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Tribological Performance for Steel–Steel Contact Interfaces Using Hybrid MWCNTs/Al_2O_3 Nanoparticles as Oil-Based Additives in Engines

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Abstract: Numerous problems occur during engine operation, such as start-up, lack of lubrication, and overheating, resulting in engine components' wear, power loss, and fuel consumption. Nanomaterials dispersed in engine oil can play an important role in improving the tribological properties of oil lubricants. This study investigated the influence of multi-walled carbon nanotubes (MWCNTs) and aluminum oxide nanoparticles (Al_2O_3 NPs) as nano-additives for lubricants. Different engine oil samples were loaded with 0.5–2.0 wt% Al_2O_3 NPs and 0.5–1.0 wt% MWCNTs and compared with unmodified oil. The tribological performance of the nano lubricants was investigated using the four-ball test method. In addition, the wear scar in the engine was evaluated using 3D micrographs and scanning electron microscopy (SEM). The results of the sliding surfaces with hybrid MWCNTs/Al_2O_3 NPs showed better friction performance and wear resistance. The coefficient of friction (COF) and wear scar width were improved by 47.9% and 51.5%, respectively, compared with unmodified oil.

Keywords: engine oil; lubricants; carbon nanotubes; aluminum oxide nanoparticles; tribology

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1. Introduction

Reducing fuel consumption and energy losses is an interesting task for many users of internal combustion engines. It has been proven that power losses account for up to 20% of the total energy generated by automotive engines [1–4]. Friction among the internal parts of the engine causes about 35–45% of power losses [5,6]. Lubricants are substances typically used to reduce friction between sliding parts. Depending on their properties, lubricants also contribute to the efficient and unambiguous operation of various mechanisms [7,8]. Therefore, nano-additives have attracted much attention due to their unique mechanical, physical, and chemical properties [9–11]. The dispersion of nanomaterials in lubricants contributes significantly to the improvement of tribological properties, and the friction and wear performance of contact surfaces [12–15]. Many studies have shown that the use of hybrid nano-additives (Al_2O_3, ZnO, TiO_2, MoS_2, SiO_2, CuO, Ag, carbon nanotubes, and graphene oxide) has a noticeable effect on the thermal and tribological properties of lubricants [16–27]. The mechanism of nanoparticles has unique properties to reduce friction and wear. These properties are the rolling effect, the formation of tribofilm, the repair property, and the abrasive effect [28,29]. Oil nano-additives aim to improve the frictional behavior of sliding surfaces, which contributes to the reduction in power loss and fuel consumption [30–34]. Nanoparticles (NPs) play an active role in heat transfer, leading to an improvement of the tribological mechanism under heat stress boundary

conditions [35]. The dispersion of nanoparticles in oils has a great impact on cooling and lubrication applications, contributing to the improvement of the heat transfer and kinematic viscosity of fluids [36,37].

Among the various nanoparticles, Al_2O_3-based nano-additives are recommended to reduce friction and wear in oil engines [38–43]. The friction and wear behavior of nano lubricants filled with Al_2O_3, and SiO_2 NPs were analyzed at high temperatures. The results showed that the coefficient of friction decreased by 25% and 22% when filled with 0.3 wt% Al_2O_3 and SiO_2 NPs, respectively [34]. Hybrid Al_2O_3/graphene nanosheets were added to lubricants to modify and improve the tribological performance during turning. The lubricants contained hybrid filler at 0.25%, 0.75%, and 1.25% volume fractions. The results confirmed that tool wear was reduced by about 12.3% and that the wettability of the nanofluid was significantly improved [44]. Moreover, functionalized carbon spheres and graphene nanosheets were dispersed in lubricating oil to measure the friction performance using a four-ball tribometer. The hybrid FCS/graphene nanosheets showed a significant improvement, as the friction coefficient decreased by about 18% [45]. A deionized water-based lubricant dispersion with GO nanosheets and Al_2O_3 NPs was prepared to evaluate the tribological properties with a block-on-ring tribometer. The contents of hybrid filler were 0.04%, 0.08%, 0.12%, 0.16%, and 0.20% in the same ratio. In the sample with the hybrid filler, the graphene nanosheets contributed to a good uniformity of distribution and the dispersion of Al_2O_3-NPs, reducing the probability of their agglomeration [46]. The results showed that the coefficient of friction (COF) and surface roughness were reduced by about 60%. Moreover, the COF and wear volume were reduced by 35% and 50%, respectively, using graphene-/Cu-filled solid lubricants [47].

Due to their very high thermal conductivity (2000 $Wm^{-1}K^{-1}$) compared with the thermal conductivity of Ag (419 $Wm^{-1}K^{-1}$), CNTs are among the most suitable nano-additives for the production of lubricating oils to increase the thermal conductivity of lubricating oils, improve the efficiency of heat dissipation of the engine, and enhance the performance of the engine [48]. MoS_2/CNT hybrid filler was incorporated into cutting nanofluid. It was found that 6 wt.% MoS_2/CNTs hybrid filler in the ratio of 2:1 resulted in lower friction coefficient and surface roughness [48]. Lubricating oil SEA 68 with MWCNT/SiO_2 NP hybrid filler was experimentally investigated. The coefficient of friction and wear resistance were determined using a four-ball tribometer. It was found that the coefficient of friction and wear scar were significantly reduced by 93% and 14%, respectively, when the filler content was 1.8% MWCNTs/SiO_2 NPs in a ratio of 1:4 [49]. Hybrid Al_2O_3/MWCNTs were also developed to evaluate thermal, wetting, and tribological performance. The cutting nanofluid was dispersed at 0.25, 0.5, and 1.25% volume fractions in a ratio of 9:1. The hybrid filler positively contributed to the improvement of the tribological performance as the surface roughness improved, and the wear decreased compared with the samples filled with one type of filler [50]. The results showed that tool wear and nodule temperature decreased significantly by 11% and 27.36%, respectively [51]. The rheological behavior of the SEA50 lubricant was examined using a suspension of Al_2O_3/MWCNTs in the ratios of 3:2 [52] and 1:1 [53]. In addition, the different viscosity performances were recorded for different lubricants samples. It could be observed that the viscosity increased by 35% for 10W40, while the viscosity decreased by 10% for 5W50 [54].

As indicated by previous studies, hybrid nano-additives can significantly improve thermal, physical, and tribological properties compared with the use of a single type of nano-additive. Accordingly, the effect of the dispersion hybrid Al_2O_3/MWCNTs was investigated in the present study. The tribological and thermal properties were investigated using lubricating oil with different contents of Al_2O_3 NPs and MWCNTs. The tribological performance of the nano lubricants was investigated using the four-ball test method. In addition, the wear scar in the engine was evaluated using 3D microphotographs and scanning electron microscopy (SEM). The use of these hybrid nanoparticles in oil is considered one of the most effective methods for reducing friction and wear, avoiding energy waste, reducing emissions, and protecting the environment.

2. Materials and Experimental Setup

The present work aimed to study the influence of the dispersion of hybrid nanofillers in 10W30 engine oil. The technical properties of the lubricating oil are presented in Table 1. Al_2O_3 NPs and MWCNTs were supplied by US Research Nanoparticles, Inc. Al_2O_3 NPs had a diameter of 50 nm, a specific surface area of 15 m^2/g, and a density of 3.97 gm/cm^3, while MWCNTs had different dimensions, on average 30–50 nm outer diameter, 5–12 nm inner diameter, a length of 10–20 um, an SSA of 60 m^2/g, and a density of 2.1 gm/cm^3. Figure 1 show the SEM images and X-ray diffraction (XRD) patterns of Al_2O_3 NPs and MWCNTs, respectively. The XRD pattern of Al_2O_3 NPs shows that the diffraction peaks are centered at 2θ of 32.7°, 39.6°, and 63.7°, which could indicate crystal planes. The XRD analysis of MWCNTs shows a diffraction peak at 2θ of 26.5°, indicating the presence of carbon. The XRD pattern shows peaks with low intensity. Oleic acid was used to improve and develop the dispersion of nanoparticles in lubricating oil. Lubricant samples containing 0.5, 1.0, 1.5, and 2.0 wt% Al_2O_3-NPs and 0.5 and 1.0 wt% MWCNTs were prepared. The compositions of the samples are listed in Table 2. The nanofillers were incorporated into the lubricating oil by stirring for 2 h at a constant speed of 300 rpm at a temperature of 30 °C and a relative humidity of 55%. Oleic acid, as a surfactant, helped to stabilize the suspension and dispersion of the nanofillers in the oil and to reduce the occurrence of the agglomeration of the nanoparticles [55]. The samples were stored for two months after preparation to monitor the stability of the nanofillers.

Table 1. Technical properties of lubricant oil 10W30.

Specifications	Value
Density (kg/L)	0.862
Viscosity index	161
Kinematic viscosity at 40 °C (mm^2/s)	60.5
Kinematic viscosity at 100 °C (mm^2/s)	10.5
Flash point (°C)	226
Pour point (°C)	−35

Table 2. Various sample compositions of hybrid nano lubricants.

