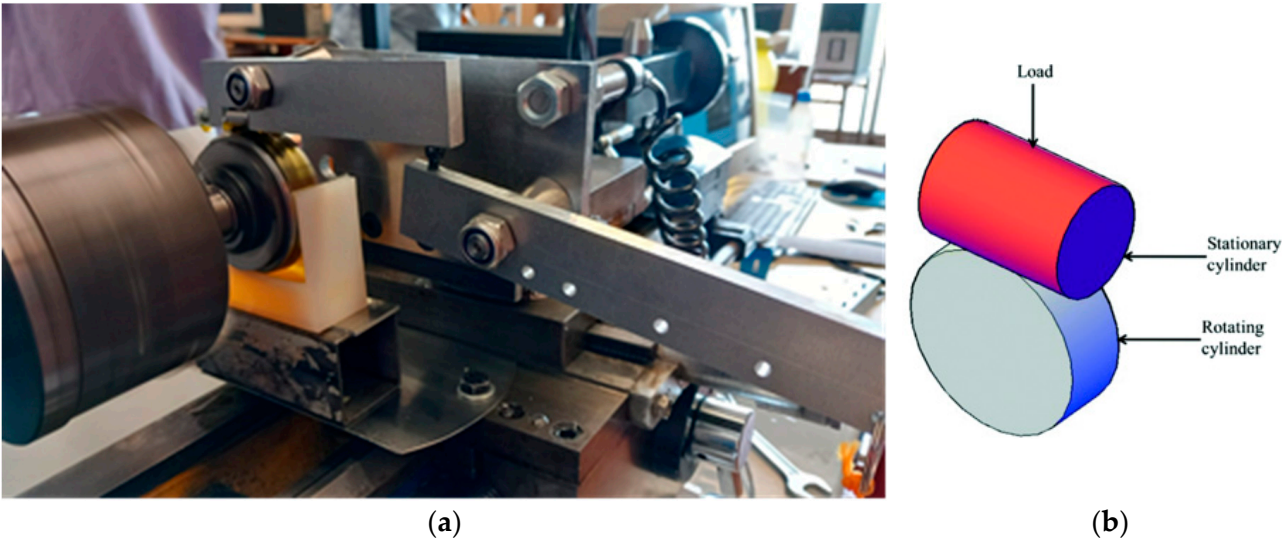


Figure 3. Reichert wear test: (a) cross-cylinder configuration (elliptical contact). (b) Schematics of the cross-cylinder configuration.

Table 3. Test parameters for Reichert wear/extreme pressure test.

Test Specimens	100Cr6 Bearing Steel for Both the Test Roller (10 mm Diameter) and the Rotating Ring (60 mm Diameter)
Contact configuration	Cross cylinders
Type of contact	Unidirectional sliding
Lubricants	PAO8 and epoxidized soybean oil (ESO)
Additives	Graphene nanoplatelets (0.05 wt.%)
Room conditions	T = 22 ± 3 °C
Contact load (contact pressure)	100, 200 and 400 N (1.3, 1.6, 2.1 GPa)
Sliding speed	1.67 m/s
Sliding distance	100 m

After the Reichert test, the wear volume loss of the test rollers was calculated using the equations below (Equations (3)–(6)). The wear scars obtained from the optical and 3D digital microscope aided in the calculation, as shown in Figure 4.

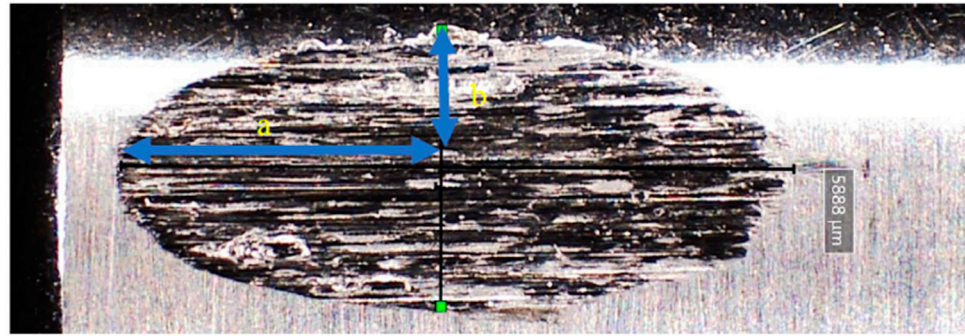


Figure 4. A typical elliptical contact from a cross-cylinder configuration (a and b are the semi-major axis and semi-minor axis of the ellipse).

Considering that R_1 (30 mm) is the radius of the rotating cylinder, R_2 (5 mm) is the radius of the stationary cylinder (test specimen), a and b are the semi-major axis and semi-minor axis of the ellipse, and h' and h'' are the maximum depth of the contact zone, analyzed in two perpendicular planes

$$h' = R_1 - \sqrt{R_1^2 - a^2} \quad (3)$$

$$h'' = R_2 - \sqrt{R_2^2 - b^2} \quad (4)$$

$$h = \frac{h' + h''}{2} \quad (5)$$

$$V = \pi h^2 \sqrt{R_1 R_2} \quad (6)$$

A Mitutoyo Surftest SJ-500P profilometer (Tokyo, Japan) was used to measure the root mean square (RMS) surface roughness of both the top cylindrical roller and the rotating ring. After each tribological test, the wear scars on the top cylindrical rollers were examined using an optical microscope LEICA DM2500 (Wetzlar, Germany) and a 3D digital microscope Hirox RX-5000 (Tokyo, Japan). Furthermore, the surface morphology and wear mechanisms of the worn surfaces were analyzed using a scanning electron microscope SEM, Hitachi SU-3800 (Tokyo, 100-8280 Japan).

