

Wear Behavior of Castor Oil Lubricant Modified with Al_2O_3 and TiO_2 Hybrid Nanoparticle Additive

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Abstract—This study investigates the tribological characteristics of cold-pressed castor oil with Al_2O_3 , TiO_2 , and a hybrid nanoparticle additive combining Al_2O_3 and TiO_2 . The anti-wear properties of the modified Al_2O_3 and TiO_2 nanoparticles used as lubricant additives were investigated experimentally using the four-ball test in accordance with ASTM D4172. Al_2O_3 nanoparticles of different sizes (10–20, 30–50, and 80–100 nm) and TiO_2 nanoparticles of 10–50 nm were dispersed in castor oil at concentrations of 0.5, 0.75, and 1.00 wt.% Concentration along with the solvent oleic acid. The performance of $\text{Al}_2\text{O}_3/\text{TiO}_2$ hybrid nanoparticles compared with Al_2O_3 or TiO_2 nanoparticles. The wear scar diameter for castor oil is 0.4067 mm. The optimal Al_2O_3 -based nano lubricant reduced the WSD to 0.3875 mm, representing a 4.7% reduction in wear scar diameter. TiO_2 nano lubricant exhibited the best performance at a concentration of 0.750 wt.%, with a minimum WSD of 0.3182 mm, representing a 21.8% reduction in wear compared with pure castor oil. The Al_2O_3 – TiO_2 hybrid nano lubricant showed a minimum WSD at 0.75 wt.% concentration using 30–50 nm Al_2O_3 of 0.3358 mm, corresponding to a 17.4% reduction compared with the blank castor oil. The enhanced performance is attributed to the formation of a protective tribofilm at the sliding interface, surface-filling effects, and nanoparticle-mediated reduction of direct asperity contact.

The results demonstrate that Al_2O_3 , TiO_2 , and a hybrid nanoparticle additive combining Al_2O_3 and TiO_2 can improve the anti-wear performance of castor oil. TiO_2 nanoparticles show the highest individual performance, and the Al_2O_3 – TiO_2 hybrid provides substantial improvement over Al_2O_3 alone. The study demonstrates the possibility of hybrid nanoparticle additives for developing high-performance, bio-based lubricants.

Index Terms—nanoparticles, Castor oil, nano lubricant, hybrid nano lubricant, wear scar diameter, tribological performance.

I. INTRODUCTION

In today's world, conserving materials and energy is becoming very important. Friction is the primary source of energy loss in mechanical systems. Lubrication is crucial for lowering friction, wear, heat production, and energy losses between interacting surfaces. Conventional lubricants derived from petroleum resources have been widely used for their advantageous physicochemical and tribological properties. However, interest in developing environmentally friendly lubricant substitutes has grown due to the low biodegradability, environmental persistence, reliance on non-renewable resources, and potential ecological damage associated with conventional lubricants.

Vegetable oils have the potential to replace traditional lubricants due to their renewable origin, biodegradability, and high lubricity. Vegetable oils have attracted considerable attention as potential bio-lubricant base stocks. Vegetable oils exhibit good boundary lubrication properties because long-chain fatty acids interact with metallic surfaces, forming a comparatively robust lubricating layer. Due to high ricinoleic acid content and inherent high viscosity, Castor oil stands out among other vegetable oils. Castor oil is limited in its use as a lubricant. It is sensitive to temperature deterioration and has relatively poor oxidation stability under extreme friction and wear conditions. Therefore, castor oil must be modified with appropriate additions to enhance its tribological performance and expand its engineering uses.[1][2][3][4]

In recent years, many studies have examined the applications of nanoparticles in lubrication. The reduction of friction and wear depends on nanoparticle characteristics such as material composition, size, shape, concentration, and dispersion stability.

