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Enhancing Tribological Performance with Aluminum Oxide Nanofluids: Experimental Investigation and Surfactant Stabilization

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Abstract

Researchers have been studying the superior heat conductivity of nanofluids compared to base fluids for over two decades, but the difficulties of dispersion and stabilizing nanoparticles in lubricants have hampered their use in tribology. To investigate the tribological characteristics of nanofluids, aluminum oxide (Al_2O_3) nanoparticles were dispersed in paraffinic mineral oil. Nanoparticles were dispersed evenly, due to the use of an ultrasonic homogenizer. Oil of olive improved the nanofluids' dispersibility and stability because it acted as a surfactant. A universal micro-tribometer set up with a ball-on-disk setup was used to assess the frictional forces exerted by the nanofluids on the mechanical parts as they moved. A surface profiler was employed to analyze the wear track, and X-ray photoelectron spectroscopy (XPS) was utilized to investigate the substance formed on the sliding contact. The effects of surfactant type, surface roughness, sliding velocity, concentration of particle, applying load, and ultrasonication period on the frictional and wear performance of nanofluids were studied. It has been demonstrated that oil-based nanofluids containing Al_2O_3 nanoparticles can reduce friction and wear under certain conditions. The nanofluids' dispersibility, stability, and friction were all improved by the addition of oleic acid (OA) as a dispersant.

Keywords

Velocity, Ultrasonication, Surface roughness, Surfactant, Nanofluid

Introduction

The increased thermal conductivity of nanofluids over conventional fluids has made them a hot topic of study. Recently, scientists have also studied the tribological characteristics of nanofluids. In addition, authors [1] reported that nanoparticles added to lubricants were successful in lowering wear and friction. The friction-reducing and anti-wear capabilities of the nanoparticles varied with their size, shape, and concentration. The slow progress of nanoparticle lubricants can be attributed to the challenges of stabilizing nanoparticles. Suspensions of CuO, Al_2O_3, and ZrO_2 nanoparticles in polyalphaolefin were demonstrated to exhibit anti-wear and extreme-pressure behavior [2]. When CuO nanoparticles were added to API-SF engine oil and base oil, friction was reduced by 18.4% and wear scar depth was reduced by 16.7%, as measured by the authors' studies [3]. TiO_2 nanofluids had a lower friction coefficient than base oil in a countering sliding testing test [4].

TiO_2 particles have been shown to decrease friction and contact temperature in pin-on-disk experiments using composite pins on polished steel at varying contact pressures and dry sliding velocities. A 33.5% decrease in wear spot diameter and a 32% decrease in friction coefficient were seen in lubricating oils containing a mixture of CeO_2 and $CaCO_3$ nanoparticles, compared to the basic oil, as noted by the authors [5]. $CaCO_3$ nanoparticles, according to the scientists, offer superior load bearing, anti-wear, and friction reduction capabilities [6]. Nano-oil with copper nanoparticles of 25 and 60 nm decreased friction by 44 and 39% when the oil temperature was raised [7, 8]. At high loads, copper nanofluids outperformed zinc dialkyldithiophosphates in terms of friction reduction and anti-wear properties. Authors [9, 10] employed copper nanoparticles as additives in lubricating oils, and the findings demonstrated anti-wear and friction reduction efficacy across a range of lubricants. As part of their tribological performance, nickel nanoparticles were shown to reduce friction by 26%, as indicated by the authors.

The capacity of oil-based nanofluids to reduce friction and wear is promising, but they are not entirely stable since nanoparticles tend to agglomerate with time. Because the dispersion molecules bind to the nanoparticles' surfaces, the particles remain suspended in the nanofluid and are distributed evenly [11]. It has been discovered by structural studies [12, 13] that OA bonds to the surface of SiO_2 nanoparticles via esterification, allowing for stable dispersion in mineral oil. This research looked at the tribological characteristics of Al_2O_3 nanofluids in an oil basis. We chose Al_2O_3 nanoparticles as Al_2O_3 nanofluids dissolved in water significantly reduced friction. The surfactant OA was utilized to enhance the dispersibility and stability of the mixture. Factors including concentration of nanoparticles, operating conditions and surface roughness were included in an analysis of nanofluids' friction and wear performance.