3. Results and Discussion

3.1. Stribeck Curves

The influence of graphene nanoplatelet concentration on the mean coefficient of friction (COF) for steel–steel contact pairs under different lubrication regimes is illustrated in Figure 5. For the base PAO8 oil, the mean COF decreased with increasing sliding velocity, ranging from approximately 0.13 under boundary lubrication conditions to about 0.06 at the highest sliding velocity corresponding to the elastohydrodynamic lubrication regime.

As shown in Figure 5, the incorporation of graphene nanoplatelets into PAO8 oil resulted in a pronounced reduction in the mean COF across all lubrication regimes. In particular, the addition of 0.08 wt.% graphene nanoplatelets led to the most significant decrease in friction throughout the entire range of operating conditions. Similarly, the addition of 0.025 wt.% graphene nanoplatelets also produced a noticeable reduction in the mean COF across all lubrication regimes, although the extent of friction reduction was lower compared to that achieved with 0.08 wt.% graphene.

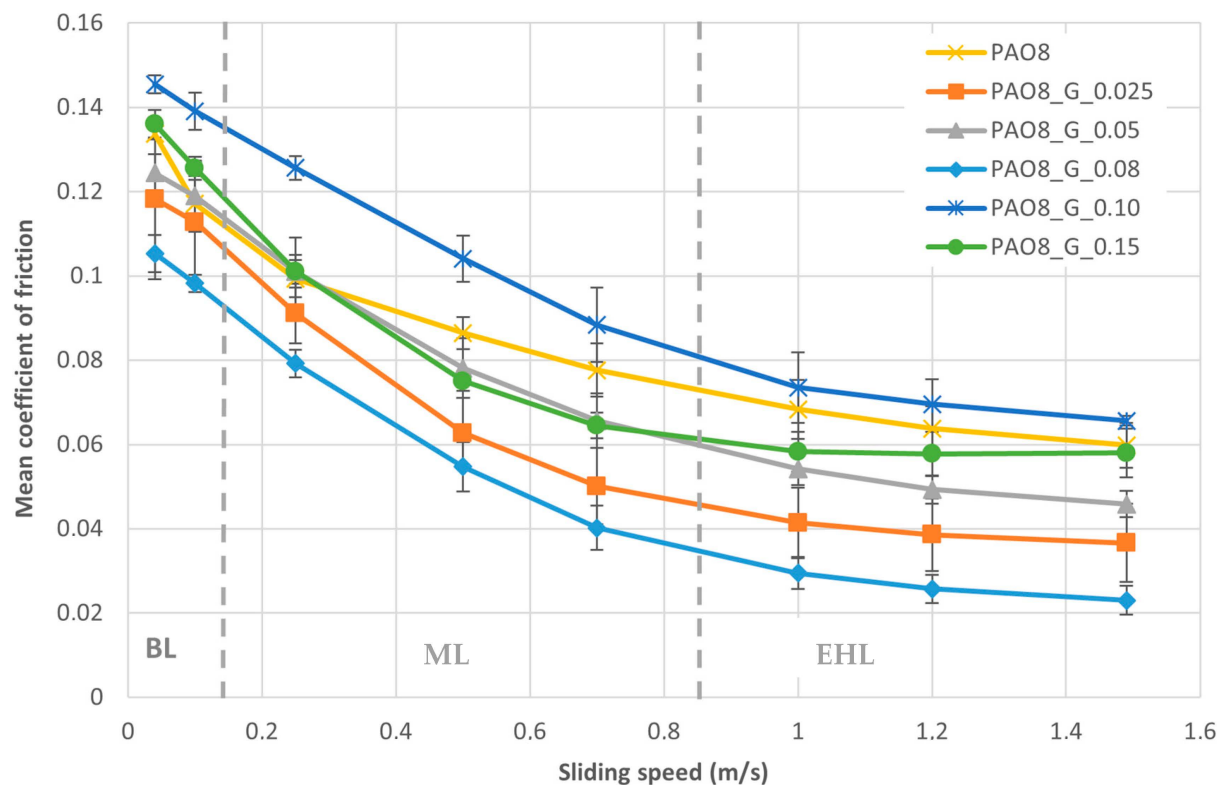


Figure 5. Evolution of the coefficient of friction with sliding speed for the steel/steel contact pairs lubricated with pure base oil (PAO8) and base oil containing 0.025–0.15 wt.% graphene platelets. The lubrication regimes identified in the figure (BL, ML, and EHL) were determined using the Hamrock–Dowson equation and the Tallian criteria.

