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ANTI-WEAR EFFECT AND THE ROLE OF DISPERSION TEMPERATURE OF NANOFLUIDS CONTAINING AL_2O_3 NANO-ADDITIVES

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ABSTRACT

The present investigation is focusing on the enhancement of the tribological performance of 20W-50 engine oil by the addition of Al_2O_3 nanoparticles. The anti-wear properties of engine oil have been tested under different sliding speeds 0.84, 1.26, 1.68, 2.1, and 2.52 m/s and operating temperature of 50, 75, and 100˚C using a tribometer with stainless steel disc and plate to simulate the working conditions in the engine. The experiments have been performed on the samples lubricated by different nanofluids prepared by dispersing the nanoparticles at three different mixed temperatures of 50ºC, 100ºC, and 150ºC. The study concluded that the lowest wear rate is achieved when the sliding surfaces were lubricated by the nanofluids mixed at temperature of 50°C. It can be found that the wear rate reduces by 34.4% during the lubrication by nanofluid containing 0.4 wt.% of Al_2O_3 nanoparticles content. It is also concluded that the increase in the mixing temperature could impede the dispersion of nanoparticles in the oil, in which the dispersion stability decreases.

KEYWORDS

Wear rate, nano-lubricant additives, engine lubricant oil, Al_2O_3.

INTRODUCTION

Nowadays, the use of nanomaterials as additives to engine oils is one of the areas that attracts great interest from researchers around the world. Nanoparticles are characterized by playing an important role by reducing the friction coefficient between the sliding parts, [1, 2]. This is due to the mechanics of the tribological system for nanoparticles such as protective film, mending effect, rolling effect, and polishing effect, [3–5]. In situ many nanomaterials have been used as additives to lubricant oil, [2] and grease, [6] to improve frictional properties and increase the wear resistance of sliding surfaces. Through Stribeck curve it displays the friction conditions for the internal engine parts during worked under one of the various lubrication regimes, as illustrated in Fig. 1, [7]. The boundary lubrication is introduced as ultra-thin film of lubricant that in which the sliding surface asperities [8]. The boundary lubrication occurs oftentimes when the

sliding parts are so close together that the surface interactions under overload and low speed, [9–11]. Wherefore the chemical and physical properties of the lubricant are of major importance, [12, 13].

Based on the characteristic chemical compounds, the various types of nanomaterials have been classified into metals, metal oxides, carbon-based, ceramics and polymers, [2]. The PTFE nanoparticles are used as lubricant additive to enhance the tribological performance of oils, generally more effective in the extreme pressure then the other nanoparticles, [14–17]. Copper oxide (CuO) used as nano-additives engine oil. Further it was found that CuO nanoparticles play a vital role for improving the tribological performance. The results display that nano-lubricant exhibits clearly reducing of coefficient of friction and anti-wear behavior by 53% and 24%, respectively, [18–20]. Carbon-based, such as carbon nanotubes, carbon nanofibers, and graphene are distinguished to have an effective role in improving the thermal conductivity of the fluids [21]. In contrast, increasing amount of the carbon leads to reduce stability and do not useful in the viscosity of nano-lubricants, [22, 23].In an attempt to reach the better results it was using hybrid nano-additives that may combine carbon and other types of nanoparticles. Hybrid carbon nanotubes with TiO_2, Al_2O_3, and other nanoparticles play a desirable role in improve the pressure characteristics and increase their thermal conductivity, [24–27].

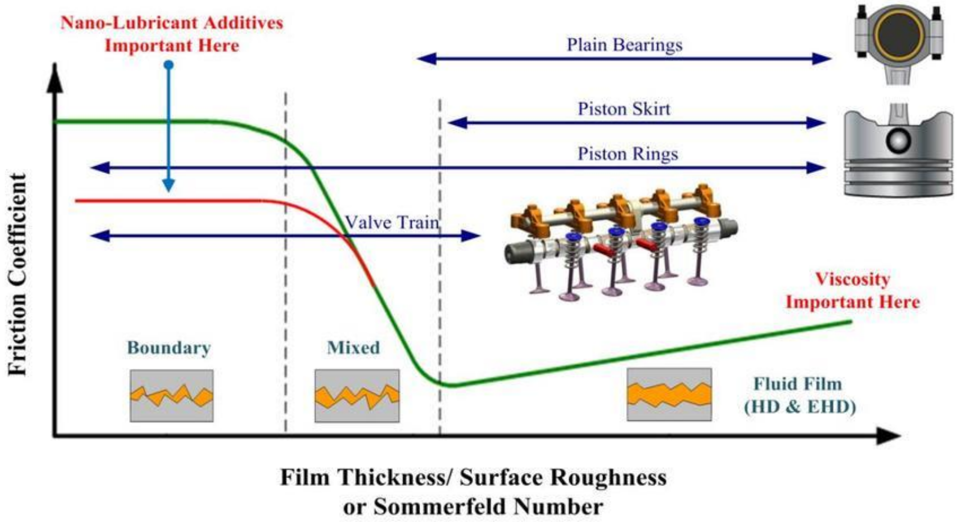

Fig. 1 The Stribeck curve showing the transition from boundary to mixed and finally to hydrodynamic lubrication regimes with clarified an impact role of the nano-additives, [7].