Experimentation

Equipment

The friction tests were conducted using the ball-on-disk configuration of a universal micro tribometer. To make swapping and cleaning the nanofluids simpler, a custom oil holder was developed for this testing apparatus. The disc was held in place by a spindle capable of 5,000 rpm, and the ball holder was linked to a perpendicular direct motion mechanism. The forces were measured precisely from 0 to 20 kg, with a precision of 1.0 g, using ultra-accurate strain-gauge sensors working in tandem. The friction coefficient was determined using 100 samples per second of data on the friction force and load (Figure 1).

Using a WYKO NT1100 3D optical surface profiler, we were able to analyze the wear track's sub-nanometer roughness and millimeter-high steps with white light interferometry. Chemical analysis with an XPS was performed and mixed nanofluids with an ultrasonic homogenizer. The 3/8-inch processing tip could only draw 320 Watts. Liquids and nanoparticles were tested using an analytical scale with a reading of 0.1 mg and an accuracy of 0.2 mg.

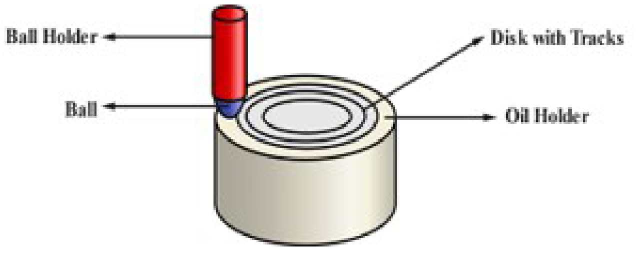

Figure 1: Universal mechanical testing-2 ball-on-disk tester.

Testing samples

Test specimens included 76.2 mm in diameter, HB53 hardness 1006/1020 steel discs and 4 mm in diameter, HRC60-67 hardness 52100 alloy steel balls. Light paraffinic oil P100N was utilized as the basis oil; at 16.2 °C, its density was 0.914 g/cm^3, and its viscosity was 21.3 cSt at 50 °C and 3.7 cSt at 100 °C. Al_2O_3 NanoGard was used as the nanopowder, and its particles were between 50 and 100 nm in size, with a surface area of 15 to 30 m^2/g. The morphology of Al_2O_3 nanoparticles was found to be linear. The surfactant was OA purified to greater than 97%.

Testing process

Before the WYKO surface profiler was used, all discs underwent many polishing operations to reduce surface roughness to acceptable levels. Each friction test began with a 5-min session in the ultrasonic cleaner with acetone to clean the disc holder, ball, and disc. The OA and nanoparticles were combined in a certain ratio, suspended in oil, and then blended together using an ultrasonic mixer. Percentages by weight are utilized throughout this investigation for all concentrations. All experiments were performed three times on independent discs containing nanofluids prepared in the same manner to guarantee the reliability of the results. The ball was always replaced after each experiment. The sliding distance was 30 m, standard load was 16 N, and sliding speed was 200 mm/s. Except for the tests that studied the impact of surface roughness, all experiments were conducted on refined, smooth surfaces with a mean surface roughness of roughly 50 nm. All experiments with nanofluids in oil followed this protocol. After the experiment was finished, the disc was taken out of the holder, cleaned using an ultrasonic cleaner, and placed in a sterile box until additional analysis using a WYKO surface profiler and XPS could be performed.

Results and Discussion

Impact of nanoparticle concentration

Figure 2 presents the disc showing wear track and the ball shows wear scar for 3% Al_2O_3. Friction as a function of Al_2O_3 nanoparticle concentration is seen in figure 3. In this experiment, OA and Al_2O_3 nanoparticles were mixed at varying quantities (from 0 to 6%) using a 1:1 ratio throughout all samples. The results demonstrated that friction was reduced when nanoparticles were dispersed in oil. The most effective combination concentration was 4.5% Al_2O_3 and OA.

The effect of nanoparticles on lowering friction was similar to that found by authors [14, 15], at around 20%.