Enhancing lubricant oil properties is important for protecting surfaces from potential damage and reducing energy consumption. Addition of nanoparticles to base lubricating fluids has become a viable strategy for enhancing friction and wear properties.[5][6]

Titanium dioxide (TiO_2) and Aluminum oxide (Al_2O_3), metal oxides, have attracted considerable interest as lubricant additives.[7] The high wear resistance and surface protection of Al_2O_3 result in excellent hardness, thermal stability, and chemical stability. TiO_2 shows favorable thermal and chemical stability and has the potential to reduce wear and friction. The combination of two different nanoparticles offers an opportunity to leverage their complementary tribological properties. Al_2O_3 and TiO_2 hybrid additives may offer several wear and friction-reduction processes. In the present work, the separately synthesized Al_2O_3 and TiO_2 nanoparticles are combined and dispersed in castor oil in various concentrations.[8]

The current study systematically evaluates both the individual and combined impacts of Al_2O_3 and TiO_2 . Although several research studies have examined Al_2O_3 and TiO_2 metal oxide nanoparticles as lubricant additives, the tribological analysis of hybrid $\text{Al}_2\text{O}_3/\text{TiO}_2$ nanoparticle additives in castor-oil-based lubricants is comparatively less extensive. The effectiveness of the binary additive system can be evaluated by a systematic comparison of the base castor oil, Al_2O_3 -modified castor oil, TiO_2 -modified castor oil, and $\text{Al}_2\text{O}_3/\text{TiO}_2$ hybrid nano lubricant.

The objective of the present research is to experimentally examine the wear and friction behaviour of castor oil by the addition of Al_2O_3 - TiO_2 hybrid nanoparticles as a lubricant additive. Standard ASTM test methods are used to investigate wear scar diameter, coefficient of friction, and load-carrying behavior. To determine the optimal formulation, effects of nanoparticle concentration and $\text{Al}_2\text{O}_3/\text{TiO}_2$ composition are also examined.

Wu et al. [9] analyzed the tribological properties of TiO_2 nano-additive water-based lubricants, and found that TiO_2 concentrations below 0.8 wt.% reduce COF; however, TiO_2 concentrations above 0.8 wt.% lead to nanoparticle agglomeration and an increase in COF.

Ting Luo et al. [10] investigate tribological properties of Al_2O_3 nanoparticles as lubricating oil additives. The

modified Al_2O_3 nanoparticles are typical of a well-dispersed suspension, with KH-560 as the solvent, thereby increasing the dispersion stability of the nanoparticles in lubricating oil. The friction coefficient changes over time for samples with different Al_2O_3 nanoparticle concentrations. The modified nanoparticles are more stable than the lubricating oil containing the original nanoparticles. When the additive concentration is 0.1 wt.%, the best anti-wear and reduced friction are achieved.

Ali et al. [11] studied tribological characteristics of Al_2O_3 and TiO_2 nanomaterials as nano-lubricant additives for piston ring assembly in automotive engines. The study indicated that Oleic acid plays an important role in blending nanoparticles to make them soluble in engine oil. Nano-lubricants were stable for 14 days at room temperature. The addition of oleic acid as a solvent improved the stability of the nanoparticle suspension. It also reduced the wear rate and the ring's friction coefficient by 2.6% and 11%, respectively. Al_2O_3 and TiO_2 nano-lubricants slightly decreased kinematic viscosity due to the presence of nanoparticles. The viscosity index increased by 1.86%. The friction coefficient decreased in the boundary, mixed, and hydrodynamic lubrication regimes by 48–50%, 33–44%, and 9–13% respectively. The wear rate for the piston ring was reduced by 21–29%.

Ting Luo et al.[12] studied tribological properties of $\text{Al}_2\text{O}_3/\text{TiO}_2$ nanocomposites as lubricant additives. The experimental results showed that an average size of 75 nm $\text{Al}_2\text{O}_3/\text{TiO}_2$ nanocomposites yielded the best results. The results also show that the dispersibility of $\text{Al}_2\text{O}_3/\text{TiO}_2$ nanocomposites in lubricating oil is vital. The results showed that the use of modified $\text{Al}_2\text{O}_3/\text{TiO}_2$ nanocomposites improved the lubricating oil's tribological performance.

Mohamed Kamal Ahmed Ali et al.[11] studied the use of Al_2O_3 and TiO_2 nanomaterials as nano-lubricant additives for improving the tribological properties of piston ring assembly in automotive engines. To improve the quality of the nanofluid, proper mixing of nanoparticles into engine oil is important. The surface modifier oleic acid is used. A magnetic stirrer was used to blend the nanoparticles into the engine oil, yielding a stable, homogeneous suspension. Different concentrations (0.05, 0.1, 0.25, and 0.5 wt.%) of Al_2O_3 and TiO_2 nanoparticles were used to evaluate the tribological properties of engine oil. The formation of

a tribofilm on worn surfaces is the main reason for the decrease in the friction coefficient and wear rate. The nanoparticles act as a solid lubricant or an ultra-thin lubricating coating. The presence of nanoparticles in the lubricant decreases the kinematic viscosity. The frictional power losses for the Al_2O_3 and TiO_2 nanolubricants were also decreased by 45% and 50%, respectively. From the results, it was concluded that conversion of sliding friction to rolling friction and the formation of tribofilms on the worn surfaces are responsible for the reduction in friction and power losses.