Sample No.	Engine Oil	Oleic Acid	Al_2O_3 NPs	MWCNTs
Lube-00	100%	-	-	-
Lube-11	97.0%	2%	0.5%	0.5%
Lube-12	96.5%	2%	1.0%	0.5%
Lube-13	96.0%	2%	1.5%	0.5%
Lube-14	95.5%	2%	2.0%	0.5%
Lube-21	96.5%	2%	0.5%	1.0%
Lube-22	96.0%	2%	1.0%	1.0%
Lube-23	95.5%	2%	1.5%	1.0%
Lube-24	95.0%	2%	2.0%	1.0%

The viscosity of the lubricant samples was determined using a B-One plus viscometer with spindles. The experiments were based on ASTM standard D446. The kinematic viscosity of the samples was determined at the temperatures of 40 °C and 100 °C. The coefficient of friction (COF) and the wear rate were determined using a block ring tribometer. The tribological performance of the nano lubricant samples was evaluated according to the procedures of ASTM G77-17. The tribometer was set with speeds of 500, 1000, 1500, 2000,

and 2500 rpm at a load of 200 N. The samples were tested at temperatures of 50, 75, and 100 °C to simulate operating conditions. For each oil sample, the steel block was replaced to avoid overlapping the experimental results. Each experiment was repeated five times, and the standard deviation was reported. The wear mechanism was performed under different working conditions, speeds, and temperatures. The surfaces of the blocks were cleaned with acetone after each test to ensure that the deposits were removed. The wear rate of the tested steel block was estimated based on the following relationship:

$$w_r = \frac{\Delta V}{F_n \times L} \quad (1)$$

where ΔV is the accumulated lost volume of the tested steel block (mm^3). It can be estimated with the ratio of $\Delta m/\rho$, where Δm is the weight loss (gm), determined by weighing the steel block before and after testing, and ρ is the steel density (gm/mm^3). F_n is the normal force, and L is the total sliding distance recorded during the test. In addition, the wear tracks and marks of each block were evaluated using an electronic microscope (OLYMPUS BX53M; Tokyo, Japan). The morphology of the worn surfaces was examined with a scanning electron microscope (SEM; JCM-6000Plus; JEOL, Tokyo, Japan).

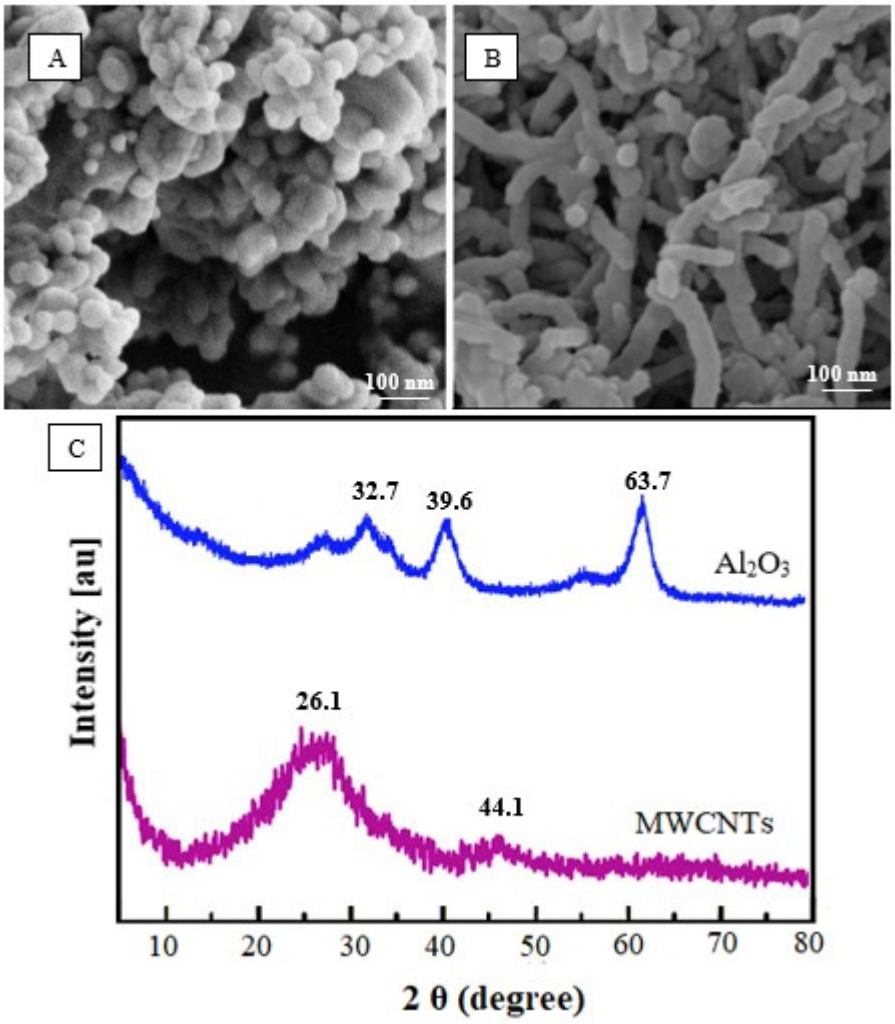


Figure 1. Characteristics of the nanoparticle additives: (**A**) SEM image of Al_2O_3 NPs; (**B**) SEM image of MWCNTs, and (**C**) XRD patterns of Al_2O_3 NPs and MWCNTs.

3. Results and Discussions

3.1. Influence of Al_2O_3/MWCNTs on Kinematic Viscosity

The effect of the dispersion of the hybrid Al_2O_3/MWCNTs in lubricating oil on the kinematic viscosity was studied at the test temperatures of 40 °C and 100 °C. A kinematic viscosity value was assumed for each sample for comparison with the additive-free oil sample. Figure 2A,B shows the kinematic viscosity of all nano lubricant samples at the temperatures of 40 °C and 100 °C. It can be seen that the kinematic viscosity increased significantly with the increase in the hybrid filler content. Moreover, the highest value of kinematic viscosity was measured when using a higher filler content. The viscosity increases of the samples loaded with 2.0 wt.% Al_2O_3 NPs and 0.5 wt.% MWCNTs were 6.8% and 2.8% at the temperatures of 40 °C and 100 °C, respectively. The dispersions loaded with 2.0 wt.% Al_2O_3 NPs and 1.0 wt.% MWCNTs increased the kinematic viscosity by 8.0% and 3.5% at the test temperatures of 40 °C and 100 °C, respectively. This could have been due to the presence of nanoparticles between the oil layers, which contributed to the improvement of the viscosity. Moreover, the phenomena of agglomeration and collision of particles contribute to the increase in the viscosity of oil even at high temperatures [31]. The results obtained by many researchers are in agreement [56–58].

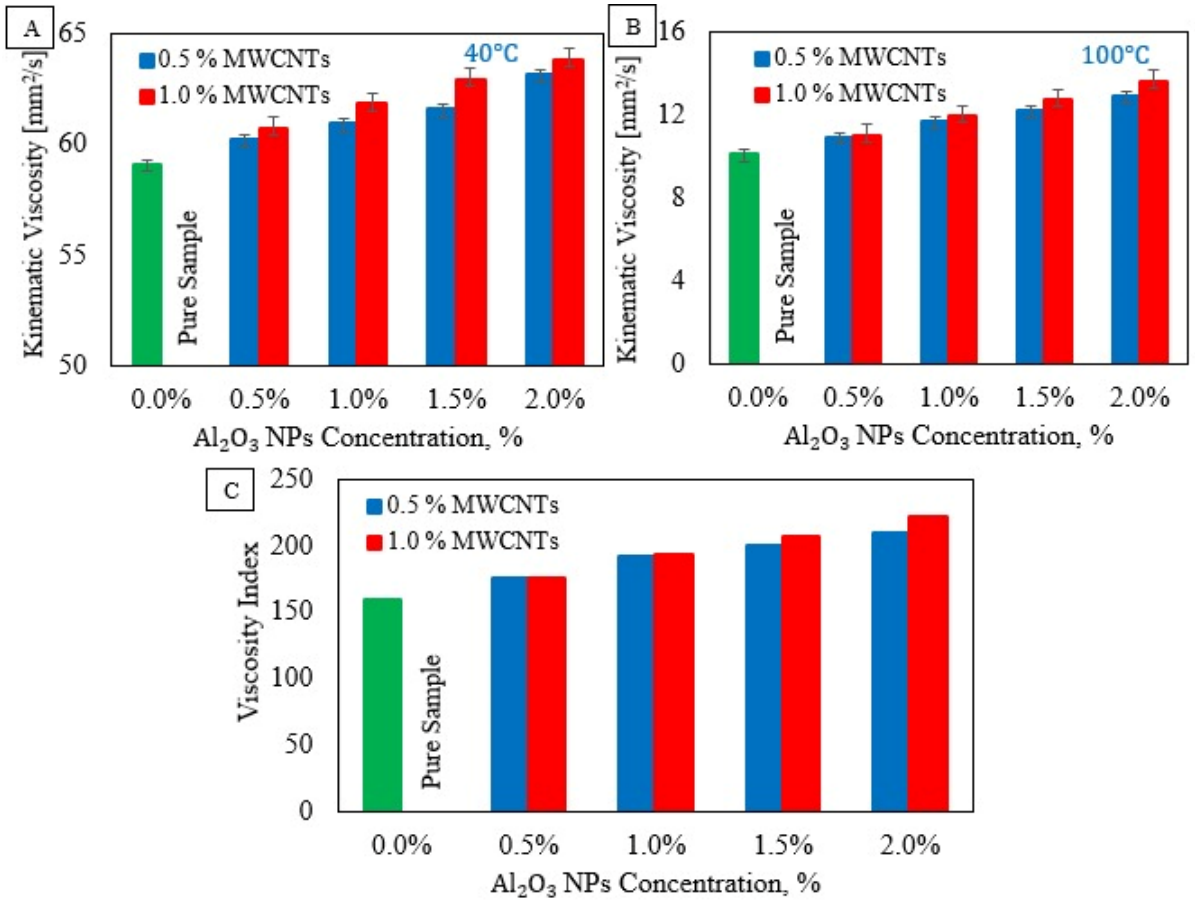


Figure 2. Kinematic viscosity of hybrid nano lubricant samples at temperatures of (**A**) 40 °C (**B**) and 100 °C. (**C**) Viscosity index of hybrid nano lubricant samples with 0.5 and 1% MWCNTs.