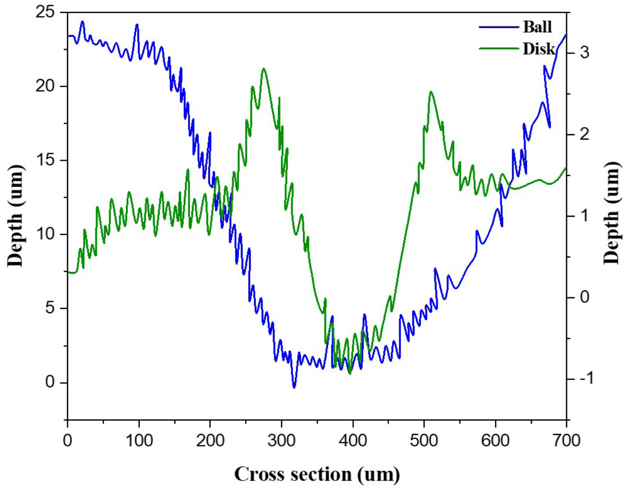

Figure 2: The disc shows wear track and the ball shows wear scar for 3% Al_2O_3.

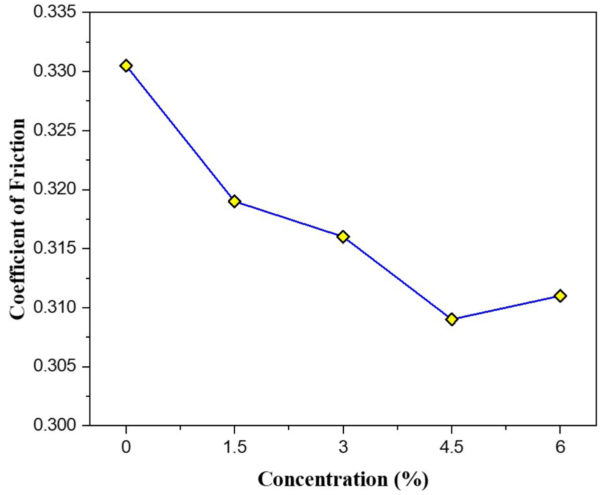

Figure 3: Impact of Al_2O_3 concentration on coefficient of friction.

While they discovered that a concentration of 6% reduced friction the most, it was discovered that a concentration of 4% did the trick (4.5%).

Impact of surfactant and ultrasonication time

In order to facilitate the dispersion of nanoparticles in oil-based nanofluids, OA was utilized as a surfactant. Because of this, the effect of the surfactant on wear and tear was studied.

First, the coefficient of friction of the nanofluids was evaluated with respect to ultrasonication time. Ultrasonic homogenization at 320 W for 20, 30, 40, 50, and 60 min was used to combine the Al_2O_3 nanofluids devoid of OA. Friction was reduced by roughly 21.45% when mixed for 40 min, compared to the basic oil (Figure 4).

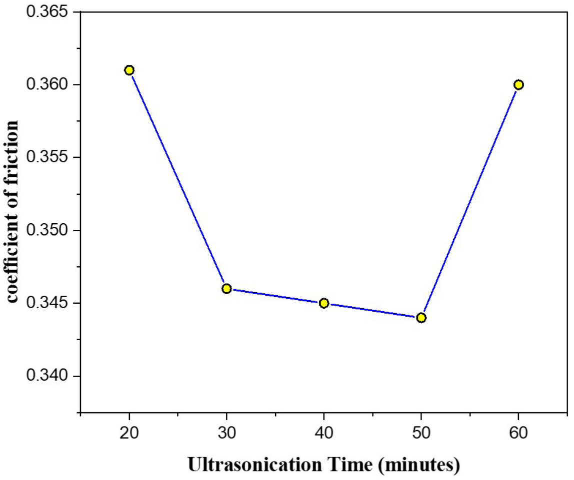

Figure 4: Coefficient of friction of Al_2O_3 nanofluids at 3% without OA with respect to variation of ultrasonication time.