The effect of dispersing diamond and SiO_2 nanoparticles to paraffin oil on the tribological performance was investigated, [28]. It was found that paraffin oil using both nanoparticles as additives have friction coefficient and wear less compared with the pure paraffin oil. The nano-lubricant paraffin with SiO_2 nanoparticles of 0.05 to 0.5 wt. % contents have the best tribological performance, [29]. The results can show that paraffin oil dispersing by tiny size of SiO_2 nanoparticles anti-wear and anti-friction characteristics under high loads. MoS_2 and SiO_2 nano-lubricants used to study the frictional properties of contacts

between magnesium alloy and steel using a reciprocating sliding ball-on-flat tribometer. The results showed that MoS_2 nano-lubricants has more clearly effect as compared with the SiO_2 nano-lubricants in terms of the load carrying capacity and the lubrication film stability, [30]. The rheological stability and friction coefficient of SAE 40 Lubricating oil using SiO_2 nanoparticles as additives with contents up to 1% by weight were studied, [31]. The fully flooded condition testing results can show that the friction coefficient decreased with the increase of the concentration of nano-lubricant up to 0.6 % while the coefficient of friction starts increasing with nano-lubricant with content above 0.6%. Titanium and aluminum oxides nanoparticles are considered the most used as additives for motor oils due to their excellent tribological, chemical and thermal properties. The nano-lubricant oil contents of TiO_2 nanoparticles reduce friction coefficient clearly, it may be due to form of a thin film on contact surfaces [32, 33]. The results of engine oil dispersing by TiO_2 nanoparticles showed the ability to withstand higher loads by of 35%, [34]. The effect of spherical titanium oxide nanoparticles, the average diameter was 50 nm, in reducing friction between two pieces of cast iron were evaluated. The rapeseed oil with 5wt% of TiO_2 nanoparticles concentration reduces the mean surface roughness by 80.84%, [35]. While, the friction coefficient and the wear scars decreased approximately by 15.2% and 11%, respectively [36]. Hybrid TiO_2/SiO_2 nano-lubricants is considered a desirable way on the control the friction coefficient and wear resistance of rubbing surfaces, [37]. The 1.0% wt. of TiO_2 nano-lubricant shows that the friction coefficient and wear rate reduced in the ranges 39–47% and 50%, respectively, as compared to the additives free engine oil, [38].

The nanoparticles were stirred in base oil with contents of with 0.5% and 1.0% by weight. The experiments evaluated under five temperatures starts from 50°C up to 150°C in the sequence increment of 25°C. The 1.0% wt. of TiO_2 nano-lubricant shows that the friction coefficient and wear rate reduced in the ranges 39–47% and 50%, respectively, as compared to the additives free engine oil. The tribological properties improved as the lubricant composition of 0.5% wt. of SiO_2 nanoparticles while with increasing the composition of nanoparticles to 1.0% wt. the friction coefficient and wear rate again increased. The thin-film reformation effect and the rolling mechanism of the nano-lubricants of the frictional contact interfaces reduce and prevent the asperity contact between rubbing surfaces. The tribological properties of the modified Al_2O_3/SiO_2 composite nanoparticles as lubricating oil additives were investigated by four-ball and thrust-ring tests in terms of wear scar diameter, friction coefficient, and the morphology of thrust-ring, [39]. Titanium and aluminum oxides nanoparticles are considered the most used as additives for motor oils due to their excellent tribological, chemical and thermal properties, [40]. The influence of using the hybrid of Al_2O_3/TiO_2 as a nano-additives in engine oil was investigated, [41, 42]. The results illustrated that the friction coefficient and wear rate of the ring decreased in the ranges 39–53% and 25–33%, respectively. The lubricant oil, SAE 20W40, with using Al_2O_3 nanoparticles with 20 nm of grain size as nano-additives were studied. The results showed that 0.5% wt. of Al_2O_3 nano-lubricant reduce the friction by 49.1% and 21.6% under flooded and starved conditions, as compared to SAE 20W40 lubricant oil, [43]. The wear rate was reduced by using 0.5% wt. of Al_2O_3 nano-lubricant with 40–80 nm of grain size, [44]. Adding of 0.1wt% concentration and 78 nm grain size of Al_2O_3 nanoparticle to engine oil leads the friction

coefficient to decrease by ranges of 17.61% and 23.92% for the four-ball and the thrust-ring test, respectively, [45]. The thermal conductivity improved by 37.49% using 3.0% wt. of Al_2O_3 nano-lubricant, [46]. Nanoparticles can easily enter into small gaps between sliding surfaces because of their ultrafine sizes, whereas the micron-scale traditional additives cannot, [47]. A study of influence of mixed temperatures on the tribological performance of Al_2O_3 nano-lubricants under different operating conditions by using friction and wear tribometer. It was found that Al_2O_3 added to 20W-50 engine oil enhanced frictional property significantly and reduced vibrations. The study concluded that the lowest coefficient of friction was obtained at 0.4 wt. % concentration of Al_2O_3 nanoparticles and working temperature of 50°C, [48].

The current work aims to complete the previous study in order to measure the wear rate and monitor the worn surfaces topography.

EXPERIMENTAL

Preparation of Al_2O_3 nano-Lubricant

Aluminum oxide nanoparticles (Al_2O_3, 80% alpha /20% gamma, purity 99.9%) has been purchased from US Research Nanoparticles, Inc. The average diameter of Al_2O_3 nanoparticles is 50 nm and the specific surface area 35 m^2/g. Figure 2 illustrates the morphology of Al_2O_3 nanostructures investigated by SEM, which confirm the uniform shape of the nanoparticles with little imperfections. As a base material for lubrication, commercial mineral oil (Total 20W50 Quartz 5000SL) was chosen. The performance index of lubricant oil is shown in Table 1. Different amounts of aluminum nanoparticles have been dispersed in the commercially available oil to form the required nanofluids. Moreover, the mineral oil-based nanofluid has been prepared by continuous stirring at 1500 rpm for 1.5 hours under three different temperatures of 50°C, 150°C, and 150°C as shown in Fig.3. The mineral oil-based nanofluid has been left sure it is four weeks of preparation to monitor any agglomeration or sedimentation. The tribological and lubricous effects of five different amounts of nanoparticles of 0, 0.1, 0.2, 0.3, and 0.4 wt. % have been tested and evaluated.