II. MATERIALS AND METHODS

Cold-pressed castor oil was selected as the base lubricant. Aluminium oxide (Al_2O_3) and titanium dioxide (TiO_2) nanoparticles were added as hybrid nanoparticle additives. The combined hybrid nanoparticle additives were incorporated into cold-pressed castor oil at varying concentrations. Oleic acid was used as the solvent to improve the dispersion stability of the nanofluid. The influence of size and concentration was evaluated using the standard ASTM method.

The different lubricant samples were prepared to compare the tribological performance. Pure castor oil (blank sample) is compared with three formulations containing nanoparticles as lubricants. The first formulation is an Al_2O_3 castor oil nano-lubricant, and the second contains TiO_2 nanoparticles in castor oil. The third formulation includes an Al_2O_3 - TiO_2 hybrid nanoadditive in castor oil. The effect of Al_2O_3 particle size and nanoparticle concentration on wear behavior was also evaluated.

The effect of hybrid Al_2O_3 / TiO_2 nanoparticles on the tribological behavior of cold-pressed castor oil is experimentally investigated. The combination of TiO_2 nanoparticles with a particle-size range of 10–50 nm and Al_2O_3 nanoparticles with three different particle-size ranges, 10–20 nm, 30–50 nm, and 80–100 nm, was considered. These alumina and titanium dioxide (TiO_2) nanoparticles of different sizes were dispersed in castor oil at concentrations of 0.25, 0.50, and 0.75 wt.%. The two-step nanofluid preparation method was used to prepare the nanofluid. In the first step, the nanoparticles are added to the base oil with oleic acid, and in the second step, the

nanolubricant is stirred using a magnetic stirrer for 60 minutes.



Fig.1 Preparation of Nano lubricant

The tribological performance of the formulated lubricants was determined using the standard ASTM D4172 using a four-ball tribometer. Three stationary steel balls were immersed in the test lubricant, while the fourth ball was rotated against them. During the test, the upper ball is rotated against the fixed balls. The test is performed under fixed conditions: load, temperature, speed, etc. The test was conducted at 600 rpm, 390 N load, 75 °C, and 60 min. After completion of the test, the wear scars formed on the stationary balls were measured using an optical microscope and can be used to assess a lubricant's wear performance.

III. RESULT AND DISCUSSION

The contribution of the Al_2O_3 , TiO_2 , and Al_2O_3 - TiO_2 hybrid additive was assessed by comparing castor oil performance without nanoparticle additives in terms of WSD. The wear scar diameter (WSD) results for castor oil, Al_2O_3 nano lubricant, TiO_2 nano lubricant, and Al_2O_3 - TiO_2 hybrid nanolubricants are presented in the tables below.

Table 1. WSD results for cold-press castor oil and Al_2O_3 - TiO_2 hybrid castor-oil-based nanolubricants.

Sample	Al_2O_3 size (nm)	concentration	WSD (mm)
W1	10-20	0.50%	0.416667
W2	10-20	0.75%	0.389167
W3	10-20	1.00%	0.3875
W4	30-50	0.50%	0.396667

W5	30-50	0.75%	0.418333
W6	30-50	1.00%	0.4
W7	80-100	0.50%	0.44875
W8	80-100	0.75%	0.400833
W9	80-100	1.00%	0.42
Castor Oil	Nil	0.00%	0.406667

Table 2. WSD results for TiO₂ and Al₂O₃ castor-oil-based nano lubricants.

Sample	Al ₂ O ₃ size (nm)	TiO ₂ size (nm)	Nanoparticle concentration	WSD (mm)
hybrid W1	10–20	10–50	0.50%	0.3433
hybrid W2	10–20	10–50	0.75%	0.3712
hybrid W3	10–20	10–50	1.00%	0.3695
hybrid W4	30–50	10–50	0.50%	0.3575
hybrid W5	30–50	10–50	0.75%	0.3358
hybrid W6	30–50	10–50	1.00%	0.3812
hybrid W7	80–100	10–50	0.50%	0.3375
hybrid W8	80–100	10–50	0.75%	0.39
hybrid W9	80–100	10–50	1.00%	0.3716

Table 3. WSD results for TiO₂ castor-oil-based nano lubricants.