Under boundary lubrication conditions, the mean COF was reduced by 21.25% with the addition of 0.08 wt.% graphene to PAO8 oil. In comparison, reductions of 11.57% and 6.95% were observed when 0.025 wt.% and 0.05 wt.% graphene were added, respectively. These results indicate that graphene concentrations of 0.025, 0.05, and 0.08 wt.% are effective for improving frictional performance in boundary lubrication regimes under the tribological conditions investigated in this study.

In the elastohydrodynamic lubrication regime, corresponding to the highest contact sliding velocity, even more pronounced reductions in friction were observed. The mean COF decreased by 61.54%, 38.79%, 23.33%, and 3% upon the addition of 0.08, 0.025, 0.05, and 0.15 wt.% graphene, respectively, to PAO8 oil. These findings demonstrate that graphene nanoplatelets are particularly effective in reducing friction under elastohydrodynamic lubrication conditions, with an optimal performance observed at intermediate graphene concentrations.

Figure 6 illustrates the optimum concentration of graphene nanoparticles in PAO8 oil across different lubrication regimes. Among the concentrations investigated, the addition of 0.08 wt.% graphene nanoparticles consistently resulted in the lowest coefficient of friction, identifying it as the optimum concentration under all lubrication conditions examined. Notably, even at the highest sliding velocity of 1.40 m/s, corresponding to the elastohydrodynamic lubrication regime, 0.08 wt.% graphene nanoparticles maintained superior friction-reducing performance compared to other concentrations.

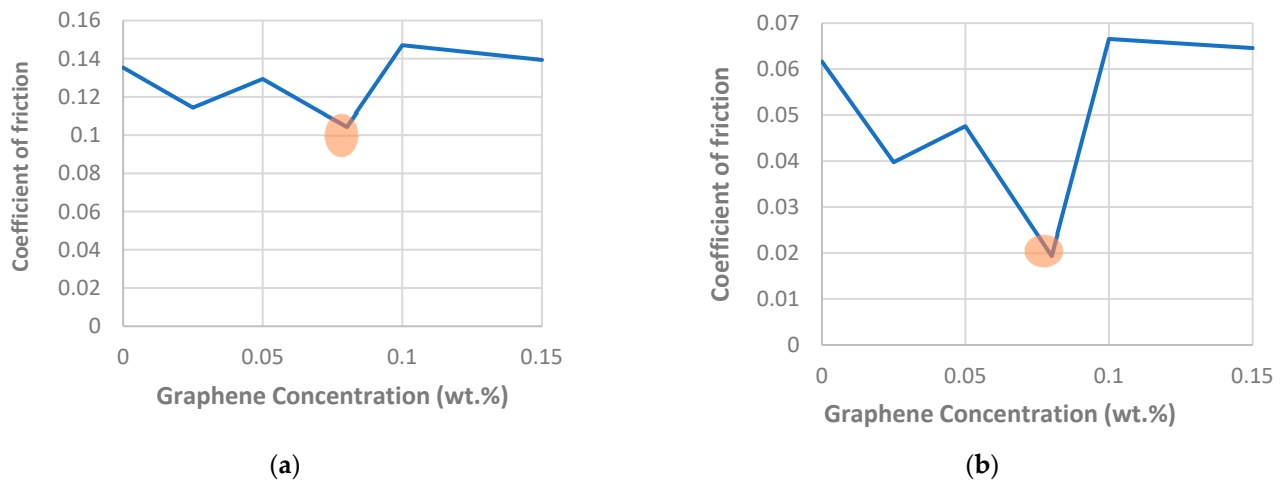


Figure 6. Evolution of the COF with the graphene nanoplatelet concentration in PAO8 for sliding speed: (a) 0.04 m/s (boundary lubrication regime); (b) 1.40 m/s (elastohydrodynamic lubrication regime).

As shown in Figure 7, the addition of 0.05 wt.% graphene nanoplatelets to soybean oil did not result in a reduction in the coefficient of friction. Instead, an increase in friction was observed across all lubrication regimes when compared to the neat soybean oil.