Table 1. Performance index of the lubricating oil.

Properties	*Test method*	*Result*
Viscosity grade	*SAE J300*	20W 50
Density at 15°C [kg/m^3]	*ASTM D1298*	892
kinematic viscosity at 40°C [mm^2/s]	*ASTM D445*	176.4
kinematic viscosity at 100°C [mm^2/s]	*ASTM D445*	19.1
Viscosity index	*ASTM D2270*	123
Flash point [°C]	*ASTM D92*	240
Pour point [°C]	*ASTM D97*	-24

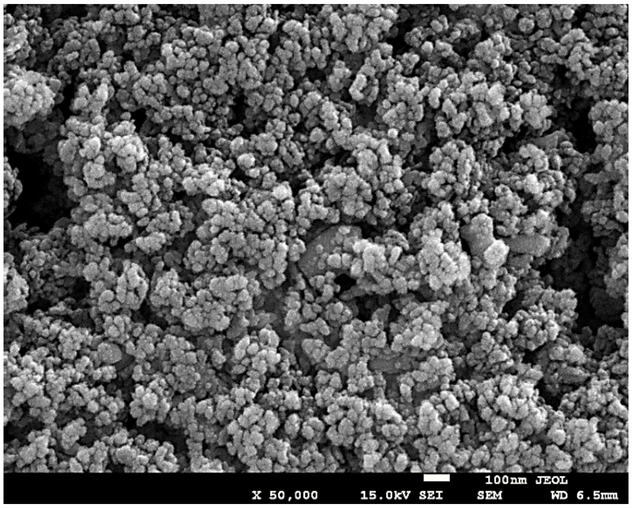

Fig. 2 SEM image of Al_2O_3 nanoparticles.

Fig. 3 Photograph of nano-lubricant oils carried out under mixing temperature (a) 50ºC, (b) 100ºC and (c) 150ºC.

The Tribometer Test-Rig

The experimental stand of the test rig consists of aluminum friction plates slides against flat-panel pin at sliding speeds of 0.84, 1.26, 1.68, 2.1 and 2.52 m/s, Fig. 4. Experiments have been performed using the tested nanofluids specimens at operating temperatures of 50, 75 and 100˚C for 10 minutes to simulate the working conditions inside the engine.

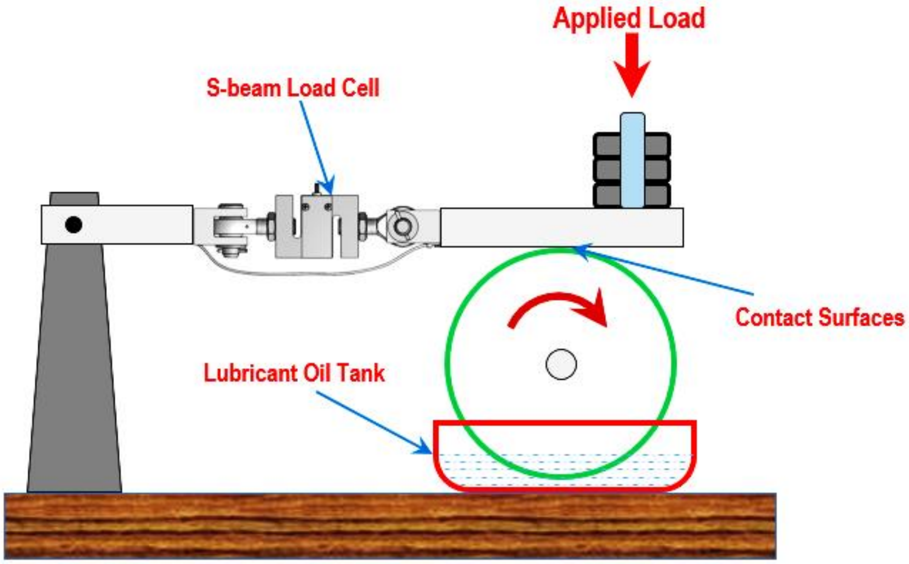

Fig. 4 Schematic diagram of the wear test-rig.

The wear rates during the sliding have been expressed by weight loss measured using an electronic balance with an accuracy of 0.0001g by calculating the difference between the final and initial weights of specimens. Consequently, the wear scar resulted on the specimens is considered as indication to the worn surfaces and thus can be used as a vital indicator for wear resistance measurements. Finally, the worn surfaces on the steel plates have been examined using optical microscopy (OLYMPUS BX53M, USA).

RESULTS AND DISCUSSIONS

Influence of Nanoparticles on the Wear Rate

Figure 5 shows the influence of Al_2O_3 nanoparticles contents on the wear rate for samples mixed at temperature 50ºC under different working temperatures and sliding velocities. The results show that 0.4 wt. % of Al_2O_3 nano-lubricant sample has the lowest value of the wear rate. It can be seen that the wear rate of the aforementioned sample decreased by 26.6 % in the comparison with the base oil at operating temperature of 50 ºC. Meanwhile, the mineral oil-based nanofluid containing 0.4 wt.% of Al_2O_3 nanoparticles exhibited the best performance (34.4% reduction in the wear rate) at temperature of 75ºC for those nanofluids which have been prepared at temperature of 50 ºC. On the other hand, the wear rate has significantly increased at temperature above 75˚C, in which the wear rate lessened (19.7% in the comparison with the reference oil) at the operating temperature 100ºC. From the results reported, the wear rate is reduced for all nano-lubricant samples compared with lubricant oil with the reference oil. The enhanced tribological performance of the nanofluid is referred to the role of the rolling effect of the nanoparticles. Furthermore, the nanoparticles play a crucial role in the separating of the asperities contact, which leads to less deformation of the rubbing surfaces. Moreover, the formation of the Al_2O_3 nanoparticles enriched lubrication film helps to protect the sliding surfaces from the severe wear and reduces the contact time in the asperity region, [49, 50].