The viscosity index was used to analyze the lubricant characteristics and was determined starting from the kinematic viscosity at the test temperatures of 40 °C and 100 °C according to ASTM D2270. Figure 2C shows the viscosity index of the nano lubricant samples. It can be observed that the viscosity index of the nano lubricant increased as the loading level increased. The best improvement rates were obtained in samples with higher loading contents, with the viscosity values increasing by 32.17% and 39.7% in

samples containing 2.0 wt.% Al_2O_3/0.5 wt% MWCNTs and 2.0 wt.% Al_2O_3/1.0 wt.% MWCNTs, respectively.

3.2. Influence of Al_2O_3/MWCNTs on the Coefficient of Friction

The tribological performance of the nano lubricant samples was analyzed and compared with the additive-free lubricant sample. The friction coefficients of the hybrid nanofillers with different charges of Al_2O_3 NPs and charges of 0.5% and 1.0 wt% MWCNTs are shown in Figure 3A,B. The first set of samples with Al_2O_3 NPs and 0.5 wt% MWCNTs was investigated at different rotational speeds and temperatures. From Figure 3A, the addition of the hybrid nanofiller showed a good response to the reduction in the COF under different working conditions. Moreover, it was clear that the increase in the loading of hybrid Al_2O_3-NPs and 0.5 wt.% MWCNTs led to the minimization of the COF as a function of the rotational speeds. Thus, the best loading was 1.5 wt% Al_2O_3 NPs and 0.5 wt.% MWCNTs, which reduced the COF by 45% on average, while increasing the loading above this limit did not give an improvement. Oleic acid plays an important role in the chemical reaction between filler and engine oil, which contributes to increasing the homogeneity of the mixture [59]. The mechanism of Al_2O_3 NPs contributes to the reduction in the COF and metal–metal contact boundaries, which can be attributed to the rolling effect of nanoparticles [1,60]. Moreover, the formation of a thin film of the nanofiller leads to preventing contact with the asperities, and the self-lubricating property of MWCNTs contributes to increasing the effectiveness and decreasing the COF [61–64]. The samples were investigated at the different temperatures of 40, 70, and 100 °C, with 200 N as normal load and at 1000 rpm speed. The COF of the sample with free filler increased significantly with the increase in the temperature. This could be attributed to the fact that the increase in the temperature directly led to a decrease in the viscosity of the oil. In addition, the COF decreased with the increase in the temperature in the presence of nanofillers, with the COF decreasing by up to 58% at 100 °C. This decrease may have been due to the presence of the nanofiller directly on the contact surface, which plays the role of the rolling element and contributes to the formation of a self-lubricating film [12,65]. The same observation holds for the samples loaded with different proportions of Al_2O_3-NPs and 1.0 wt% MWCNTs (see Figure 4). The results of this set of samples showed that the hybrid sample loaded with 1.0 wt% Al_2O_3 NPs and 1.0 wt.% MWCNTs had a significantly reduced COF of 47.9% compared with the base lubricant sample. It can be concluded that the COF of hybrid nano lubricants decreased due to the presence of the nanofiller, and the best results were obtained with the loading of 0.0 wt.% Al_2O_3 NPs and 1.0 wt.% MWCNTs.

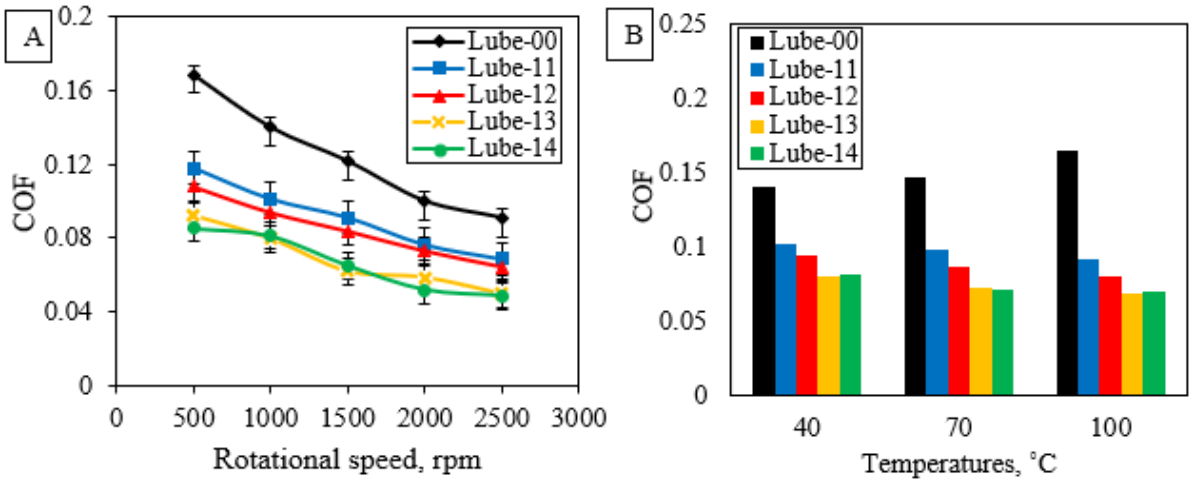


Figure 3. The friction coefficient of hybrid nano lubricant samples with various loading contents of 0.5 to 2 wt% Al_2O_3 NPs and 0.5 wt% MWCNTs (**A**) at different speeds and (**B**) at different temperatures.

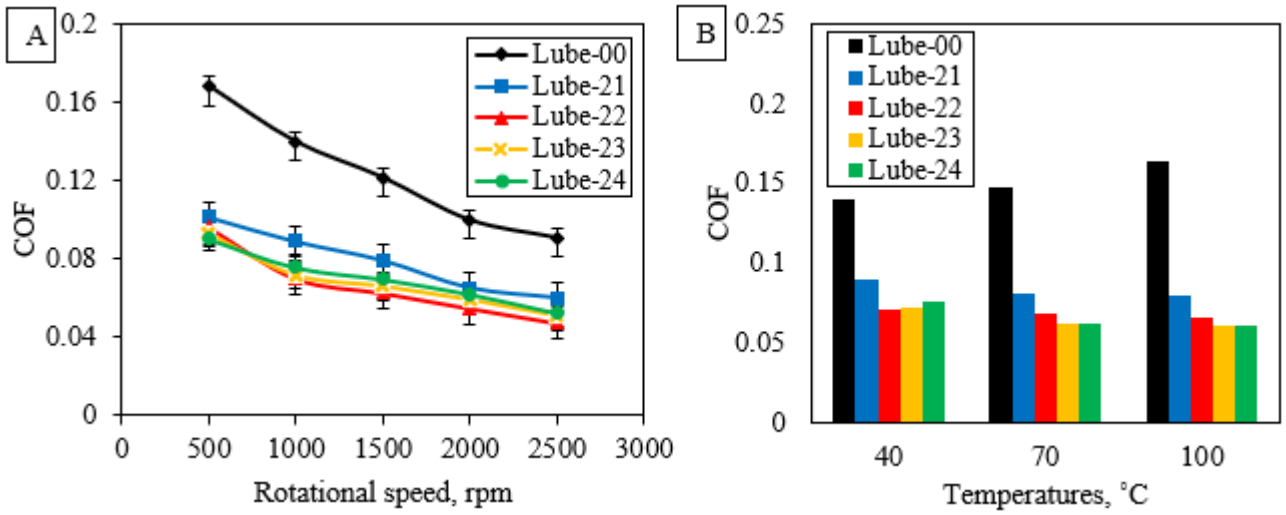


Figure 4. Coefficient of friction of hybrid nano lubricant samples with different loading levels of 0.5 to 2 wt% Al_2O_3 NPs and 1.0 wt% MWCNTs (**A**) at different velocities and (**B**) at different temperatures.