Sample	TiO ₂ size (nm)	concentration	WSD (mm)
T1	10–50	0.50%	0.3201
T2	10–50	0.75%	0.3182
T3	10–50	1.00%	0.3331

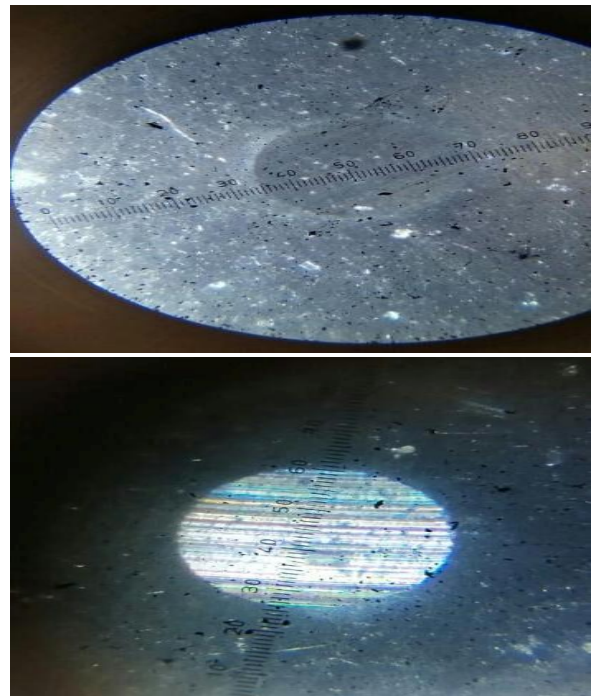


Fig. 2. Wear scar diameter obtained by optical microscope for Al₂O₃–TiO₂ hybrid castor-oil-based nano lubricants.

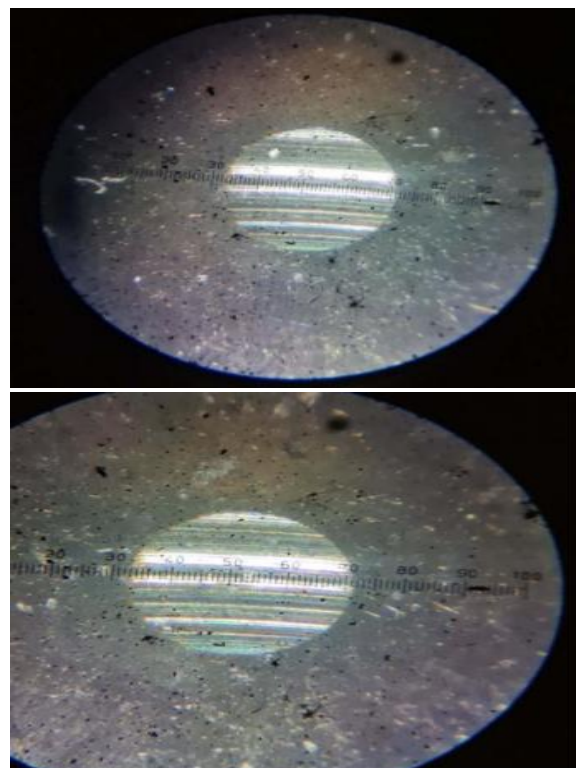


Fig. 3. Wear scar diameter obtained by optical microscope for Al₂O₃ castor-oil-based nano lubricants.

The base castor oil yields a wear scar diameter (WSD) of 0.4067 mm. The addition of Al_2O_3 nanoparticles in castor oil results in a minimum WSD of 0.3875 mm at 1.00 wt.% concentration for 10–20 nm particle size, which is approximately a 4.7% reduction compared with pure castor oil. The greater reduction in wear was observed with the TiO_2 nano lubricant. The minimum WSD is obtained at 0.75 wt.% TiO_2 concentration. The minimum wear scar diameter is reported to be 0.3182 mm, representing an approximately 21.8% reduction compared with castor oil.

For the Al_2O_3 – TiO_2 hybrid nanolubricants, the minimum WSD was obtained for 30–50 nm Al_2O_3 + 10–50 nm TiO_2 at 0.75 wt.% concentration; the minimum wear scar value is 0.3358 mm, which corresponds to a 17.4% reduction in WSD compared with pure castor oil. The reduced wear scar diameter value suggests the hybrid formulation considerably improved the wear resistance of castor oil.