Three separate experiments were conducted immediately following ultrasonic mixing, and the average of their findings is presented below. Tests of friction reduction indicated that mixing durations of 20 and 60 min showed no difference without the surfactant. The aggregated nanoparticles were resistant to being broken apart by ultrasonic power even after 20 min of mixing. However, the base oil degraded due to the ultrasonic power's produced heat after being mixed for 60 min. Using oleic acid concentrations between 1.5 and 6%, the second series of studies compared the results of friction tests performed with oil, OA, and Al_2O_3 nanoparticles to those performed with oil and OA alone. All samples were treated the same in terms of the ratio of OA to Al_2O_3 nanoparticles; for example, if a certain nanofluid had 3% Al_2O_3 nanoparticles, it also included 3% OA. OA and Al_2O_3 particle concentrations varied from 0% to 6%. We combined the specimen for 20 min.

Figure 5 demonstrates that the friction-reducing effects of OA alone are not as noticeable as those achieved by mixing nanoparticles into oil. While using oil and 4.5% OA, friction was decreased by 7.37%; when using oil, OA, and nanoparticles, friction was reduced by 20%. The amount of OA applied has no bearing on the friction-reducing effects. Therefore, OA's presence aided in nanoparticle dispersibility and nanofluid stability more than it did in reducing friction. The discs' wear tracks were also measured for quantity of wear in addition to the friction data. Figure 6 compares the effects of OA alone and in conjunction with Al_2O_3 nanoparticles.

At a concentration of 1.5%, oil containing OA performed

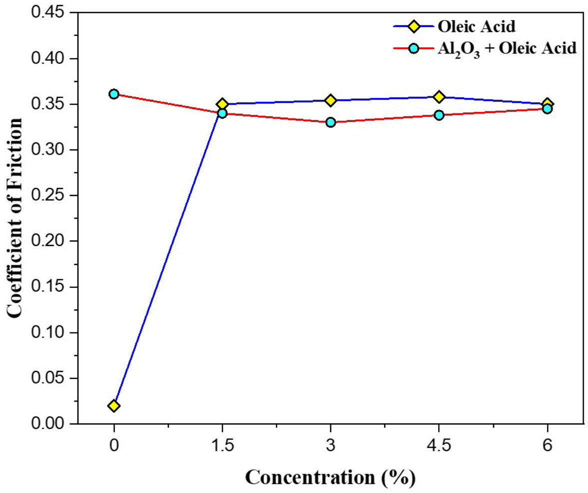

Figure 5: Impact of OA on coefficient of friction.

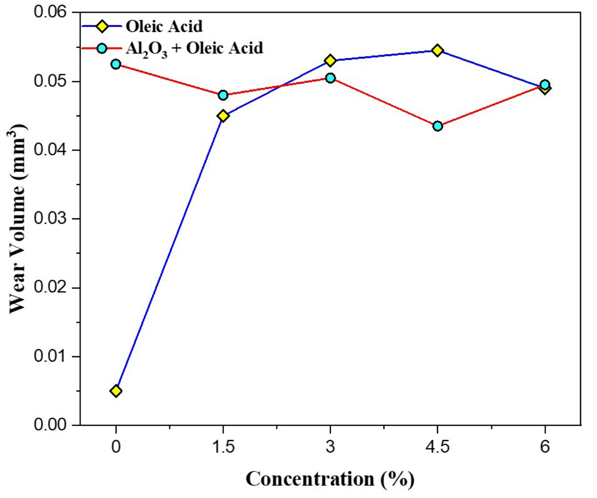

Figure 6: Impact of OA on wear rate.

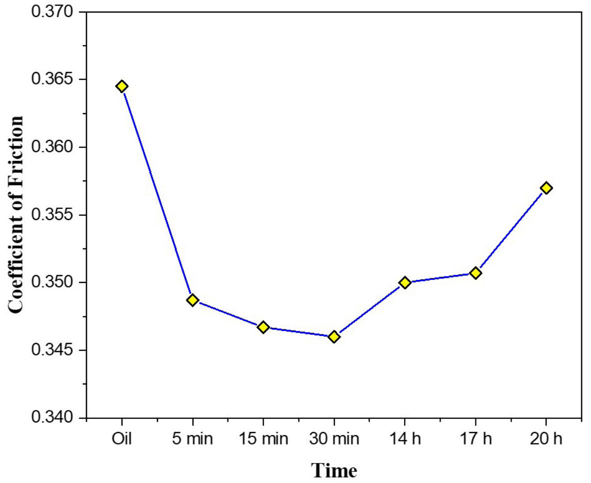

Figure 7: Evaluation of coefficient of friction and time for 3% Al_2O_3 nanofluids without OA with 30-min mixing duration.