The performance of the nanofluids mixed at temperature of 100ºC have been evaluated at different working temperatures and sliding velocities sliding velocities as shown in Fig.

6. It is clear that the mineral oil-based nanofluid containing 0.3 wt. % of Al_2O_3 nanoparticles displayed the best wear rate at all operating temperatures as compared with the reference oil. This behavior is attributed to the rolling effect of the nanoparticles, which leads to the decrease of the metal-to-metal contact causing a decline in the wear rate. Fig. 7 shows that the wear rate at 0.3 wt.% of Al_2O_3 nano-fluid has been reduced by 25.6%, 24.7% and 19.81% at working temperatures of 50, 75 and 100ºC, respectively. The wear rate of all nanofluids prepared at 150ºC of dispersion temperature, has been reduced. The results indicate that the general trend of the wear rate curve for all working temperatures has improved the tribological performance during the tests. Furthermore, the wear rate of the steel plate lubricated by mineral oil-based nanofluid containing 0.1 wt.% of Al_2O_3 nanoparticles has been reduced by 22.18 %, 21.53 %, and 23.37 % in the comparison with the reference oil at working temperatures of 50, 75 and 100ºC, respectively. Moreover, increasing the content percentage of Al_2O_3 nano-additives above 0.1% is corresponding with the increase in the wear rate. This behavior could be attributed to the instable nanoparticle's dispersion in the base oil at high mixing temperature. Table 2 compiles the enhancement percentages of wear rate for all samples lubricated by the proposed nanofluids. The increase of the mixing temperature impedes the dispersion and the suspending of nanoparticles in the base oil. Hence, dispersion of nanoparticles in the base oil is more stable at low mixing temperatures. Therefore, the Al_2O_3 nanoparticle content percentage of 0.4 wt. % exhibited promising performance at low working temperatures. As the mixing temperature rises, average agglomerate size goes down which leads to decrease the viscosity of nano-lubricant, [51].

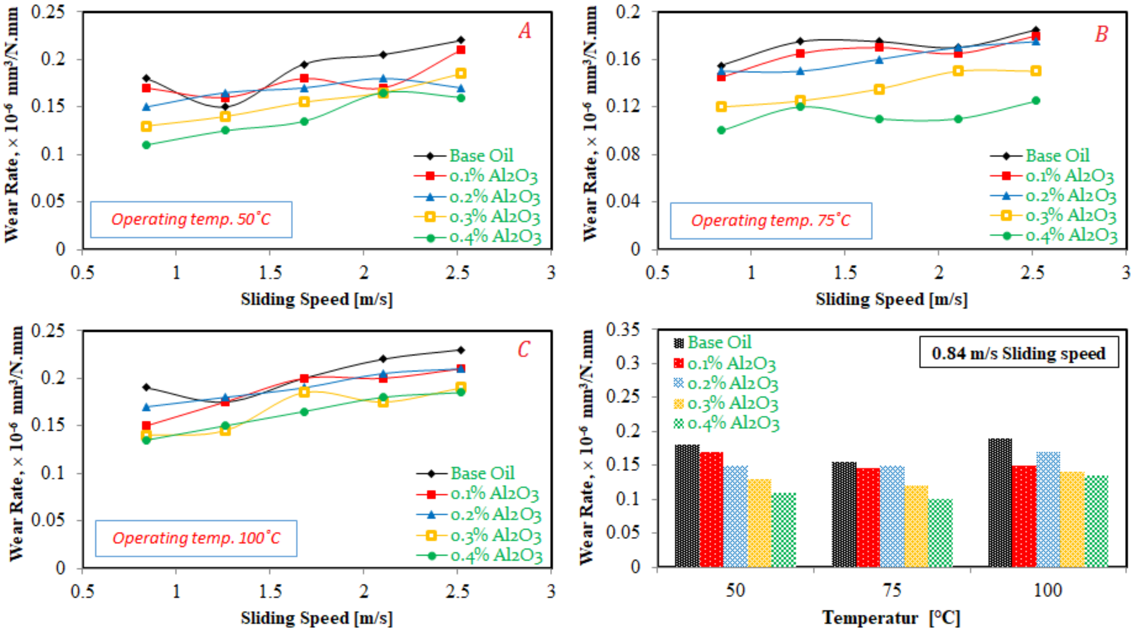

Fig. 5 Influence of Al_2O_3 nano-lubricant mixed at temperature 50°C on the wear rate at different working temperatures (a) 50ºC, (b) 75 ºC and (c) 100ºC.