3.1 Impact of Al_2O_3 with TiO_2 combination

The addition of Al_2O_3 nanoparticles, along with TiO_2 , generally improved anti-wear performance compared with Al_2O_3 alone. The improved results were particularly significant for the 30–50 nm Al_2O_3 + TiO_2 hybrid at 0.75 wt.% concentration, where WSD decreased from 0.4183 mm for Al_2O_3 alone to 0.3358 mm for the Al_2O_3 + TiO_2 hybrid nanoparticles, representing approximately a 19.7% improvement.

With 80–100 nm Al_2O_3 at 0.50 wt.% concentration, the hybrid nanoparticle formulation reduced WSD from 0.4488 to 0.3375 mm, a 24.8% improvement. These results indicate that the combined Al_2O_3 + TiO_2 hybrid nanoparticles can provide improved surface protection through mechanisms such as reduction of direct metal-to-metal contact, rolling/ball-bearing action, and filling of surface asperities.

However, in certain situations, the Al_2O_3 + TiO_2 hybrid system did not outperform. The TiO_2 -only sample shows 0.3182 mm WSD, and the best hybrid sample shows 0.3358 mm. Therefore, the findings show that the Al_2O_3 – TiO_2 combination offers a significant improvement over Al_2O_3 nano lubricant alone.

3.2 The impact of Nanoparticle Concentration and Size

Nanoparticle Concentration and Size significantly influenced the wear behaviour. The optimal hybrid results were obtained with 30–50 nm size Al_2O_3 at a

0.75 wt.% concentration. Increasing the concentration beyond the optimum formulation did not consistently reduce WSD. The WSD of the 30–50 nm sized hybrid nanoparticle combination increased from 0.3358 mm at 0.75 wt.% to 0.3812 mm at 1.00 wt.% concentration. Agglomeration of nanoparticles at higher concentrations could be the attribute of this behavior. Excessive nanoparticle concentration can cause wear by interfering with the production of a homogeneous lubricating coating and increasing particle–particle contact.

Table 4 Comparison of Different Lubricant Systems

Lubricant system	Minimum WSD (mm)	% Reduction vs. Castor Oil
Castor oil	0.4067	—
castor oil+ Al_2O_3	0.3875	4.70%
castor oil+ TiO_2	0.3182	21.80%
castor oil+ Al_2O_3 – TiO_2	0.3358	17.40%

The comparison of different nanoparticle formulations in castor oil shows that both individual and hybrid nanoparticles improve its tribological performance. Al_2O_3 nanoparticles yield a moderate improvement; however, TiO_2 nanoparticles achieve the greatest reduction in WSD. The hybrid Al_2O_3 – TiO_2 formulation offers intermediate performance by combining the distinct tribological mechanisms of Al_2O_3 and TiO_2 nanoparticles.

Four-ball wear test findings reveal that adding Al_2O_3 – TiO_2 hybrid nanoparticles to the base oil can increase or decrease anti-wear performance, depending on the particle-size-concentration combination. The conflicting effects of tribofilm development, particle-mediated rolling/mending action, and particle agglomeration can account for this non-monotonic behavior, which is consistent with mechanisms commonly reported for nanoparticle-based lubricant additives.

IV. CONCLUSION

The tribological analysis shows that adding nanoparticles can effectively improve castor oil's anti-

wear capabilities. Al_2O_3 nanoparticles reduced WSD, albeit only slightly, compared with pure castor oil. TiO_2 nanoparticles showed the best performance, with a minimum WSD of 0.3182 mm at a concentration of 0.75 wt%.

The Al_2O_3 – TiO_2 hybrid nano lubricant showed a minimum WSD of 0.3358 mm using 30–50 nm Al_2O_3 at 0.75 wt.% concentration, resulting in approximately 17.4% lower WSD than castor oil. The hybrid Al_2O_3 – TiO_2 formulation reduced WSD by approximately 19.7% as compared with Al_2O_3 alone under the corresponding condition. Therefore, the combination of Al_2O_3 with TiO_2 is an effective strategy for improving the wear resistance of castor-oil-based lubricants. Since TiO_2 alone exhibited a lower minimum WSD than the hybrid formulation, further optimization of the nanoparticle ratio and concentration is required before concluding that a synergistic effect exists.

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