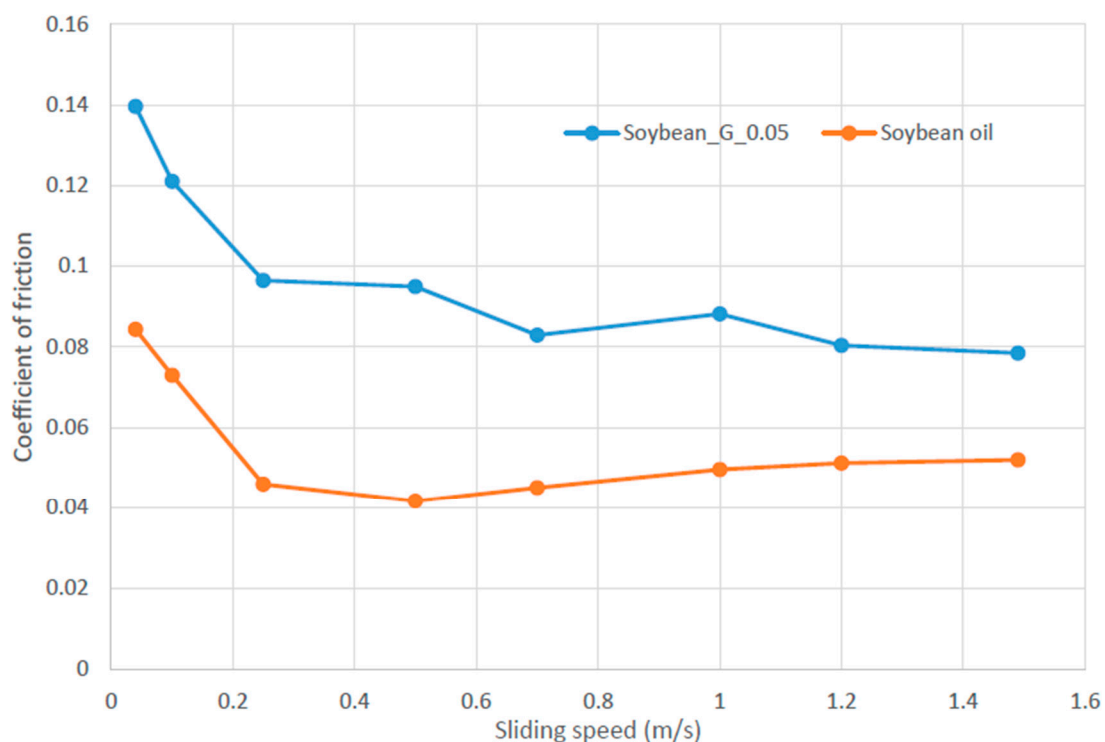


Figure 7. Evolution of the coefficient of friction as a function of sliding speed for steel–steel contact pairs lubricated with soybean oil containing graphene nanoplatelets.

Similarly, as illustrated in Figure 8, the incorporation of 0.05 wt.% graphene nanoplatelets into epoxidized soybean oil did not lead to a reduction in friction across any of the lubrication regimes investigated. In contrast, the neat epoxidized soybean oil consistently exhibited a lower coefficient of friction across all lubrication regimes when compared to the pure PAO8 base oil. These results indicate that epoxidized soybean oil demonstrated superior frictional performance relative to PAO8 under the temperature range examined.

in the present study, highlighting its potential as a viable biobased alternative lubricant. The different behavior observed between PAO8 and epoxidized soybean oil is attributed to their fundamentally different chemical structures and lubrication mechanisms. PAO8 is a non-polar synthetic oil, and the addition of graphene nanoplatelets enhances load-carrying capacity and tribofilm formation. In contrast, epoxidized soybean oil is highly polar and already forms an effective boundary lubrication film without additives. When graphene nanoplatelets are added to epoxidized soybean oil, the combined effect of strong oil–surface affinity and solid particle presence may lead to increased shear resistance or abrasive interactions at the interface.

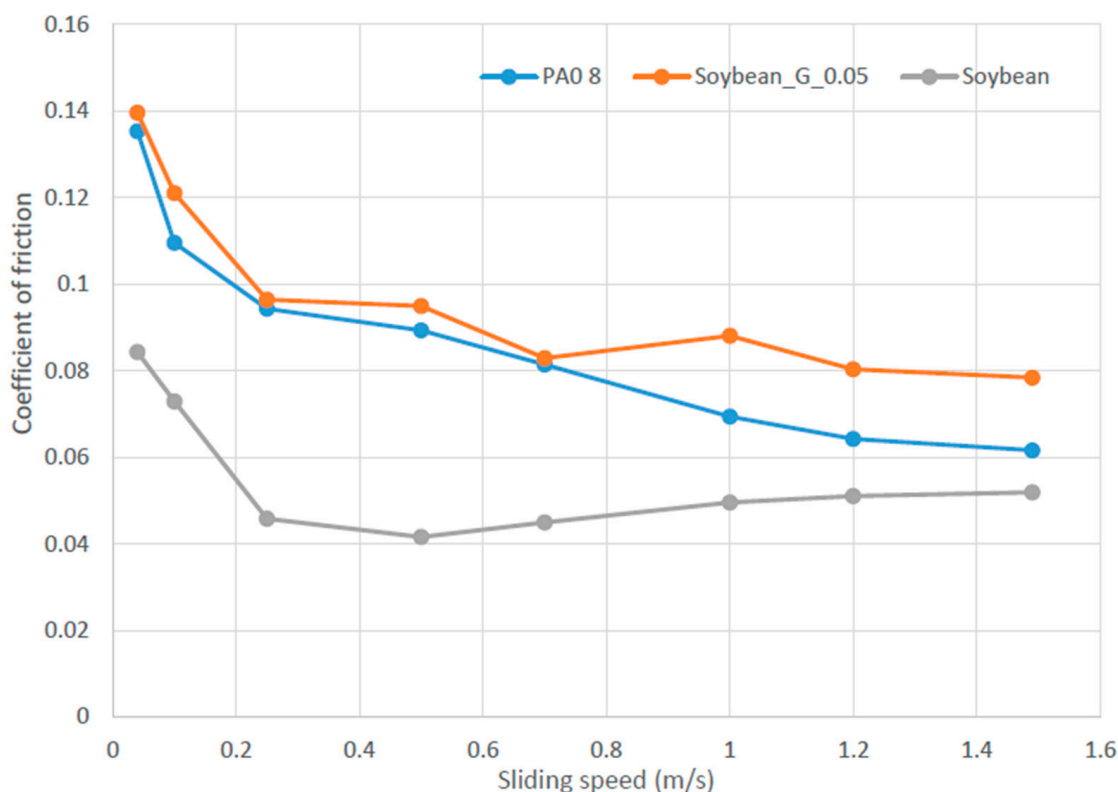


Figure 8. Evolution of the coefficient of friction with the sliding speed for the steel/steel contact pairs lubricated with pure base oils without graphene (ESO and PAO8) and ESO with 0.05 wt.% of graphene.