3.3. Influence of Al_2O_3/MWCNTs on the Wear Rate

The wear rate was evaluated in the samples loaded with hybrid Al_2O_3 NPs and MWCNTs as a function of the working conditions. Figure 5 shows the effect of adding the Al_2O_3/MWCNT hybrid nanofiller to engine oil on the wear rate at a constant load of 200 N, different sliding paths, and temperatures of 40, 70, and 100 °C. In general, a decrease in the wear rate was observed with the increase in the sliding distance, indicating increased wear resistance. Moreover, the presence of hybrid nanofillers contributes to the reduction in the wear rate at different sliding distances [1,5]. It can be observed that the dispersed engine oil with 1.5 wt.% Al_2O_3 NPs and 1.0 wt.% MWCNTs, Lube-13, had the lowest wear rate. The reduction in the wear rate was up to 58% compared with the additive-free sample, Lube-00. On the other hand, an increase in the temperature led to a decrease in viscosity, which reduced wear resistance. This means that care should be taken when using this sample, Lube-00, at high temperatures. Nevertheless, the hybrid nanofiller responded well to the high temperature, which helped to increase the wear resistance. Hybrid fillers play an effective role in reducing the wear rate, which could be due to their properties, such as surface enhancement and the formation of oil nanofilm [51]. The effect of increasing the MWCNT loading from 0.5% to 1.0 wt.% is shown in Figure 6. It could be assumed that the wear rate decreased with the addition of 1.0 wt.% MWCNTs. This could be attributed to the increase in the MWCNT loading, which may favor the presence of particles on the fibers [66]. This may have helped to improve the dispersion of the nanofiller in the oil. From the results, dispersion of the samples with 1.0 wt% MWCNTs reduced the wear rate similar to the previous samples. However, these samples showed a significant response at a high temperature when it was set higher than the previous samples. Thus, the wear rate decreased by 70% on average at 100 °C. It was found that the addition of hybrid Al_2O_3/MWCNTs increased the wear resistance, and the results were also in agreement with previous results [49,53,58,62].

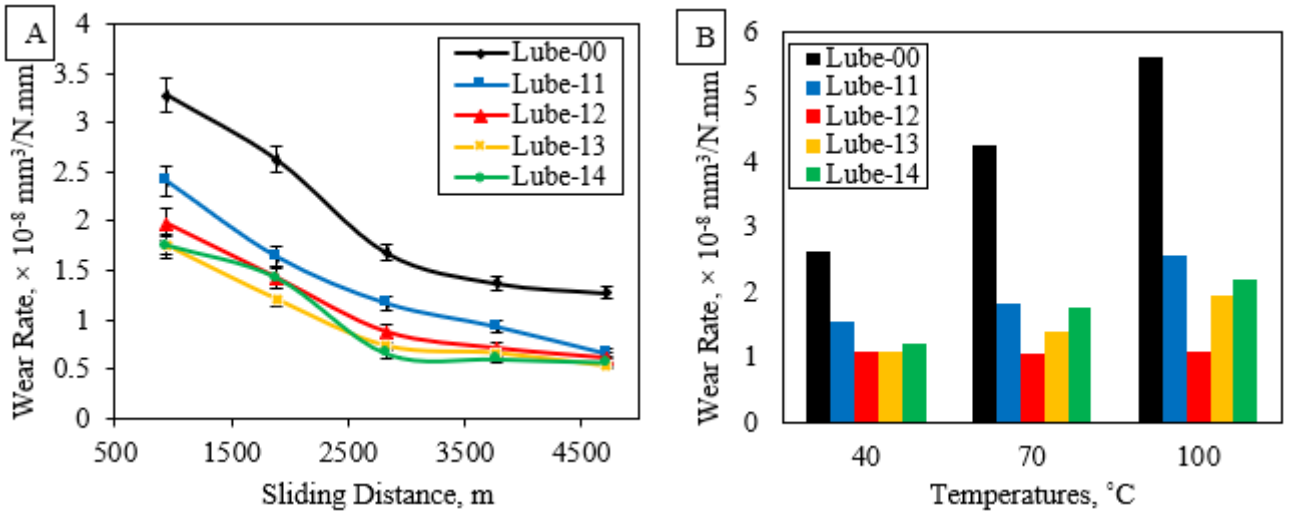


Figure 5. Wear rate of hybrid nano lubricant samples with various loading contents of Al_2O_3 NPs and 0.5 wt.% MWCNTs (**A**) at different speeds and (**B**) at different temperatures.

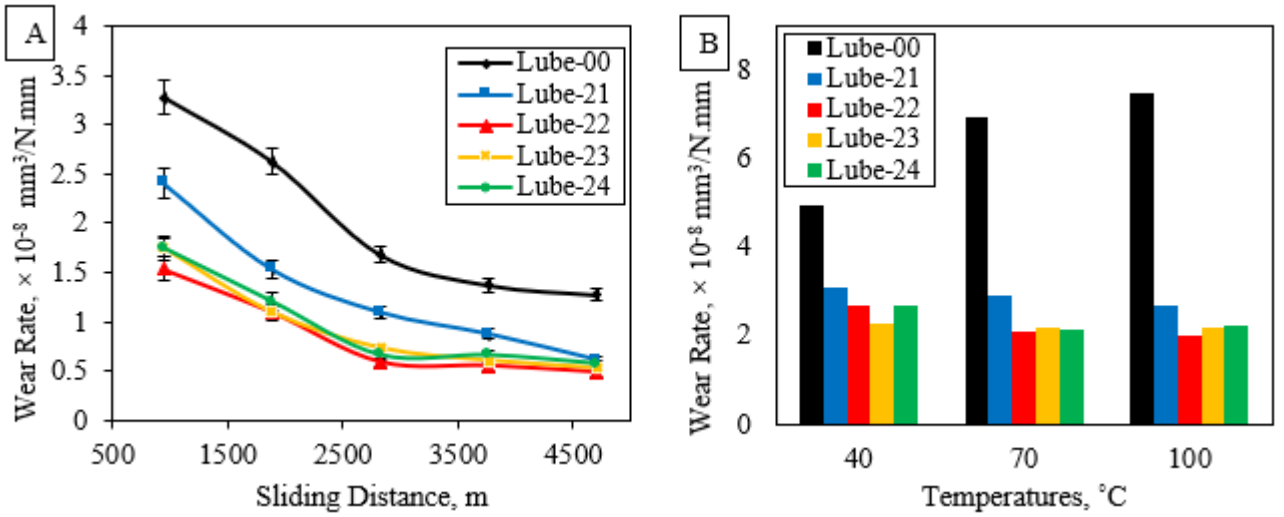


Figure 6. Wear rate of hybrid nano lubricant samples with various loading contents of Al_2O_3 NPs and 1.0 wt.% MWCNTs (**A**) at different speeds and (**B**) at different temperatures.

3.4. Influence of Al_2O_3/MWCNTs on Worn Surfaces

The scar width on worn surfaces was examined to assess the lubricant mechanism of the tested samples. Figure 7 presents the wear scar width as a function of the loading content of the hybrid nanofiller under a constant applied load of 200 N at 40 °C. The results indicated that the wear scar width reduced due to the presence of the nanofiller. Compared with the additive-free sample, the wear scar width was minimized by about 36% in sample Lube-13, while the increase in filler loading did not give a good indication of the wear scar, as displayed in sample Lube-14. Moreover, it was evident that adding 1.0 wt.% MWCNTs helped to improve the wear mechanism of the lubricant. It could be observed that the maximum wear scar width was achieved for a sample dispersion of 1.0 wt.% Al_2O_3 NPs and 1.0 wt.% MWCNTs (Lube-22), with a reduction ratio of 51.5%.

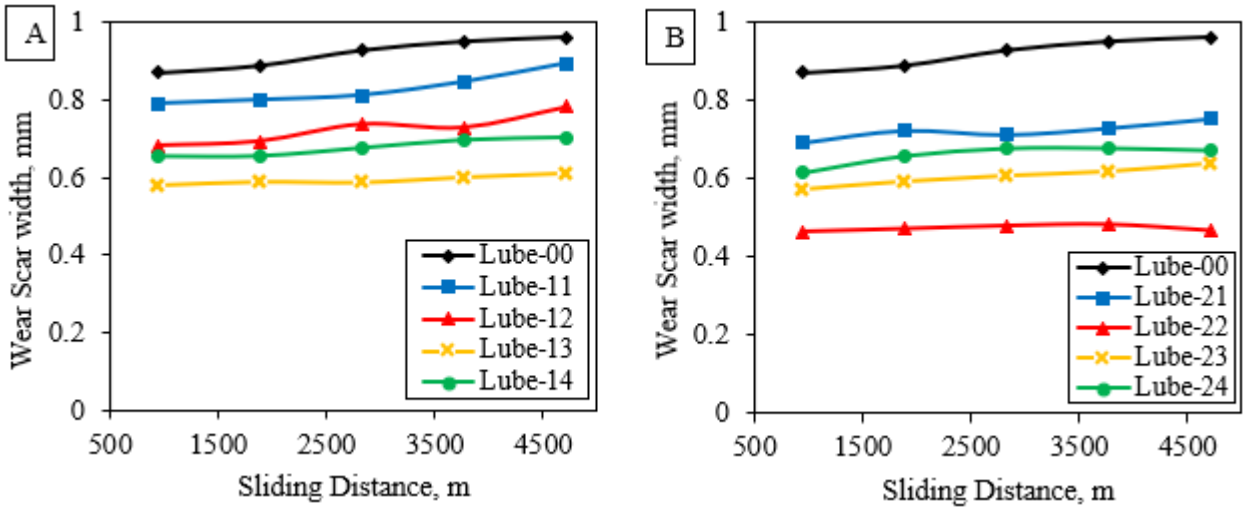


Figure 7. Wear scar width of hybrid nano lubricant samples: (**A**) 0.5 wt.% MWCNTs and (**B**) 1.0 wt.% MWCNTs.