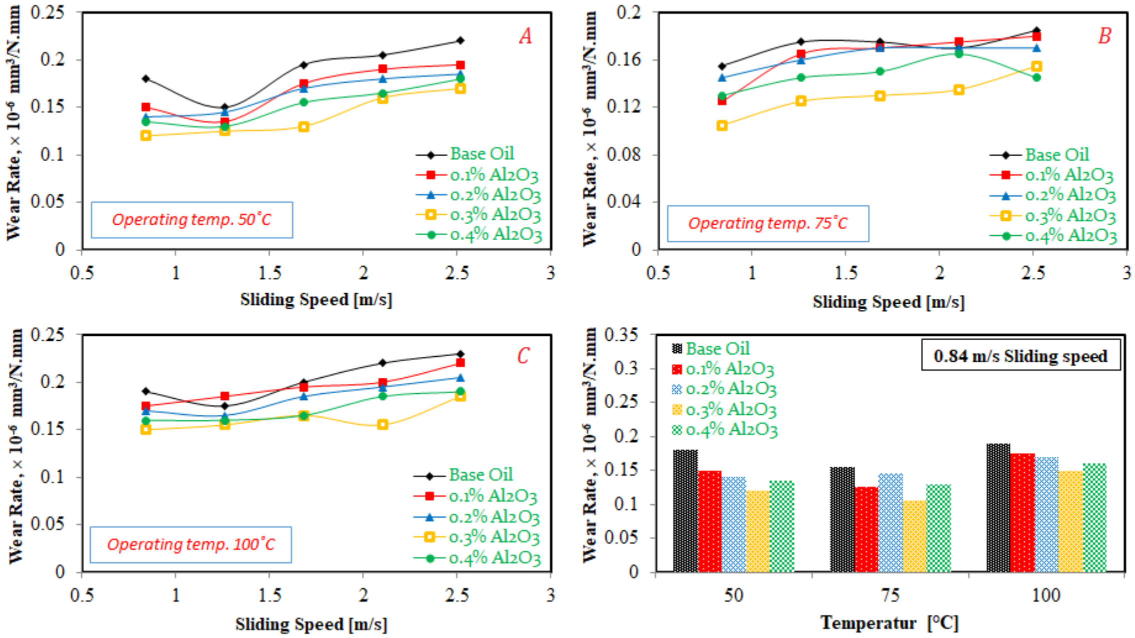

Fig. 6 Influence of Al_2O_3 nano-lubricant mixed at temperature 100°C on the wear rate at different working temperatures (a) 50°C, (b) 75 °C and (c) 100°C.

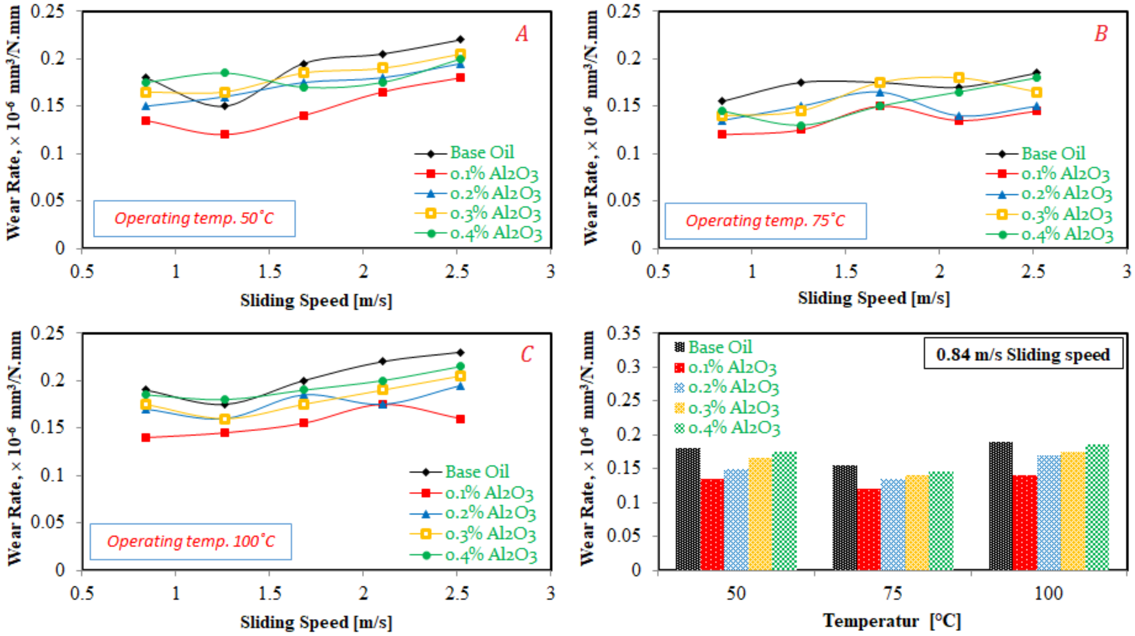

Fig. 7 Influence of Al_2O_3 nano-lubricant mixed at temperature 150°C on the wear rate at different working temperatures (a) 50°C, (b) 75 °C and (c) 100°C.

Table 2 Reduction percentage of wear rate of best Al_2O_3 nano-lubricants.

Mixing Temperature	Working Temperatures			Al_2O_3 nano-lubricant Contents
	50°C	75°C	100°C	
50°C	*26.6%*	*34.35%*	19.7%	0.4%
100°C	25.6%	24.7%	19.81%	0.3%
150°C	22.18%	21.53%	*23.37%*	0.1%

Topography of the Worn Surfaces

Topography of worn surfaces nave been carried out to more clearly describe the contact mechanism of rubbing surfaces lubricated by the nanofluids prepared at different mixing temperatures. Figure 8 illustrates the wear tracks on the steel disc lubricated by the tested nanofluids at applied load of 20 N and average sliding speed of 1.68 m/s. Clear grooves parallel to the sliding direction can be clearly noticed on the wear track of those sample lubricated by the nanofluids mixed at 50°C. Furthermore, some exfoliation could be seen as the results of the cracks propagation and contact fatigue, [52], as illustrated in Fig. 8 (a, b and c). On the other hand, the worn surfaces of the samples lubricated by nanofluids prepared at mixing temperatures of 75°C were relatively smoother and free of surface cracks.

The formation of Al_2O_3 nanoparticles enriched tribo-film inhibits metal-to-metal contact and helps the mating surfaces to become smoother, [53]. Figure 8 (g, h and i) indicates that the relative higher spread of surface pits on the wear track. Furthermore, delamination wear mechanism is the dominant mechanism, which is directly corresponding to the higher wear rates. Moreover, the rise of the working temperature of frictional surfaces assisted to go down of the average agglomerate size which leads to decrease the viscosity of nano-lubricant. These results are attributed to the increase of the wear rate and plastic deformation, causing the exfoliation damage of the contact surfaces.