The minimum film thickness (h_0) and the lambda ratio (λ), also known as the Tallian parameter—defined as the ratio of the minimum film thickness to the composite surface roughness—were calculated using viscosity data, contact conditions, and the mechanical properties of the tribological system. The calculated values are summarized in Table 4.

An increase in lubricant viscosity plays a critical role in promoting transitions between lubrication regimes. As shown in Table 4, three lubrication regimes were present within the investigated range of sliding speeds for the different lubricants examined. For all lubricants, the transition from boundary lubrication (BL) to mixed lubrication (ML) occurred between sliding speeds of 0.1 and 0.25 m/s. The transition from mixed lubrication to elastohydrodynamic lubrication (EHL) was observed between 0.70 and 1.0 m/s, while the transition from elastohydrodynamic lubrication to fully hydrodynamic lubrication (HL) could not be seen under the contact conditions chosen.

Table 4. Minimum film thickness values at different sliding speeds, illustrating transitions between lubrication regimes. BL = boundary lubrication; ML = mixed lubrication; EHL = elastohydrodynamic lubrication; HL = hydrodynamic lubrication.

	μ (30°) (mm ² /s)	u (m/s)	0.04	0.1	0.25	0.5	0.70	1	1.2	1.49
PAO8	71.58	h_0 (m)	6.04^{-8}	1.13^{-7}	2.10^{-7}	3.37^{-7}	4.23^{-7}	5.39^{-7}	6.11^{-7}	7.07^{-7}
		λ	0.3	0.6	1.2	1.9	2.4	3.1	3.5	4.0
PAO8 + 0.025G	71.84	h_0 (m)	6.06^{-8}	1.13^{-7}	2.11^{-7}	3.37^{-7}	4.24^{-7}	5.41^{-7}	6.12^{-7}	7.09^{-7}
		λ	0.3	0.6	1.2	1.9	2.4	3.1	3.5	4.0
PAO8 + 0.05G	71.89	h_0 (m)	6.06^{-8}	1.13^{-7}	2.11^{-7}	3.38^{-7}	4.24^{-7}	5.41^{-7}	6.12^{-7}	7.09^{-7}
		λ	0.3	0.6	1.2	1.9	2.4	3.1	3.5	4.0
PAO8 + 0.08G	72.52	h_0 (m)	6.10^{-8}	1.14^{-7}	2.12^{-7}	3.40^{-7}	4.27^{-7}	5.44^{-7}	6.16^{-7}	7.14^{-7}
		λ	0.3	0.6	1.2	1.9	2.4	3.1	3.5	4.0
PAO8 + 0.10G	72.89	h_0 (m)	6.12^{-8}	1.14^{-7}	2.13^{-7}	3.41^{-7}	4.28^{-7}	5.46^{-7}	6.18^{-7}	7.16^{-7}
		λ	0.3	0.6	1.2	1.9	2.4	3.1	3.5	4.1
PAO8 + 0.15G	73.04	h_0 (m)	6.18^{-8}	1.15^{-7}	2.15^{-7}	3.44^{-7}	4.33^{-7}	5.51^{-7}	6.24^{-7}	7.23^{-7}
		λ	0.4	0.7	1.2	2.0	2.5	3.1	3.5	4.1
			BL	BL	ML	ML	ML	EHL	EHL	EHL

Based on the friction experiments conducted in the present study, lubrication initially occurs under elastohydrodynamic conditions at higher sliding speeds. As the sliding speed decreases, the lambda ratio correspondingly decreases, leading to a gradual shift through mixed lubrication regimes. At sufficiently low sliding speeds, the lubrication regime transitions entirely to boundary lubrication, resulting in direct contact between the block and ring surfaces and an increased likelihood of surface wear.

3.2. Reichert Wear Test

Three-dimensional digital microscopy was employed to quantify the wear volume of the test roller surfaces following the Reichert test conducted under extreme pressure conditions. As illustrated by the 3D digital microscopy images in Figure 9, pronounced adhesive wear features accompanied by material transfer were evident on the test cylinder surfaces. The incorporation of graphene nanoplatelets was effective in mitigating wear, as reflected by the reduced size and severity of wear scars observed on the test cylinders.

Figure 10 presents the variation in wear volume of the counterbody under different contact conditions and applied loads for the various test lubricants. At an applied load of 100 N (corresponding to a maximum contact pressure of 1.3 GPa), the wear scar volume of the test cylinder lubricated with PAO8 containing 0.05 wt.% graphene nanoplatelets was reduced by more than 90% compared to that lubricated with neat PAO8 oil. This substantial reduction highlights the significant role of graphene nanoparticles in enhancing the anti-wear performance of PAO8 under moderate loading conditions.