better than oil containing OA plus Al_2O_3 nanoparticles, but when the concentration of Al_2O_3 nanoparticles grew, the contribution of OA reduced. Oil containing 4.5% OA and nanoparticles demonstrated less wear than OA oil alone. Consequently, the incorporation of nanoparticles was likely the primary factor in the observed decrease in wear.

For each nanoparticle concentration, a similar reduction in wear was seen. This might be because of changes in the testing procedure, nanoparticle type, and base oil. Authors also investigated OA's impact on nanofluids' stability and dispersibility. The Al_2O_3 nanofluid (without OA) was left in the device for varying amounts of time before the friction tests were conducted. The results are shown in figure 7. For pure oil and nanoparticles, as shown in figure 4, the mixing time of 20 min had no noticeable effect on friction reduction, whereas the mixing time of 30 min produced clear effects. Although initial observations indicated nanoparticle precipitation on the disk's surface, further tests revealed a decrease in friction. Over time, however, nanofluids' ability to reduce friction waned, and significant nanoparticle precipitation was seen.

The same experiments were performed using Al_2O_3 nanofluids at 3% and OA at 3%, both for 20 and 30 min (see figure 8). As can be observed in figure 8, the friction reduction was readily apparent after only 20 min of mixing with the addition of OA as the surfactant. As a result, we can say that OA enhanced the nanoparticles' dispersibility. The coefficient of friction rose, however, when the mixing time was extended from 20 to 30 min, since the longer mixing time led to a larger temperature increase, which degraded the OA. As a result, for the remaining experiments, a 20-min mixing period was adopted. Moreover, as observed in figure 8, the coefficient of friction remained unaltered 40 h after the first mixing. Comparison of coefficient of friction between OA-containing and OA-free nanofluids is shown in figure 7. The coefficient of friction of the OA-free nanofluids were usually lower. Without the OA, however, the nanofluids were unstable. Over time, the coefficient of friction rose sharply. Figure 8 clearly shows the impact of OA on nanofluid stability, even if the coefficient of frictions were not evaluated at the same periods.

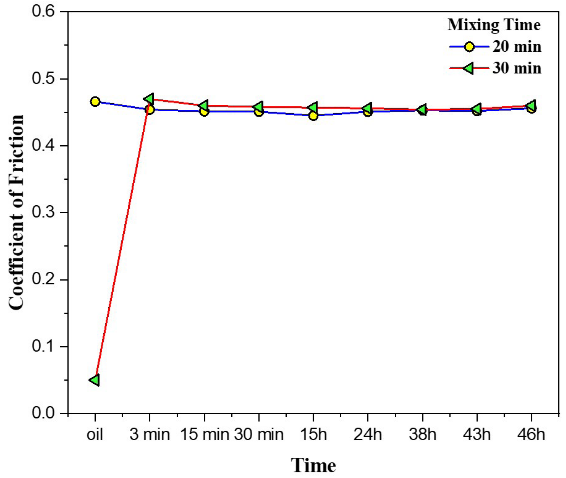

Figure 8: Evaluation of coefficient of friction and time for 3% Al_2O_3 nanofluids with OA with 20- and 30-min mixing duration.

Since OA may hinder friction reduction to some amount, its primary function is to increase the nanofluids' stability and dispersibility.

Figure 9 depicts the disc and ball wear track geometry while operating in oil only, and figure 2 depicts the geometry when operating in a mixture of 3% Al_2O_3 nanofluids. In both situations, debris accumulated on the disk's wear tracks, but the test using nanofluid produced a far smoother wear track. In contrast to the wear scar analyzed in our earlier work [16, 17] employing water-based nanofluids, there was no accumulation and the ball showed relatively moderate wear.