3.5. Influence of Al_2O_3/MWCNTs on Topography

For better illustration, the topography of the worn contact surfaces of the nano lubricant samples is shown in Figure 8 for the loading levels of 0.5% and 1.0% by weight MWCNTs, respectively. The topography of the Lube-00 sample showed the presence of many wear marks and the propagation of the grooves and wear residues. In addition, the 3D topography showed the depth of these traces and the roughness of the friction surface. Moreover, the dispersion of the hybrid nanofiller led to a reduction in the wear marks and their depth, which could have been due to the formation of tribofilm performed by the nano lubricant. It could be observed that the sliding surfaces of the samples filled with Al_2O_3 NPs and 0.5 wt.% MWCNTs became less rough. Moreover, it could be observed that an oil film was deposited on the sliding surface. This could have been the main reason for the decreases in the COF and the wear rate. The same observations could be confirmed by examining samples with Al_2O_3 NPs and 0.5 wt% MWCNTs, as shown in Figure 9. Finally, the topography of the sliding surfaces showed that the samples with the nanofiller had cracks, grooves, wear marks, and deposits, and the surface roughness was lower than that of the sample without additive.

Figure 10 shows the SEM images of the nano lubricant samples. To obtain a clear analysis, all samples were scanned at the same magnification factor. The SEM image of the pure engine oil sample showed clear damage to the sample surface in the form of delamination and scuffing. In contrast, the surfaces of the nano lubricant samples were less damaged and smoother. The surfaces with the least damage were found in Lubricant 13 and Lubricant 22 samples. It could be concluded that these samples had smooth surfaces without wear marks. It could be assumed that the MWCNTs contributed to the improvement of the wear mechanism because they formed tribofilm that separated and prevented metal–metal contact [66], while the Al_2O_3 NPs played an effective role as nano-rolling elements that reduced the COF and repaired the worn surfaces [1,53].

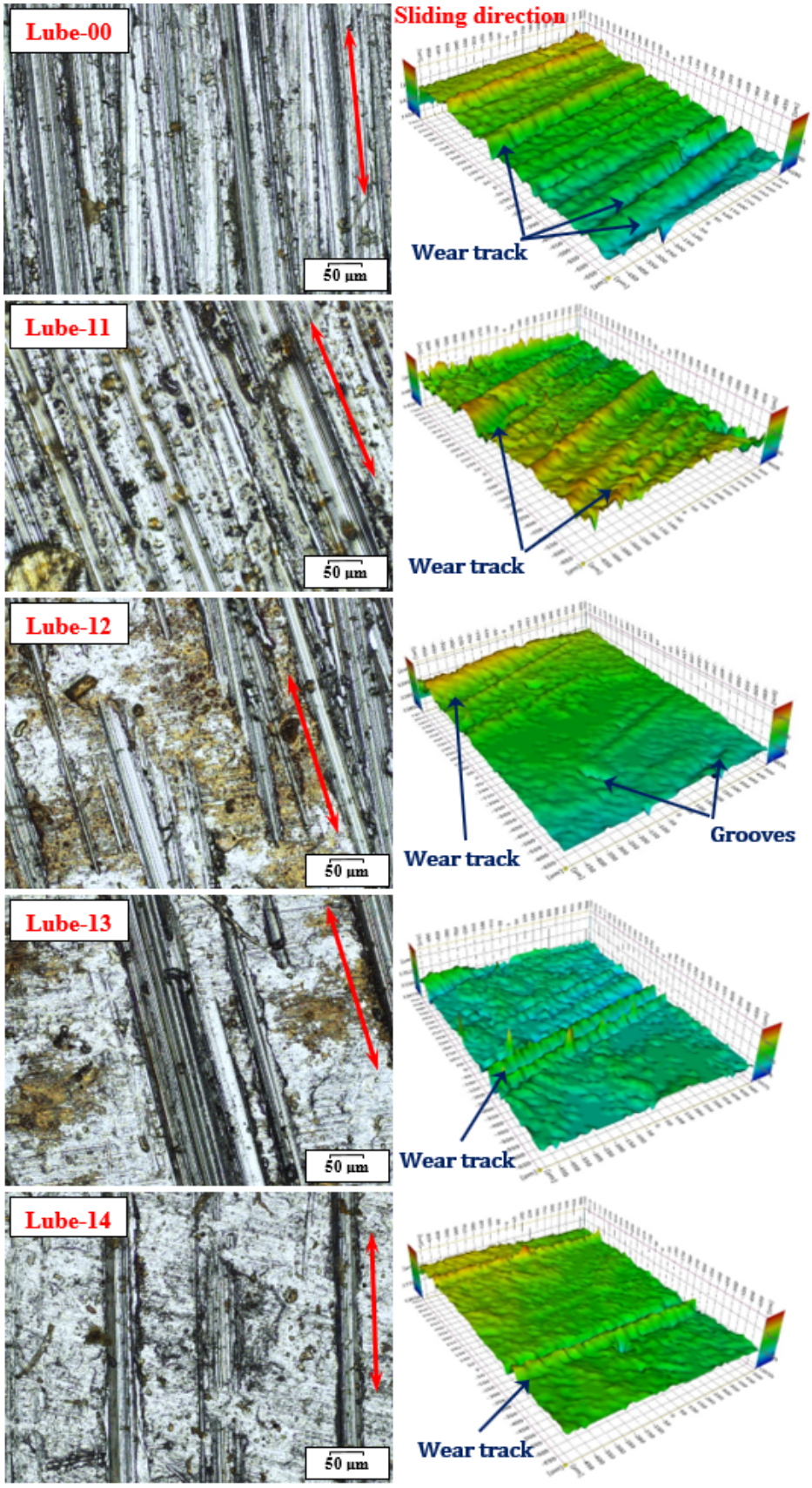


Figure 8. Micrographs of worn surface of samples (Lube-00, Lube-11, Lube-12, Lube-13, and Lube-14) with various loading contents of Al_2O_3 NPs and 0.5 wt.% MWCNTs at different speeds and temperatures.

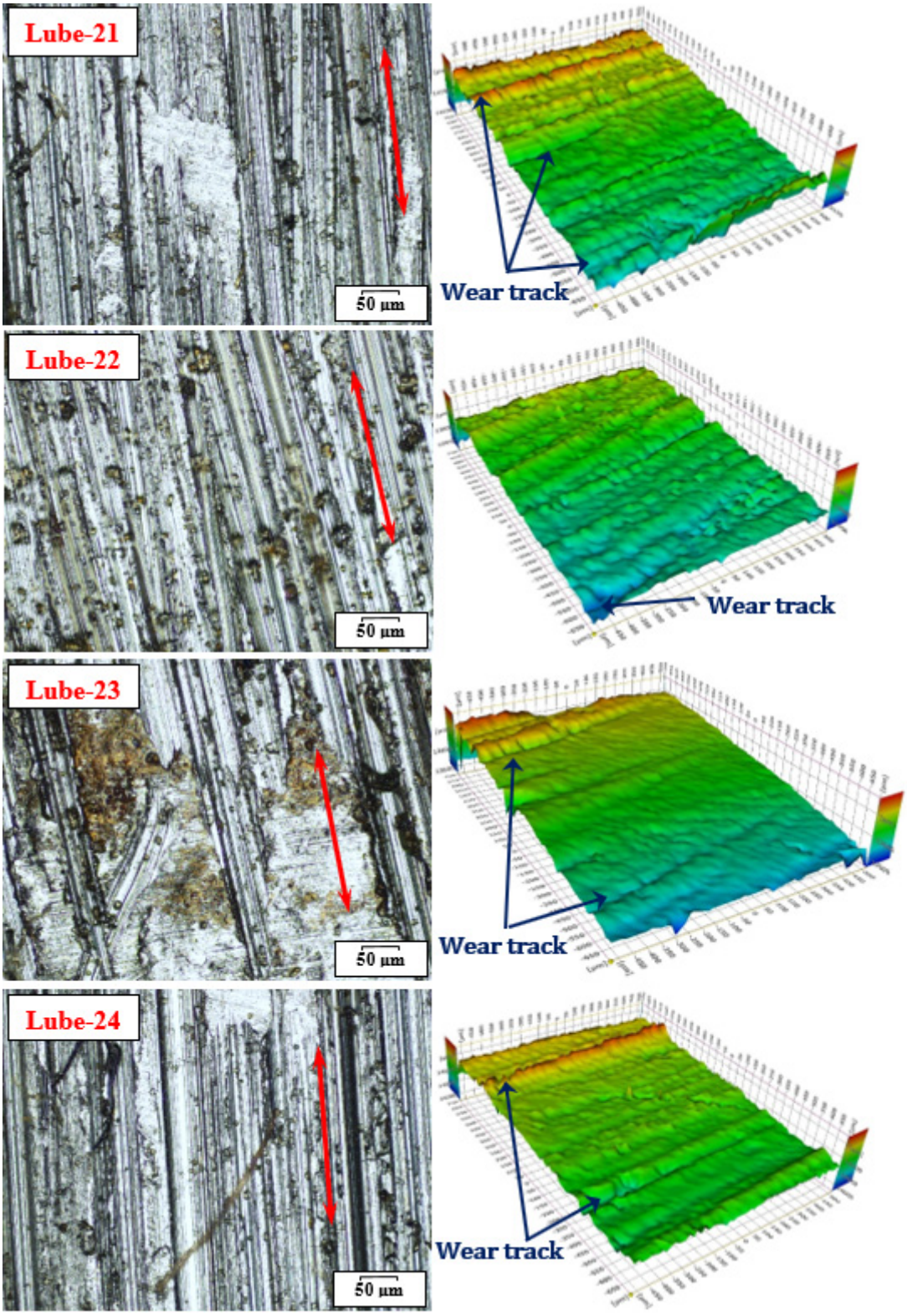


Figure 9. Micrographs of worn surface of samples (Lube-21, Lube-22, Lube-23, and Lube-24) with various loading contents of Al_2O_3 NPs and 1.0 wt.% MWCNTs at different speeds and temperatures.