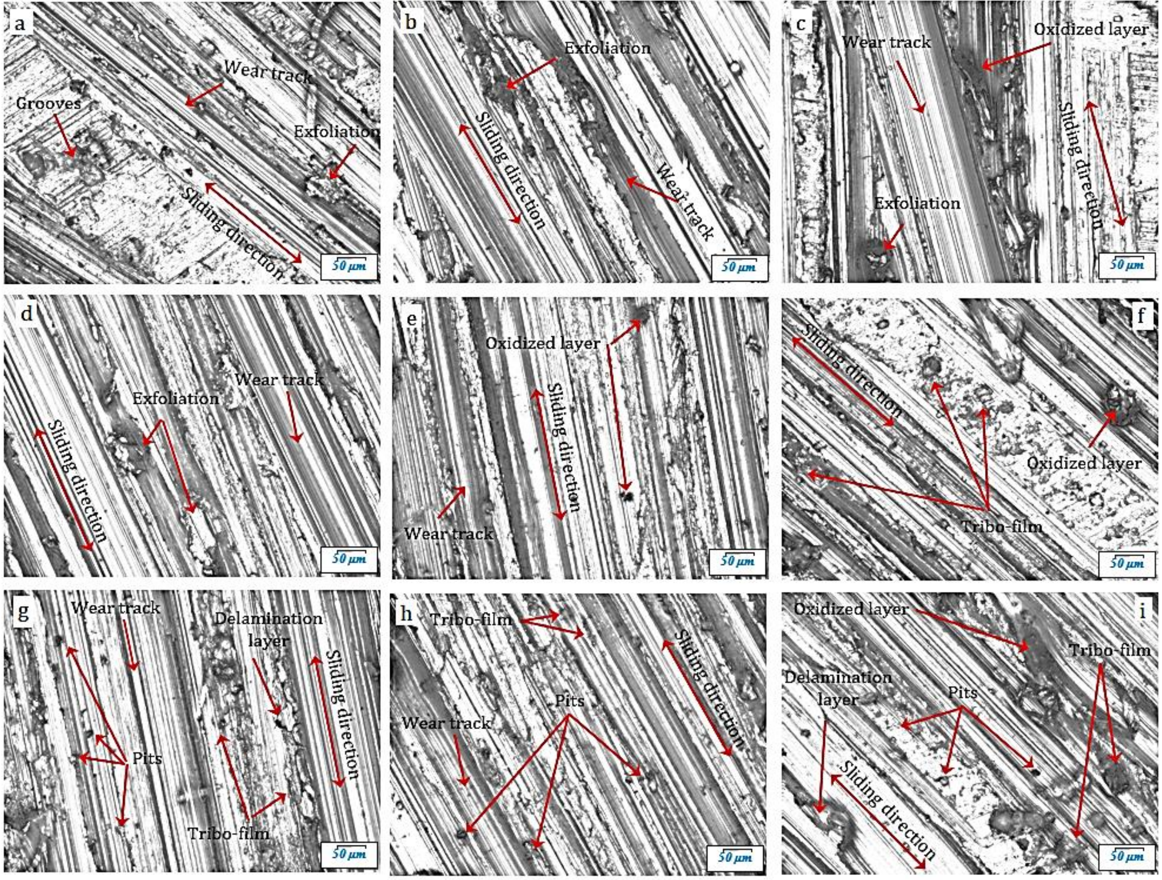

Fig. 8 Microscopic images of the worn surfaces of Al_2O_3 nano-lubricant samples at different working temperatures (a, b and c) 50°C, (d, e and f) 75 °C and (g, h and i) 100°C.

Considering Al_2O_3 nanoparticles as anti-wear additives that is referred to the reformation thin-film on the worn surfaces. This thin layer prevents the metal-to-metal contact between rubbing surfaces. However, the rolling effect ability of nanoparticles between the contact surfaces helps in delaying the damage of friction and wear. The mechanism of action of the nanoparticles in the contact can be summarized in their rolling on the sliding surfaces, filling the pits and fine cracks and separating the two contact surfaces.

CONCLUSIONS

In this work, different nanofluids prepared by dispersing different content percentages of Al_2O_3 nanoparticles in commercial mineral oil (Total 20W50 Quartz 5000SL) at different mixing temperatures have been prepared and evaluated tribologically. The experimental results proved that the mixing temperature plays a major role to determine the appropriate Al_2O_3 nano-additives percentage. For instance, the mineral oil-based nanofluids containing 0.4 wt.% of Al_2O_3 nanoparticles content and mixed at 50°C exhibited the lowest wear rate. It can be seen that the wear rate reduces by 26.6%, 34.4%, and 19.7% under the working temperature of 50, 75, and 100°C, respectively. Meanwhile, the higher mixing temperatures lead to a drastic increase in the wear rate as the result of the average agglomerate size, which reduces the viscosity of the nanofluids. The reduction observed in the wear rate can be attributed to the rolling of the nanoparticles. The tiny size of nanoparticles enables them to fill scratches and wear tracks and makes the friction surface smoother, where the sliding surfaces are protected by hard layer of nanomaterials and consequently, friction and wear decrease.

REFERENCES

1. Bakunin V.N., Suslov A.Y., Kuzmina G.N., Parenago O.P., Topchiev A.V., “Synthesis and application of inorganic nano-particles as lubricant components-a review”, Journal Nanopart. Res., 6, pp. 273–284, (2004.)

2. Dai W., Kheireddin B., Gao H., Liang H., “Roles of nanoparticles in oil lubrication”, Tribology international, 102, pp. 88–98, (2016).

3. Tarasov S., Belyaev S., “Alloying contact zones by metallic nanopowders in sliding wear”, Wear, 257, pp.523–530, (2004).