Impact of surface roughness

Surface roughness's impact in lowering friction was also studied. The disc samples were polished to surface roughness = 50, 150, and 250 nm, each representing a different level of surface roughness. Nanoparticles of Al_2O_3 and OA both made up 3% of the total. As can be seen in figure 10, nanoparticles contributed more to lowering friction on smoother surfaces. It was also shown that while Al_2O_3 nanoparticles help keep polished surfaces wearing longer, they also speed up wear on

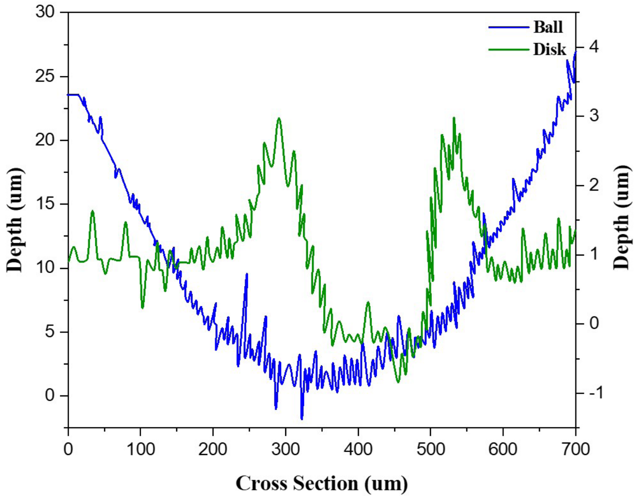

Figure 9: Wear the disk's track and the ball's scar for oil only.

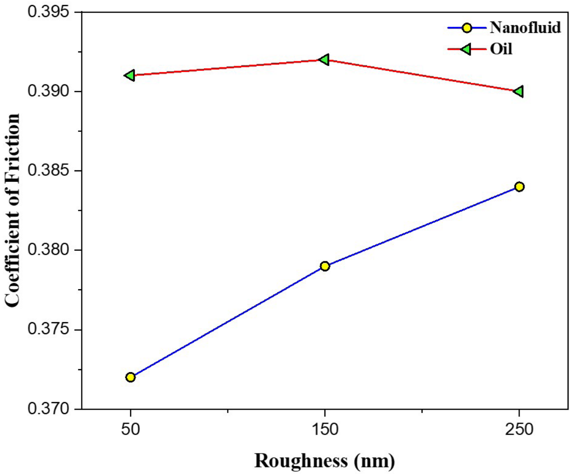

Figure 10: Impact of surface roughness on coefficient of friction.

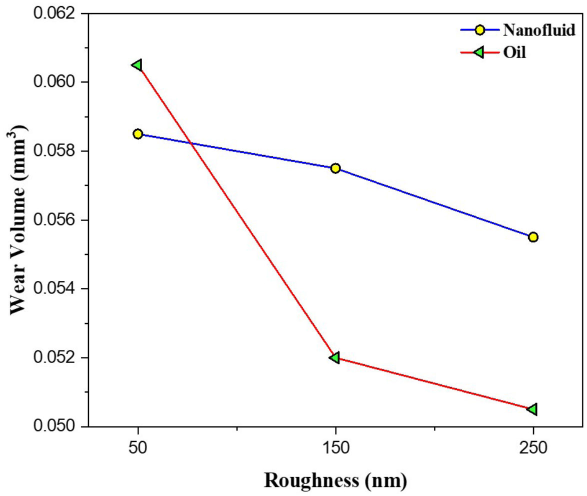

Figure 11: Wear volume at variant surface roughness.

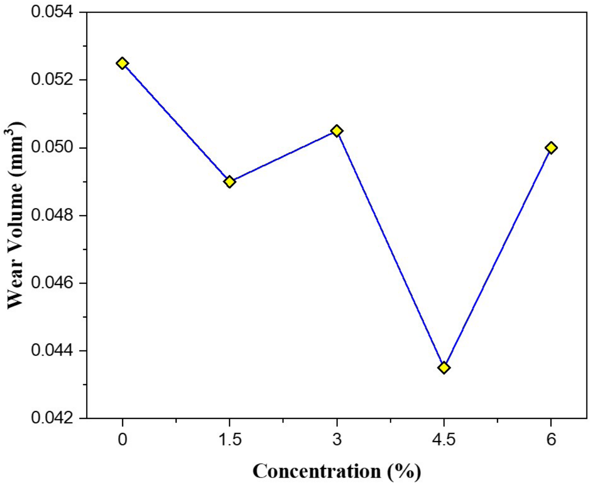

Figure 12: Impact of Al_2O_3 on wear volume.

rougher ones (Figure 11). The breadth of the wear track was evaluated with the friction and wear levels. When nanoparticles were included, the wear path expanded uniformly.