When the applied load was increased to 200 N (1.6 GPa), the wear volume of the test cylinder lubricated with PAO8 + 0.05 wt.% graphene was still reduced, although to a lesser extent. Under these conditions, a wear reduction of approximately 14.3% was observed relative to the neat PAO8 oil, indicating that the effectiveness of graphene nanoplatelets in mitigating wear diminishes with increasing contact load.

In contrast, the incorporation of graphene nanoplatelets into epoxidized soybean oil did not yield a beneficial effect in terms of wear reduction. As shown in Figure 10, the wear volume increased at both applied loads of 100 N (1.3 GPa) and 200 N (1.6 GPa) when graphene nanoplatelets were added to the epoxidized soybean oil. In comparison, the use of neat epoxidized soybean oil resulted in lower wear volumes, underscoring its inherently good lubricating properties, which are commonly attributed to the presence of long, polar fatty acid chains in vegetable oils.

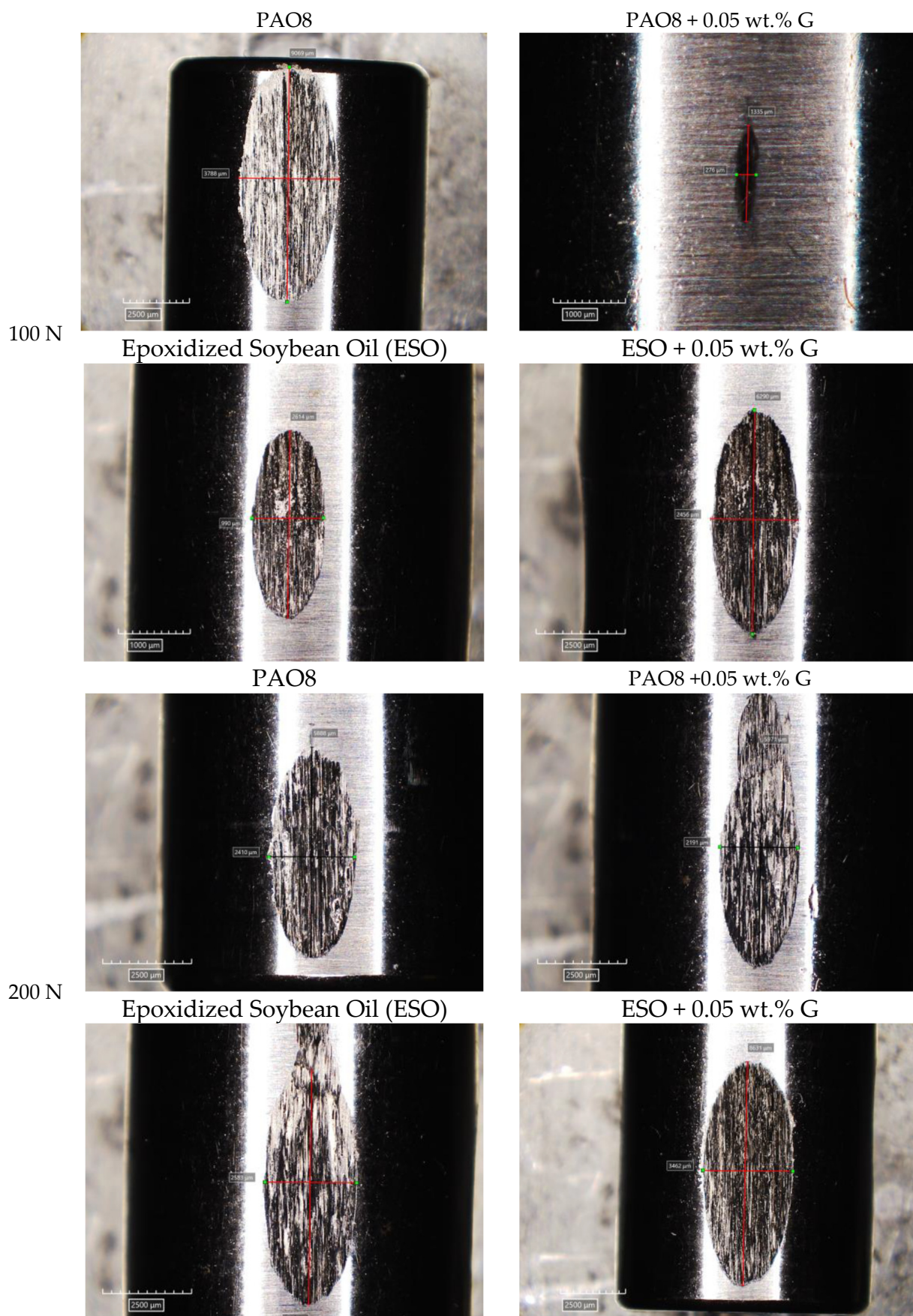


Figure 9. Three-dimensional digital micrographs of wear scars on the counterbody obtained under varying applied loads and lubricating conditions.