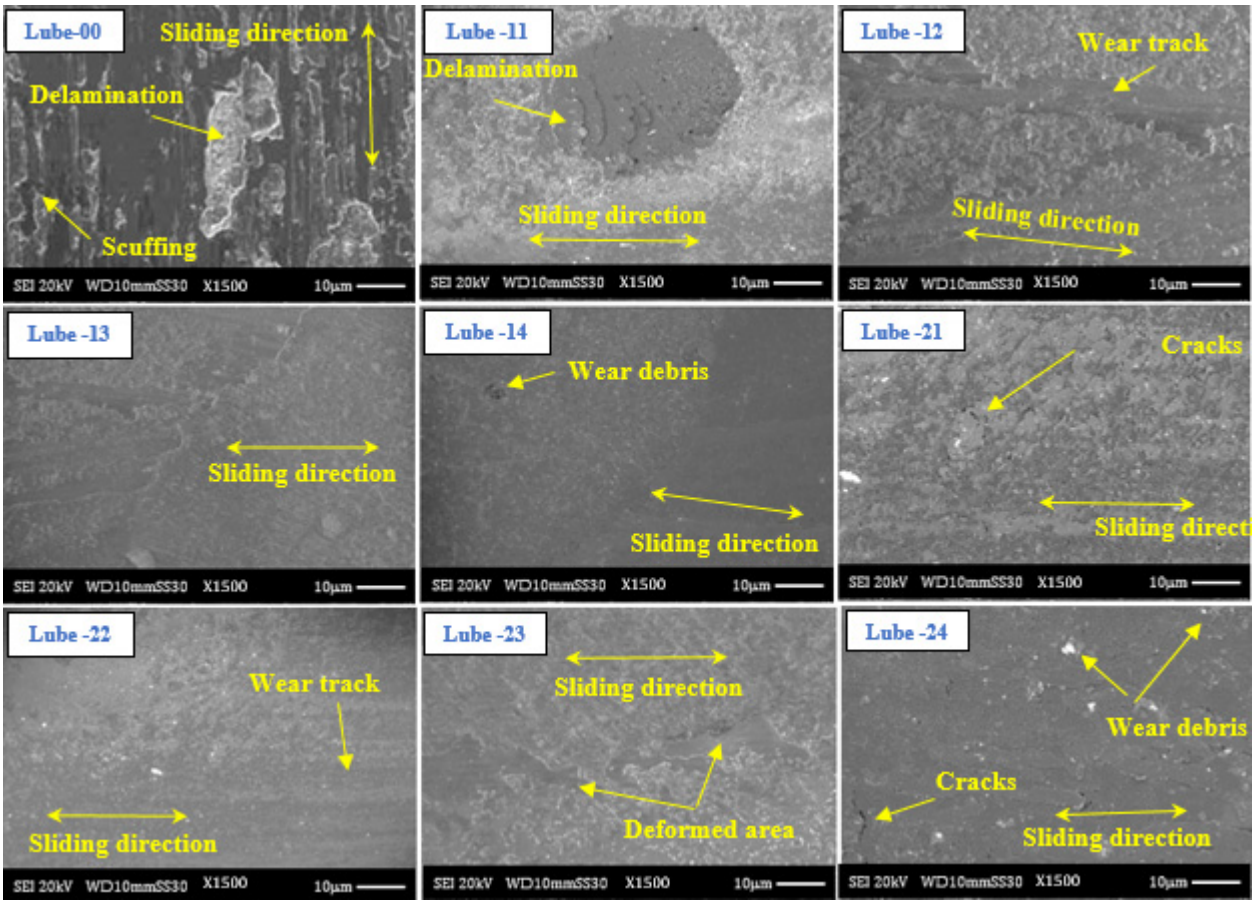


Figure 10. SEM images of hybrid nano lubricant samples, i.e., Lube-00, Lube-11, Lube-12, Lube-13, Lube-14, Lube-21, Lube-22, Lube-23, and Lube-24.

Compared to our work on Al_2O_3/MWCNTs, several nanoparticles have been reported in the literature. For instance, ZnO NPs were dispersed in diesel oil to evaluate the thermal and tribological properties. The results showed that an oil sample supplemented with 0.7 wt% ZnO NPs contributed to a decrease in the purity point and weight loss of 15.2% and 86%, respectively, compared with the pure oil sample [30]. In addition, MoS_2 and ZnO NPs were used as nanofillers for diesel oil. The samples were tested at an operating temperature of 100 °C to evaluate the loading degree. The results showed that the oil viscosity increased by 9.58% and 10.14% with the content of 0.7 wt% MoS_2 and ZnO NPs, respectively. It was possible to confirm that ZnO NPs is a more suitable option for dispersion in diesel oil [31]. Moreover, polyol ester oil filled with ZnO NPs was investigated to study the tribological and thermal properties at different operating temperatures [32]. It was found that at a content of 0.3 wt% of ZnO NPs, the pour point decreased by 13.6%; the flash point increased by 3.5%; and the COF decreased by 7%. Moreover, base oil dispersed with MoS_2, and SiO_2 NPs was used as a lubricant between magnesium alloy and steel contacts. It was observed that the best results were obtained with 0.1% and 0.7% by weight MoS_2 and SiO_2 NPs, respectively [33]. In addition, engine oil dispersed with TiO_2 and SiO_2 NPs (0.5 and 1.0 wt.%) was investigated. The experiments were evaluated using a tribometer under different operating conditions, such as load, speed, and temperature [38,39]. The best results were obtained for samples with a loading amount of 1.0 wt% TiO_2 NPs and 0.5 wt% SiO_2 NPs. Moreover, the wear rate and the COF decreased by 47% to 39% compared with additive-free oil. The COF decreased by 86% with engine oil filled with 0.3 wt% TiO_2 NPs under mixed and boundary lubrication conditions [40]. Engine oil 10W-30 with suspended TiO_2 NPs was also investigated using a four-ball tribometer at 75 °C. The TiO_2 NPs were filled with different amounts of 0.01%, 0.025%, 0.050%, and 0.075% by

weight [41]. In the wear scar results, the sample filled with 0.075 wt% TiO_2 NPs showed the best tribological performance.

4. Conclusions

The high thermal conductivity and mechanical properties of Al_2O_3 nanoparticles and MWCNTs help to dissipate heat generated by friction, which helps the lubricant to maintain its viscosity, ultimately resulting in less metal-to-metal contact and reduced friction and wear. In the present work, the tribological properties and viscosity of lubricating oil 10W-30 with Al_2O_3/MWCNT hybrid nanofiller were investigated. From the experimental results, it could be concluded that (1) Al_2O_3/MWCNT hybrid nanofiller had the significant effect of improving the lubricant properties; (2) the viscosity of the nano lubricant increased with the increase in the proportion of the hybrid nanofiller, so that the kinematic viscosity at 40 °C increased by 6.8% and 8% in samples containing 2.0 wt.% Al_2O_3 and 0.5 wt.% MWCNTs and 2.0 wt.% Al_2O_3 and 1.0 wt.% MWCNTs, respectively, while the viscosity index increased significantly by 32.17% and 39.7%, respectively; (3) the COF examined at a temperature of 40 °C decreased by 45% and 47.9% in the samples loaded with 1.5 wt.% Al_2O_3 and 0.5 wt.% MWCNTs and 1.0 wt.% Al_2O_3 and 1.0 wt.% MWCNTs, respectively; (4) the nano lubricant samples responded well to the increase in the temperature, resulting in a 58% decrease in the COF at 100 °C compared with base oil; (5) the wear rate was also reduced by 58% at 40 °C, while the reduction was up to 70% at 100 °C. Moreover, the width of wear scar decreased by 36% and 51.5% in samples loaded with 1.5 wt.% Al_2O_3 and 0.5 wt.% MWCNTs and 1.0 wt.% Al_2O_3 and 1.0 wt.% MWCNTs, respectively. Based on these results, it is recommended that Al_2O_3/MWCNT hybrid nanofiller for engine oil 10W-30 be used effectively at high operating temperatures. Moreover, the loading amount of 2.0 wt% Al_2O_3/MWCNTs in a ratio of 1:1 is the optimal dispersion amount.