4. Lee K., Hwang Y., Cheong S., Choi Y., Kwon L., Lee J., “Understanding the role of nanoparticles in nano-oil lubrication”, Tribology Letters, 35, pp. 127–131, (2009).

5. Zhang Z., Zhang J., Xue Q., “Synthesis and characterization of a molybdenum disulfide Nanocluster”, Journal Phys. Chem., 98, pp. 12973–12977, (1994).

6.Ahmed E., Nabhan A., Ghazaly N. M., Abd El Jaber G.T., “Tribological Behavior of Adding Nano Oxides Materials to Lithium Grease: A Review.” American Journal of Nanomaterials, 8 (1), pp. 1-9, (2020). DOI: 10.12691/ajn-8-1-1.

7. Ali M. K. A., Abdelkareem M. A., Elagouz A., Essa F., Xianjun H., “Mini Review on the Significance Nano-Lubricants in Boundary Lubrication Regime,” Int. J. Biosen. Bioelectron., 2(2), pp. 00014, (2017).

8. Erdemir A., “Review of engineered tribological interfaces for improved boundary lubrication,” Tribol. Int., 38 (3), pp. 249–256, (2005).

9. Alahmer A., “Influence of Using Emulsified Diesel Fuel on the Performance and Pollutants Emitted From Diesel Engine,” Energy. Convers. Manage, 73, pp. 361–369, (2013).

10. Ali M. K. A., Xianjun H., Elagouz A., Essa F. A., Abdelkareem M. A. A., “Minimizing of the Boundary Friction Coefficient in Automotive Engines Using Al2O3 and TiO_2 Nanoparticles,” J. Nanopart. Res., 18(12), pp. 377, (2016).
11. Guo D., Xie G., Luo J., “Mechanical Properties of Nanoparticles: Basics and Applications,” Journal Phys. D., Appl. Phys., 47(1), pp. 013001, (2013).
12. Pettersson U., Jacobson S., “Influence of surface texture on boundary lubricated sliding contacts,” Tribol. Int., 36, (11), pp. 857–864, (2003).
13. Shram V. G., Lysyannikov A. V., Kovaleva M. A., “The Mechanism of Lubricants Protective Layers Formation in Friction Sliding,”Procedia Eng., 150, pp. 458–463, (2016).
14. Dubey M. K., Bijwe J., Ramakumar S. S. V., “PTFE based nano-lubricants”, Wear, 306, pp.80–88, (2013). DOI: 10.1016/j.wear.2013.06.020.
15. Dubey M. K., Bijwe J., Ramakumar S. S. V., “Nano-PTFE: new entrant as a very promising EP additive”, Tribology International, 87, pp. 121–131, (2015). DOI: 10.1016/j.triboint.2015.01.026.
16. Dubey M. K., Bijwe J., Ramakumar S. S. V., “Effect of dispersant on nano-PTFE based lubricants on tribo-performance in fretting wear mode”, RSC Adv., 6, pp. 22604–22614, (2016). DOI: 10.1039/C5RA16795G.
17. Saini V., Bijwe J., Seth S., Ramakumar S. S. V., “Role of base oils in developing extreme pressure lubricants by exploring nano-PTFE particles”, Tribology International, 143, 106071, (2019). DOI: 10.1016/j.triboint.2019.106071.
18. Asrula M., Zulkiflia N. W. M., Masjukia H. H., Kalama M. A., “Tribological properties and lubricant mechanism of Nanoparticle in Engine Oil”, Procedia Engineering, 68, pp. 320–325, (2013).
19. Bhaumik S., Pathak S. D., “Analysis of anti-wear properties of CuO nanoparticles as friction modifiers in mineral oil (460cSt Viscosity) using pin-on-disk tribometer”, Tribol. Indust., 37 (2), pp. 196–203, (2015).
20. Saxena N. D., Chauhan N., “An overview on characterization of CuO based nano lubricant”, Materials Today: Proceedings, (2019). DOI: 10.1016/j.matpr.2019.12.206.
21. Sastry N. N. V., Avijit B., Sundararajan T., Sarit K. D., “Predicting the effective thermal conductivity of carbon nanotube based nanofluids”, Nanotechnology 19 (5), pp. 055704–055708, (2008).
22. Sharma S. K., Gupta S. M., “Preparation and evaluation of stable nanofluids for heat transfer application: a review”, Exp. Thermal Fluid Sci., 79. pp. 202–212, (2016).
23. Devendiran D. K., Amirtham V. A., “A review on preparation, characterization, properties and applications of nanofluids”, Renew. Sust. Energ. Rev., 60, pp. 21–40, (2016).
24. 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, pp. 1–16, (2018).
25. Akhgar A., Toghraie D., “An experimental study on the stability and thermal conductivity of water-ethylene glycol/TiO_2-MWCNTs hybrid nanofluid: developing a new correlation”, Powder Technol. 338, pp. 806–818, (2018).
26. Asadi M., Asadi A., “Dynamic viscosity of MWCNT/ZnO–engine oil hybrid nanofluid: an experimental investigation and new correlation in different temperatures and solid concentrations”, Int. Commun. Heat Mass Transf., 76, pp. 41–45, (2016).