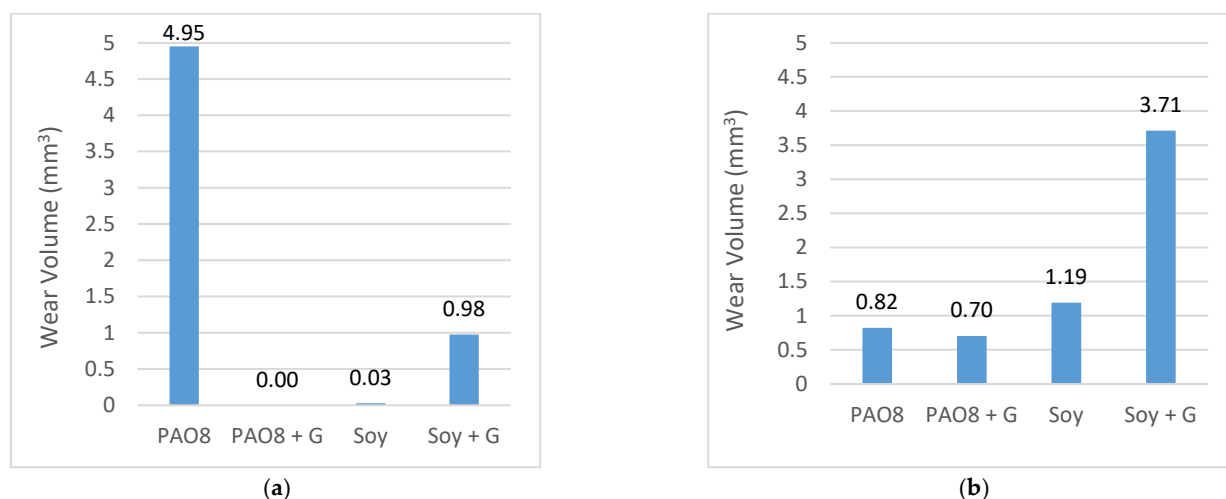


Figure 10. Wear volume from the Reichert wear test under an applied load of: (a) 100 N (1.3 GPa); (b) 200 N (1.6 GPa).

The adverse effect of graphene nanoplatelets observed in epoxidized soybean oil is consistent with the findings reported by Talib et al. [28], who observed degraded tribological performance when excessive amounts of a two-dimensional material (hexagonal boron nitride) were added to a vegetable oil (Jatropha oil). The presence of excessive solid additives, particularly layered two-dimensional particles, can lead to abrasive wear by increasing shear stress concentrations within the asperity valleys at the contact interface. Therefore, it is likely that the graphene nanoplatelet concentration of 0.05 wt.% in epoxidized soybean oil was either excessive or non-optimal for effective wear reduction under the test conditions employed in this study.

From the Reichert extreme-pressure tests, it was observed that at a contact load of 100 N (1.3 GPa), no seizure occurred between the test cylindrical roller and the rotating ring for any of the lubricants, regardless of the presence of graphene nanoplatelets. However, when the contact load was increased to 400 N (2.1 GPa), seizure occurred after 8 s of operation.

In addition to optical microscopy and 3D digital microscopy, scanning electron microscopy (SEM) was employed to evaluate the worn surfaces of the test cylinders and to assess the effect of graphene nanoplatelets (GNPs) when added to PAO8 oil and epoxidized soybean oil. The wear mechanisms on the test roller surfaces were characterized using SEM. Figure 11a–d presents the SEM micrographs of the worn surfaces.

Figure 11a,b shows the wear scars on test surfaces lubricated with PAO8 oil and PAO8 + 0.05 wt.% G under a contact load of 200 N (1.6 GPa), respectively. Abrasive wear was the dominant wear mechanism on both surfaces, with the presence of wear debris and tribofilms observed in each case. However, the surface lubricated with PAO8 oil alone appeared significantly rougher than that lubricated with PAO8 + 0.05 wt.% G, which exhibited a comparatively smoother morphology. This difference can be attributed to the role of graphene nanoplatelets. The formation of a tribofilm likely reduced direct contact between the tribopair surfaces, while the unique morphological structure of graphene nanoplatelets facilitated their entry into the contact zone during sliding. The observed wear behavior is consistent with the findings of Cai et al. [32], who reported ploughing—a form of abrasive wear—under PAO8 lubrication, whereas the addition of graphene flakes resulted in a relatively smoother worn surface.