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References

1. Ali, M.K.A.; Xianjun, H. Improving the tribological behavior of internal combustion engines via the addition of nanoparticles to engine oils. *Nanotechnol. Rev.* **2015**, *4*, 347–358. [CrossRef]
2. Srivyas, P.; Charoo, M. A Review on Tribological Characterization of Lubricants with Nano Additives for Automotive Applications. *Tribol. Ind.* **2018**, *40*, 594–623. [CrossRef]
3. Wang, B.; Qiu, F.; Barber, G.C.; Zou, Q.; Wang, J.; Guo, S.; Yuan, Y.; Jiang, Q. Role of nano-sized materials as lubricant additives in friction and wear reduction: A review. *Wear* **2022**, *490*, 204206. [CrossRef]
4. Ahmed, E.; Nabhan, A.; Ghazaly, N.M.; el Jaber, G.T.A. Tribological Behavior of Adding Nano Oxides Materials to Lithium Grease: A Review. *Am. J. Nanomater.* **2020**, *8*, 1–9.
5. Jason, Y.; How, H.; Teoh, Y.; Chuah, H. A Study on the Tribological Performance of Nanolubricants. *Processes* **2020**, *8*, 1372. [CrossRef]
6. Lawrence, K.D.; Ramamoorthy, B. Multi-surface topography targeted plateau honing for the processing of cylinder liner surfaces of automotive engines. *Appl. Surf. Sci.* **2016**, *365*, 19–30. [CrossRef]
7. Mortier, R.M.; Orszulik, S.T.; Fox, M.F. *Chemistry and Technology of Lubricant*; Springer: Berlin/Heidelberg, Germany, 2010; Volume 107115.
8. Mang, T.; Dresel, W. *Lubricants and Lubrication*; John Wiley & Sons: Hoboken, NJ, USA, 2007.
9. Bhushan, B.; Luo, D.; Schricker, S.R.; Sigmund, W.; Zauscher, S. *Handbook of Nanomaterials Properties*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2014.

10. Asha, A.B.; Narain, R. Nanomaterials properties. In *Polymer Science and Nanotechnology*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 343–359.
11. Vollath, D. Nanomaterials an introduction to synthesis, properties and application. *Environ. Eng. Manag. J.* **2008**, *7*, 865–870.
12. Kotia, A.; Rajkhowa, P.; Rao, G.S.; Ghosh, S.K. Thermophysical and tribological properties of nanolubricants: A review. *Heat Mass Transf.* **2018**, *54*, 3493–3508. [CrossRef]
13. Ilie, F.; Covaliu, C. Tribological Properties of the Lubricant Containing Titanium Dioxide Nanoparticles as an Additive. *Lubricants* **2016**, *4*, 12. [CrossRef]
14. Nabhan, A.; Rashed, A.; Ghazaly, N.M.; Abdo, J.; Haneef, M.D. Tribological properties of Al_2O_3 nanoparticles as lithium grease additives. *Lubricants* **2021**, *9*, 9. [CrossRef]
15. Chen, B.; Liu, L.; Zhang, C.; Zhang, S.; Zhang, Y.; Zhang, P. Tribological Properties and Lubrication Mechanism of Protic Ionic Liquid-modified Nanosilica as High-temperature Antiwear Additive for Pentaerythritol Ester. *Tribol. Int.* **2022**, *176*, 107886. [CrossRef]
16. Lijesh, K.P.; Muzakkir, S.M.; Hirani, H. Experimental tribological performance evaluation of nano lubricant using multi-walled carbon nano-tubes (MWCNT). *Int. J. Appl. Eng. Res.* **2015**, *10*, 14543–14550.
17. Nabhan, A. Vibration analysis of adding contaminants particles and carbon nanotubes to lithium grease of ball bearing. *Vibroengineering Procedia* **2016**, *8*, 28–32.
18. Singh, A.; Chauhan, P.; Mamatha, T. A review on tribological performance of lubricants with nanoparticles additives. *Mater. Today Proc.* **2020**, *25*, 586–591. [CrossRef]
19. Pownraj, C.; Arasu, A.V. Effect of dispersing single and hybrid nanoparticles on tribological, thermo-physical, and stability characteristics of lubricants: A review. *J. Therm. Anal. Calorim.* **2021**, *143*, 1773–1809. [CrossRef]
20. Zhang, W.; Demydov, D.; Jahan, M.P.; Mistry, K.; Erdemir, A.; Malshe, A.P. Fundamental understanding of the tribological and thermal behavior of Ag–MoS2 nanoparticle-based multi-component lubricating system. *Wear* **2012**, *288*, 9–16. [CrossRef]
21. Ettefaghi, E.-O.; Ahmadi, H.; Rashidi, A.; Nouralishahi, A.; Mohtasebi, S.S. Preparation and thermal properties of oil-based nanofluid from multi-walled carbon nanotubes and engine oil as nano-lubricant. *Int. Commun. Heat Mass Transf.* **2013**, *46*, 142–147. [CrossRef]
22. Lee, K.; Hwang, Y.; Cheong, S.; Kwon, L.; Kim, S.; Lee, J. Performance evaluation of nano-lubricants of fullerene nanoparticles in refrigeration mineral oil. *Curr. Appl. Phys.* **2009**, *9*, e128–e131. [CrossRef]
23. Rasheed, A.; Khalid, M.; Javeed, A.; Rashmi, W.; Gupta, T.; Chan, A. Heat transfer and tribological performance of graphene nanolubricant in an internal combustion engine. *Tribol. Int.* **2016**, *103*, 504–515. [CrossRef]
24. Ettefaghi, E.-O.; Rashidi, A.; Ahmadi, H.; Mohtasebi, S.S.; Pourkhalil, M. Thermal and rheological properties of oil-based nanofluids from different carbon nanostructures. *Int. Commun. Heat Mass Transf.* **2013**, *48*, 178–182. [CrossRef]
25. Peng, Y.; Xu, Y.; Geng, J.; Dearn, K.D.; Hu, X. Tribological assessment of coated piston ring-cylinder liner contacts under bio-oil lubricated conditions. *Tribol. Int.* **2017**, *107*, 283–293. [CrossRef]
26. Soleimani, M.; Bagheri, E.; Mosaddegh, P.; Rabiee, T.; Fakhar, A.; Sadeghi, M. Stable waterborne epoxy emulsions and the effect of silica nanoparticles on their coatings properties. *Prog. Org. Coat.* **2021**, *156*, 106250. [CrossRef]
27. Bagheri, E.; Montazeri, R.; Bagheri, R. Effect of solid state ball milling on wear and structural properties of polytetrafluoroethylene/alumina nanocomposite coatings. *Mater. Res. Express* **2019**, *6*, 125315. [CrossRef]
28. Tang, Z.; Li, S. A review of recent developments of friction modifiers for liquid lubricants (2007–present). *Curr. Opin. Solid State Mater. Sci.* **2014**, *18*, 119–139. [CrossRef]
29. Lee, K.; Hwang, Y.; Cheong, S.; Choi, Y.; Kwon, L.; Lee, J.; Kim, S.H. Understanding the Role of Nanoparticles in Nano-oil Lubrication. *Tribol. Lett.* **2009**, *35*, 127–131. [CrossRef]
30. Mousavi, S.B.; Heris, S.Z. Experimental investigation of ZnO nanoparticles effects on thermophysical and tribological properties of diesel oil. *Int. J. Hydrogen Energy* **2020**, *45*, 23603–23614. [CrossRef]
31. Mousavi, S.B.; Heris, S.Z.; Estellé, P. Experimental comparison between ZnO and MoS2 nanoparticles as additives on performance of diesel oil-based nano lubricant. *Sci. Rep.* **2020**, *10*, 5813. [CrossRef]
32. Kumar, V.P.S.; Subramanian, K.M.; Stalin, B.; Vairamuthu, J. Influence of ZnO nanoparticles on thermophysical and tribological properties of polyolester oil. *Mater. Res. Express* **2021**, *8*, 045502. [CrossRef]
33. Xie, H.; Jiang, B.; He, J.; Xia, X.; Pan, F. Lubrication performance of MoS_2 and SiO_2 nanoparticles as lubricant additives in magnesium alloy-steel contacts. *Tribol. Int.* **2016**, *93*, 63–70. [CrossRef]
34. Kotia, A.; Ghosh, G.K.; Srivastava, I.; Deval, P.; Ghosh, S.K. Mechanism for improvement of friction/wear by using Al_2O_3 and SiO_2/Gear oil nanolubricants. *J. Alloy Compd.* **2019**, *782*, 592–599. [CrossRef]
35. Umavathi, J.; Patil, S.L.; Mahanthesh, B.; Bég, O.A. Unsteady squeezing flow of a magnetized nano-lubricant between parallel disks with Robin boundary conditions. *Proc. Inst. Mech. Eng. Part N J. Nanomater. Nanoeng. Nanosyst.* **2021**, *235*, 67–81. [CrossRef]
36. Amidu, M.A.; Addad, Y.; Riahi, M.K.; Abu-Nada, E. Numerical investigation of nanoparticles slip mechanisms impact on the natural convection heat transfer characteristics of nanofluids in an enclosure. *Sci. Rep.* **2021**, *11*, 15678. [CrossRef] [PubMed]
37. Riahi, M.K.; Ali, M.; Addad, Y.; Abu-Nada, E. Combined Newton–Raphson and Streamlines-Upwind Petrov–Galerkin iterations for nanoparticles transport in buoyancy-driven flow. *J. Eng. Math.* **2022**, *132*, 22. [CrossRef]