Impact of sliding velocity and load

Figure 12 depicts the influence of Al_2O_3 nanoparticle concentration on disc wear. At 4.5% particle concentration, Al_2O_3 nanoparticles showed the greatest reduction in wear of 39.12% compared to the base oil.

The correlation between sliding velocity and coefficient of friction was also studied (Figure 13). Three different speeds (200, 400, and 600 mm/s) were used in the testing. Al_2O_3 nanoparticles and OA concentrations were both 3%, and the typical load applied was 16 N. The effect of Al_2O_3 nanofluids on lowering friction was shown to diminish as travelling speed increased. The results showed that the friction reduction was 17.24% at 200 mm/s, 14.29% at 400 mm/s, and 0.94% at 600 mm/s, suggesting that the higher the speed, the less of a contribution there was to the overall decrease.

Using Hamrock's equation [18], we found that raising the sliding velocity from 200 to 600 mm/s resulted in a 300% increase in the oil layer thickness at 16 N load. Therefore, the role of nanoparticles in the sliding contact, and therefore their contribution to lowering friction, diminished as the sliding velocity increased. Friction reduction with respect to load is seen in figure 14.

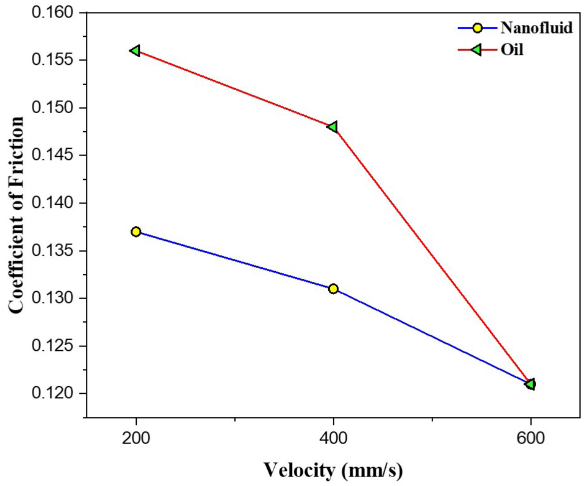

Figure 13: Impact of velocity on coefficient of friction for OA and Al_2O_3.

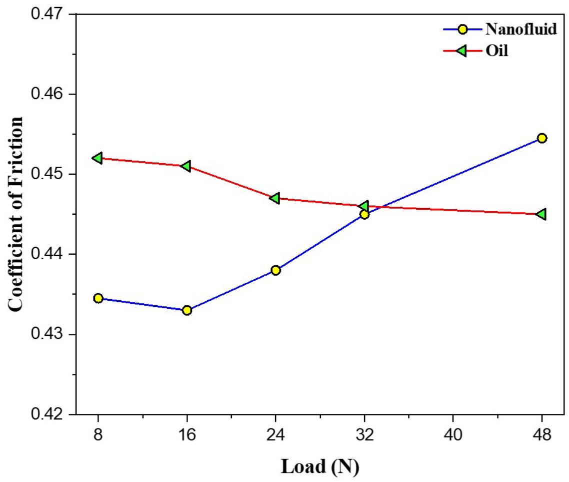

Figure 14: Impact of load on coefficient of friction for OA and Al_2O_3.

The results demonstrated that nanoparticles contributed more to friction reduction at lower loads and less when loads were raised. The nanoparticles' impact reversed when the load exceeded a particular threshold, increasing friction instead. Film viscosity and the λ ratio ($h$min/σ) both reduced with increasing load, as calculated by Hamrock's equation. Abrasive wear might be caused by the nanoparticles under greater stress. Authors [19-21] also found that CuO nanoparticles reduced friction better at lower loads, but their data did not reveal the load threshold. The role of speed on disc deterioration was also studied.