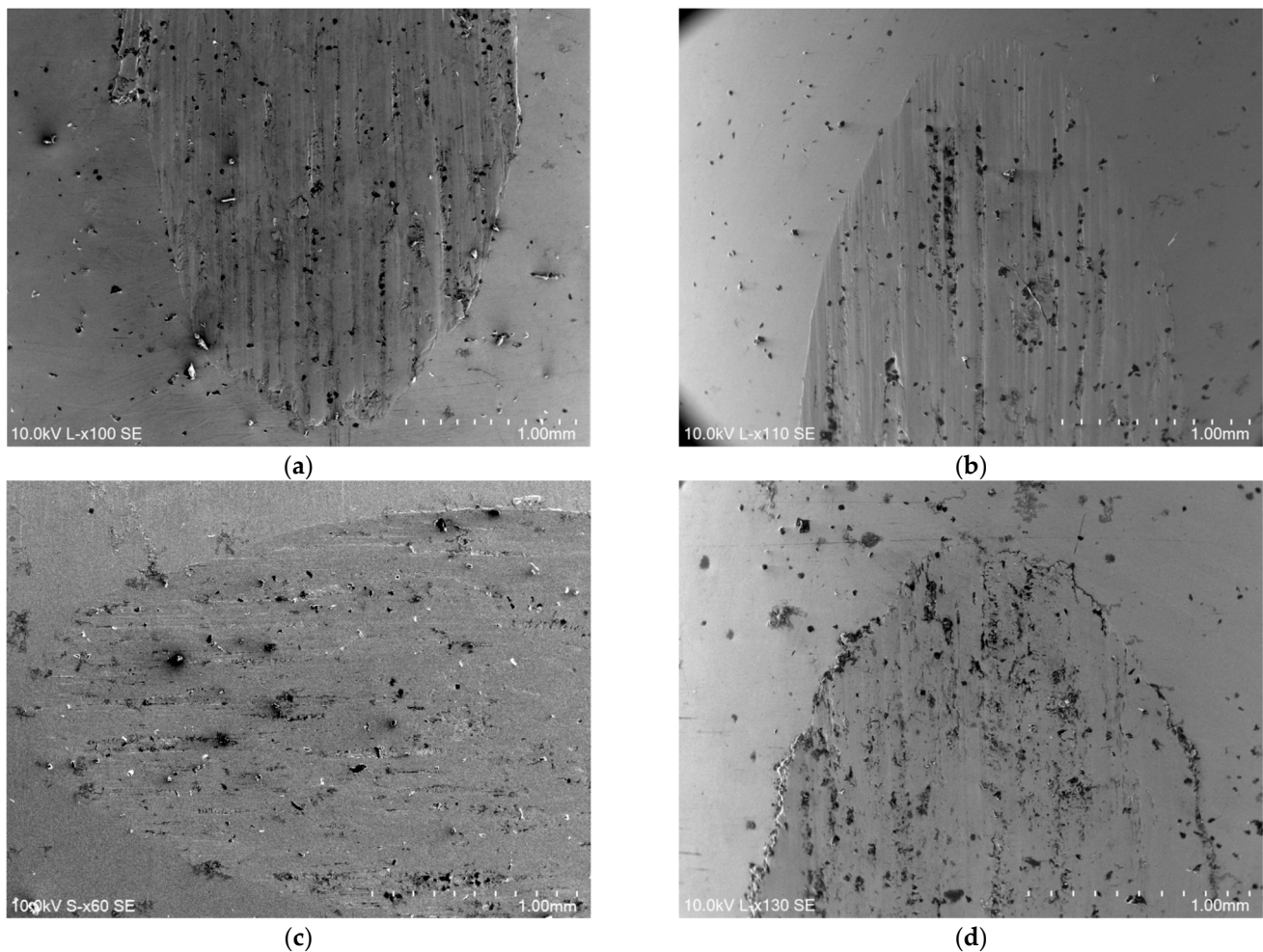


Figure 11. SEM micrographs of wear scars on the test surface lubricated with: (a) PAO8 (contact load = 200 N (1.6 GPa)); (b) PAO8 + 0.05 wt.% G (contact load = 200 N (1.6 GPa)); (c) epoxidized soybean oil (contact load = 100N (1.3 GPa)); (d) epoxidized soybean oil + 0.05 wt.% G (contact load = 100 N (1.3 GPa)).

Figure 11c,d shows the wear scars on test surfaces lubricated with epoxidized soybean oil and epoxidized soybean oil +0.05 wt.% G under a contact load of 100 N. Abrasion was again identified as the primary wear mechanism, and wear debris was present on both surfaces. In contrast to the PAO8 results, the surface lubricated with epoxidized soybean oil alone appeared smoother than that lubricated with epoxidized soybean oil containing graphene nanoplatelets. This suggests that the addition of graphene nanoplatelets did not enhance the antiwear performance of epoxidized soybean oil. Instead, the results indicate that epoxidized soybean oil can function effectively without additives. The high degree of unsaturation in pure soybean oil inhibits the formation of strong tribofilms due to limitations in carbon chain interactions; epoxidation mitigates this issue, giving epoxidized soybean oil a distinct advantage over pure soybean oil.

4. Conclusions

The following conclusions can be drawn from this study:

Friction Tests

- The addition of 0.08 wt.% graphene nanoplatelets to PAO8 significantly reduced friction across all lubrication regimes, with an approximately 25% reduction observed in the boundary lubrication regime.

- In contrast, the addition of 0.10 wt.% graphene nanoplatelets to PAO8 resulted in increased friction across all lubrication regimes.
- Epoxidized soybean oil, even without additives, demonstrated comparable lubricating performance to PAO8. This behavior can be attributed to the reduction in the degree of unsaturation in soybean oil following epoxidation, which enhances its tribological performance.

Reichert (Wear/Extreme-Pressure) Tests

- The incorporation of 0.05 wt.% graphene nanoplatelets into the PAO8 base oil led to a significant reduction in wear, achieving a 14.3% decrease under a contact load of 200 N (1.6 GPa).
- Epoxidized soybean oil exhibited effective anti-wear performance without the need for additives, whereas the addition of graphene nanoplatelets did not lead to further wear reduction under the conditions investigated.

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