38. Rashed, A.; Nabhan, A. Effects of TiO_2 and SiO_2 nano additive to engine lubricant oils on tribological properties at different temperatures. In Proceedings of the 20th International Conference on Aerospace, Mechanical, Automotive and Materials Engineering, Rome, Italy, 19–20 September 2018; pp. 30–31.
39. Nabhan, A.; Ghazaly, N.M.; Mousa, H.M.; Rashed, A. Influence of TiO_2 and SiO_2 Nanoparticles Additives on the Engine Oil Tribological Properties: Experimental Study at Different Operating Conditions. *Int. J. Adv. Sci. Technol.* **2020**, *29*, 845–855.
40. Laad, M.; Jatti, V.K.S. Titanium oxide nanoparticles as additives in engine oil. *J. King Saud Univ. Eng. Sci.* **2018**, *30*, 116–122. [CrossRef]
41. Birleanu, C.; Pustan, M.; Cioaza, M.; Molea, A.; Popa, F.; Contiu, G. Effect of TiO_2 nanoparticles on the tribological properties of lubricating oil: An experimental investigation. *Sci. Rep.* **2022**, *12*, 5201. [CrossRef] [PubMed]
42. Ahmed, E.; Nabhan, A.; Nouby, M.; el Jaber, G.T.A. Influence of Dispersing Lithium Grease by Hybrid Nano Titanium and Silicon Oxides on Friction Coefficient. *J. Egypt. Soc. Tribol. EGTRIB J.* **2018**, *15*, 61–71.
43. Ma, S.Y.; Zheng, S.H.; Ding, H.Y.; Li, W. Anti-wear and reduce-friction ability of ZrO_2/SiO_2 self-lubricating composites. *Adv. Mater. Res.* **2009**, *79*, 1863–1866. [CrossRef]
44. Sharma, A.K.; Tiwari, A.K.; Dixit, A.R.; Singh, R.K.; Singh, M. Novel uses of alumina/graphene hybrid nanoparticle additives for improved tribological properties of lubricant in turning operation. *Tribol. Int.* **2018**, *119*, 99–111. [CrossRef]
45. Radhika, P.; Sobhan, C.; Chakravorti, S. Improved tribological behavior of lubricating oil dispersed with hybrid nanoparticles of functionalized carbon spheres and graphene nano platelets. *Appl. Surf. Sci.* **2021**, *540*, 148402. [CrossRef]
46. Huang, S.; He, A.; Yun, J.-H.; Xu, X.; Jiang, Z.; Jiao, S.; Huang, H. Synergistic tribological performance of a water based lubricant using graphene oxide and alumina hybrid nanoparticles as additives. *Tribol. Int.* **2019**, *135*, 170–180. [CrossRef]
47. Shi, S.-C.; Jiang, S.-Z. Influence of graphene/copper hybrid nanoparticle additives on tribological properties of solid cellulose lubricants. *Surf. Coat. Technol.* **2020**, *389*, 125655. [CrossRef]
48. Zhang, Y.; Li, C.; Jia, D.; Zhang, D.; Zhang, X. Experimental evaluation of the lubrication performance of MoS2/CNT nanofluid for minimal quantity lubrication in Ni-based alloy grinding. *Int. J. Mach. Tools Manuf.* **2015**, *99*, 19–33. [CrossRef]
49. Haldar, A.; Kotia, A.; Kumar, N.; Ghosh, S.K. Enhancing the tribological properties of hydraulic oil-based nanolubricants using MWCNT-SiO_2 hybrid nanoparticles. *J. Braz. Soc. Mech. Sci. Eng.* **2022**, *44*, 223. [CrossRef]
50. Bagheri, E.; Mosaddegh, P.; Behzad, T. Mechanical, thermal, and structural properties of uniaxially drawn polylactic acid/halloysite nanocomposites. *J. Appl. Polym. Sci.* **2020**, *137*, 49134. [CrossRef]
51. Sharma, A.K.; Katiyar, J.K.; Bhaumik, S.; Roy, S. Influence of alumina/MWCNT hybrid nanoparticle additives on tribological properties of lubricants in turning operations. *Friction* **2019**, *7*, 153–168. [CrossRef]
52. Esfe, M.H.; Esfandeh, S.; Alidoust, S.; Toghraie, D. Experimental study of rheological characteristics of MWCNT-Al_2O_3 (40:60)/SAE50 hybrid nano-lubricant to identify optimal lubrication conditions and post-processing of results using the response surface method. *J. Mater. Res. Technol.* **2021**, *15*, 2059–2074. [CrossRef]
53. Esfe, M.H.; Alidoust, S.; Ardeshiri, E.M.; Kamyab, M.H.; Toghraie, D. Experimental Study of Rheological Behavior of MWCNT-Al_2O_3/SAE_{50} Hybrid Nanofluid to Provide the Best Nano-lubrication Conditions. *Nanoscale Res. Lett.* **2022**, *17*, 4. [CrossRef] [PubMed]
54. Esfe, M.H.; Esfandeh, S.; Alidoust, S.; Toghraie, D. Comparison of viscosity behavior of hybrid nano-lubricants containing Al_2O_3-MWCNT nanoparticles dispersed in SAE XWX engine oils to determine the optimal behavior of nano-lubricants based on experimental studies. *Colloids Surf. A Physicochem. Eng. Asp.* **2022**, *641*, 128446. [CrossRef]
55. Tadmor, R.; Rosensweig, R.E.; Frey, A.J.; Klein, J. Resolving the Puzzle of Ferrofluid Dispersants. *Langmuir* **2000**, *16*, 9117–9120. [CrossRef]
56. Ranjbarzadeh, R.; Chaabane, R. Experimental Study of Thermal Properties and Dynamic Viscosity of Graphene Oxide/Oil Nano-Lubricant. *Energies* **2021**, *14*, 2886. [CrossRef]
57. Kedzierski, M.A. Viscosity and density of CuO nanolubricant. *Int. J. Refrig.* **2012**, *35*, 1997–2002. [CrossRef]
58. Goodarzi, M.; Toghraie, D.; Reiszadeh, M.; Afrand, M. Experimental evaluation of dynamic viscosity of ZnO–MWCNTs/engine oil hybrid nanolubricant based on changes in temperature and concentration. *J. Therm. Anal.* **2019**, *136*, 513–525. [CrossRef]
59. Loehle, S.; Matta, C.; Minfray, C.; Le Mogne, T.; Martin, J.-M.; Iovine, R.; Obara, Y.; Miura, R.; Miyamoto, A. Mixed Lubrication with C18 Fatty Acids: Effect of Unsaturation. *Tribol. Lett.* **2013**, *53*, 319–328. [CrossRef]
60. Dai, W.; Kheireddin, B.; Gao, H.; Liang, H. Roles of nanoparticles in oil lubrication. *Tribol. Int.* **2016**, *102*, 88–98. [CrossRef]
61. Sharma, A.K.; Tiwari, A.K.; Dixit, A.R.; Singh, R.K. Measurement of machining forces and surface roughness in turning of AISI 304 steel using alumina-MWCNT hybrid nanoparticles enriched cutting fluid. *Measurement* **2020**, *150*, 107078. [CrossRef]
62. Sahoo, B.; Chary, N.; Paul, J. Surface mechanical and self-lubricating properties of MWCNT impregnated aluminium surfaces. *Surf. Eng.* **2019**, *35*, 970–981. [CrossRef]
63. Reinert, L.; Varenberg, M.; Mücklich, F.; Suárez, S. Dry friction and wear of self-lubricating carbon-nanotube-containing surfaces. *Wear* **2018**, *406*, 33–42. [CrossRef]
64. Vardhaman, B.A.; Amarnath, M.; Ramkumar, J.; Mondal, K. Enhanced tribological performances of zinc oxide/MWCNTs hybrid nanomaterials as the effective lubricant additive in engine oil. *Mater. Chem. Phys.* **2020**, *253*, 123447. [CrossRef]

65. Wu, H.; Jia, F.; Zhao, J.; Huang, S.; Wang, L.; Jiao, S.; Huang, H.; Jiang, Z. Effect of water-based nanolubricant containing nano-TiO_2 on friction and wear behaviour of chrome steel at ambient and elevated temperatures. *Wear* **2019**, *426*, 792–804. [CrossRef]
66. Mohamed, A.; Hamdy, M.; Bayoumi, M.; Osman, T. Synthesis and tribological properties of nanogrease. *Ind. Lubr. Tribol.* **2018**, *70*, 512–518. [CrossRef]