27. Ghaffarkhah A., Bazzi A., Dijvejin Z. A., Talebkeikhah M., Moraveji M. K., Agin F., "Experimental and numerical analysis of rheological characterization of hybrid nano-lubricants containing COOH-Functionalized MWCNTs and oxide nanoparticles", Int. Commun. Heat Mass Transf., 101, pp. 103–115, (2019).
28. Peng D. X., Kang Y., Hwang R. M., Shyr S. S., Chang Y. P., "Tribological properties of diamond and SiO_2 nanoparticles added in paraffin," Tribol. Int., vol. 42, no. 6, pp. 911–917, (2009).
29. Peng D., Chen C., Kang Y., Chang Y., Chang S., "Size effects of SiO_2 nanoparticles as oil additives on tribology of lubricant," Industrial Lub. and Tribology, 62(2), pp. 111–120, (2010).
30. 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," Tribology Int., 93, pp. 63–70, (2016).
31. Chaudhary S., Singh R. C., Chaudhary R., "Experimental Investigation of Influence of SiO_2 Nanoparticles on the Tribological and Rheological properties of SAE 40 Lubricating Oil," International Journal of Engineering and Technology, 9(6), pp. 4307–4314, (2018).
32. Ingole S., Charanpahari A., Kakade A., Umare S. S., Bhatt D. V., Menghani J., "Tribological behavior of nano TiO_2 as an additive in base oil'", Wear, 301, pp. 776–85, (2013).
33. Wu Y., Tsui W., Liu T., "Experimental analysis of tribological properties of lubricating oils with nanoparticle additives", Wear, 262, pp. 819–25, (2007).
34. Shenoy B., Binu K., Pai R., Rao D., Pai R. S., "Effect of nanoparticles additives on the performance of an externally adjustable fluid film bearing", Tribol Int, 45, pp. 38–42, (2012).
35. Kao M. J., Lin C. R., "Evaluating the role of spherical titanium oxide nanoparticles in reducing friction between two pieces of cast iron", Journal Alloys Compd., 483, pp. 456–459, (2009).
36. Arumugam S., Sriram G., "Preliminary study of nano and micro scale TiO_2 additives on tribological behavior of chemically modified rapeseed oil", Tribology Trans., 56, pp. 797–805, (2013).
37. Rashed A., Nabhan A., "Effects of TiO_2 and SiO_2 Nano Additive to Engine Lubricant Oils on Tribological Properties at Different Temperatures" 20^{th} Int. Conf. on Aerospace, Mech., Automotive and Mat. Eng., Rome, Italy, (2018).
38. 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" International Journal of Advanced Science and Technology, 29(1), pp. 845-855, (2020).
39. Jiao D., Zheng S., Wang Y., Guan R., Cao B., "The tribology properties of alumina/silica composite nanoparticles as lubricant Additives", Applied Surface Science, 257, pp. 5720 - 5725, (2011).
40. Bahramian A., Raeissi K., Hakimizad A., "An investigation of the characteristics of Al_2O_3/TiO_2 PEO nano composite coating", Appl. Surf. Sci., 351, pp. 13–26, (2015).
41. Ali M. K. A., Xianjun H., Mai L., Bicheng C., Turkson R. F., Qingping C., "Reducing frictional power losses and improving the scuffing resistance in automotive engines using hybrid nanomaterials as nano-lubricant additives", Wear, 364-365, pp. 270–828, (2016).

42. Ali M. K. A., Xianjun H., Essa F. A., Abdelkareem M. A. A., Elagouz A., Sharshir S. W., "Friction and Wear Reduction Mechanisms of the Reciprocating Contact Interfaces using Nanolubricant under Different Loads and Speeds", Journal of Tribology, 140(5), 051606, (2018).
43. Mohan N., Sharma M., Singh R., Kumar N., "Tribological properties of automotive lubricant SAE 20W40 containing nano-Al_2O_3 particles", SAE Technical Paper 2014-01-2781, (2014). DOI: 10.4271/2014-01-2781.
44. Elwain S.E. M., Blanchet T. A., Schadler L. S., Sawyer W. G., "Effect of particle size on the wear resistance of alumina-filled PTFE micro and nano-composites", Tribology Trans, 51, pp. 247–253, (2008).
45. Luo T., Wei X., Huang X., Huang L., Yang F., "Tribological properties of Al_2O_3 nanoparticles as lubricating oil additives", Ceram Int; 40, pp. 7143–7149, (2014).
46. Vasheghani M., Marzbanrad E., Zamani C., Aminy M., Raissi B., Badzadeh E. T., Barzegar-Bafrooei H., "Effect of Al_2O_3 phases on the enhancement of thermal conductivity and viscosity of nano fluids in engine oil", Heat Mass Transfer, 47, pp. 1401–1405, (2011).
47. Tang Z., Li S., "A review of recent developments of friction modifiers for liquid lubricants (2007–present)", Current Opinion in Solid State and Materials Science, 18, pp. 119–139, (2014).
48. Nabhan A., Rashed A., "Friction and Vibration Analysis of Sliding Surfaces Lubricated by Engine Oils Dispersed by Aluminum Oxide Nanoparticles" Journal of the Egyptian Society of Tribology (EGTRIB Journal), 17(1), pp. 14-26, (2020).
49. Alazemi A. A., Etacheri V., Dysart A. D., Stacke L. E., Pol V. G., Sadeghi F., "Ultrasmooth Submicrometer Carbon Spheres as Lubricant Additives for Friction and Wear Reduction," ACS Appl. Mater. Inter., 7(9), pp. 5514–5521, (2015).
50. Stott F. H., "The Role of Oxidation in the Wear of Alloys," Tribology Int., 31(1–3), pp. 61–71, (1998).
51. Afrand M., Najafabadi K. N., Akbari M., "Effects of temperature and solid volume fraction on viscosity of SiO_2 -MWCNTs/SAE40 hybrid nanofluid as a coolant and lubricant in heat engines", Appl. Thermal Eng., 102, pp. 45-54, (2016).
52. Dong H., Bell T., "Enhanced Wear Resistance of Titanium Surfaces by a New Thermal Oxidation Treatment," Wear, 238(2), pp. 131–137, (2000).
53. Sun J., Simon S., "The Melting Behavior of Aluminum Nanoparticles," Thermochim. Acta, 463 (1–2), pp. 32–40, (2007).