As can be seen in figure 15, the nanoparticles' contribution to lowering wear was greatest at lower velocities, whereas they had no impact at higher speeds. Wear was increased by 600 mm/s due to the presence of nanoparticles. The load's influence followed a similar pattern (see figure 16).

Nanoparticles in the oil enhanced wear reduction at low loads, but this effect was lost at greater loads, and under these conditions the nanoparticles actually increased the wear volume. Abrasive wear was caused by nanoparticles, proving their role as a third body.

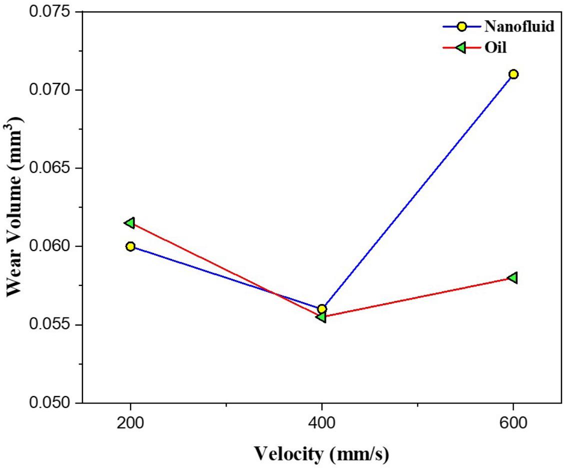

Figure 15: Wear volume at different velocities.

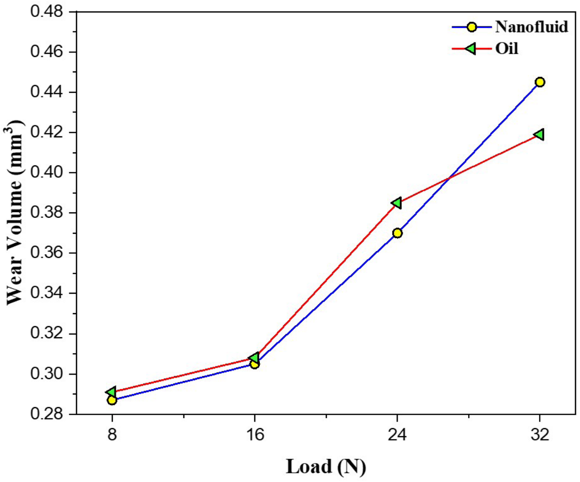

Figure 16: Wear volume at variant loads.

Conclusions

Al_2O_3 nanofluid friction and wear was studied by altering velocity, surfactant concentration, concentration of nanoparticle, load, mixing duration and surface roughness. The following results make sense in light of the study's experimental design.

- Smooth surfaces saw less friction and wear thanks to oil-based nanofluids containing Al_2O_3 nanoparticles. Under the parameters of this study, the best reduction in friction occurred at a concentration of 4.5%.
- When added to oil-based nanofluids, OA improved their dispersibility and stability while also reducing friction.
- Al_2O_3 nanoparticles aided in lowering friction at low speeds. At 600 mm/s, the benefit of reduced friction had already diminished significantly.
- Furthermore, the amount of disc wear was less at lower speeds than with the basic oil. Increasing the speed resulted in a greater volume of wear.
- The decrease in friction was most noticeable at moderate loads. The capacity of nanofluids to reduce friction was diminished at increasing stresses. The same pattern was also observed in clothing. Wear was decreased with the nanofluid at lower loads, but at higher loads, it was worse than with the standard oil.
- Nanofluids were shown to be effective in lowering friction in friction testing using discs of varying roughness. Smooth surfaces only showed reduced wear at low velocities and loads. The wear was worse than with only oil on uneven surfaces and under heavy loads.
- For nanofluids based on oil, nanoparticle deposition on the wear track was negligible. Instead of just being deposited on the surface, nanoparticles may play a role in lowering friction by acting as nanosized bearings. We need more research on the mechanism of coefficient of friction.

Acknowledgements

None.

Conflict of Interest

None.

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