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TRIBOLOGICAL PERFORMANCE EVALUATION OF TMPTO BASED NANO-LUBRICANTS

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ABSTRACT

In recent years, nano lubricants have gained significant attention due to their potential to enhance lubricant efficacy and reduce friction and wear. This research work aims to investigate the effects of TiO2 nanoparticles into trimethylolpropane trioleate (TMPTO) based bio-lubricant on its friction and wear characteristics. The four-ball tester is employed to evaluate the lubricating performance of the TMPTO-TiO2 nano-lubricant at varying additive concentrations under controlled conditions of speed, load, and temperature. The parameters were ranked based on the results of the Taguchi experiments and their corresponding single-to-noise ratios. The combination of TMPTO base oil and TiO2 nano-lubricant exhibited a synergistic effect in diminishing friction and wear. This research aligns with the growing demand for environmentally friendly and efficient lubrication solutions in various metalworking industries. Further investigation of the wear mechanism under TMPTO oil-based nano lubricants and its applicability in high-speed metal cutting applications is suggested.

Keywords: *Trimethylolpropane trioleate, Coefficient of friction, Wear Scar, ANOVA, TiO2.*

1. INTRODUCTION

The tribological properties and overall performance of vegetable-based lubricants can be improved by exploring advanced additive technology and chemical modifications. With further research and innovation, vegetable-based lubricants have the potential to replace mineral-based oils, offering environmentally friendly alternatives [1]. The Four Ball Tester is a commonly used apparatus for evaluating the performance of additives and their synergy in lubricating oils. By improving the anti-wear and extreme-pressure properties of lubricating oils through additives, the performance and durability of the lubricants can be significantly enhanced, meeting the demands of heavy metalworking industries [2-3].

Trimethylolpropane trioleate (TMPTO) is a vegetable-based lubricant that can potentially reduce environmental pollution compared to mineral oils. TMPTO is synthesized through the esterification of oleic acid (OA) and trimethylolpropane (TMP) [4]. Including sulfurized vegetable oil-based additives combined with TMPTO in the lubricating oil formulation enhances its tribological performance. It leads to improved efficacy, as evidenced by higher weld loads, improved load wear index values, and reduced anti-wear scar diameters [5-6]. These performance indicators indicate that the lubricating oil with the blend of additives provides better protection, reduces wear, and enhances the durability of the lubricated components in various industrial applications. Graphene and boron hexagonal nitride nanoparticles positively reduce friction between surfaces when incorporated into lubricating systems [7-9]. The exact mechanisms of friction reduction with nanoparticles can vary and may depend on the size of nanoparticles, their concentration, dispersion, and interaction with the lubricant and surfaces. Understanding the influence of surface roughness and lube oil viscosity on lubrication regimes and oil film thickness is crucial for selecting appropriate vegetable oil-based lubricants and optimizing additive types to minimize friction, wear, and energy losses in various mechanical systems [10]. An appropriate base stock selection is essential to achieve additive synergy and optimum formulation pertaining to specific applications [11-12].

This research work focuses on the tribological performance evaluation of Trimethylolpropane Trioleate (TMPTO) based oil and TiO2 nano-lubricant using a four-ball tester in order to optimize the nano-lubricant formulations for improved friction reduction and wear protection.

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2. Materials and Method

2.1 Lubricants

The base oil selected for the bio-lubricant formulation is TMPTO due to the superior fatty acid composition, which was procured from Subhash Chemicals Pvt. Ltd., Pune. The physical properties of TMPTO as per the suppliers' catalogue are shown in Table 1.

Table 1 Physical Properties of TMPTO Base Oil

Item	Specifications
Appearance	clear liquid
Viscosity (mm^2/s) at 40^0C	45-55
Viscosity Index	180-183
Acid Value (mg KOH/g)	1 Max
Flash Point (^0C)	290 Min
Pour Point (^0C)	30 Max
Hydroxy Value (mg KOH/g)	10 Max
Saponification Value (mg KOH/g)	185-190

Using ultrasonication, TiO2 nanoparticles (with 0.5%, 1% and 1.5% concentration) are uniformly dispersed in TMPTO base oil. Stir the mixture for an appropriate duration to ensure complete mixing and stability of the sample.

2.2 Test Balls

A 12.7 mm diameter AISI 52100 steel balls with 64–66 Rc were used for tribological evaluation of formulated lube oil on four ball tester. A standard test ball with EP grade having Young's modulus 200GPa, Density 7.81 g/cm3 and Poisson's ratio 0.3 was used.

3. Experimentation

3.1 Four-Ball Wear Test

The anti-wear performance of TMPTO with TiO_2 additives at different concentrations was evaluated using a DUCOM TR-30L four-ball tester. The test duration is 60 Minutes, test load 392N, rotational speed 1200 rpm and temperature 75^0C were set according to wear-preventive (ASTM D 4172). The test results are shown in section 4.1.

3.2 Experimental Design

Further experiments were planned using Taguchi's design of experiments [L_9 Orthogonal Array]. The factors under consideration and their levels are shown in Table 2. L_9 OA was selected to evaluate the effect of percentage TiO_2 concentration, load, speed and temperature. The responses measured were coefficient of friction and wear.

Table 2 Different Levels of Variables

Factors	Levels		
	I	II	III
Type of Oil	Type A (0.5% TiO_2)	Type B (1% TiO_2)	Type C (1.5% TiO_2)
Load (N)	392	588	785
Speed(rpm)	400	600	800
Temp. (^0C)	35	45	55

4. Results and Discussion

4.1 Anti-wear test performance

To assess the efficacy of TiO_2 with respect to base oil in preventing wear, the average wear scar diameter (AWSD) was measured on the surface of the lower three balls. The results are depicted in Fig. 1.

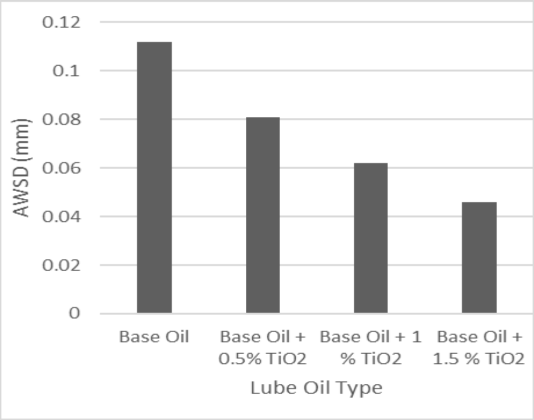

Fig. 1 Effect of additive concentration on AWSD

TiO_2 nanoparticles can form a protective film on the surfaces, reducing metal-to-metal contact and leading to better lubrication and reduced wear on critical components. It is observed that adding TiO_2 nanoparticles improves the thermal stability of the lubricant, making it more resistant to high temperatures and reducing the risk of oil degradation under extreme operating conditions.

4.2 Analysis of Data

A Taguchi [L9] test was conducted to identify the significant parameters affecting friction and wear coefficients. The scatter around a target value was quantified using the signal-to-noise ratio (S/N). The Taguchi loss function was employed, which represents the Mean Square deviation and S/N ratio.

$$S/N = -10 \log(MSD) \qquad (1)$$

Where MSD = Mean Square Deviation.

For Smaller is better,

$$MSD = \frac{K_1^2+K_2^2+K_3^2+\cdots\cdots K_n^2}{n} \qquad (2)$$

Where n is the number of observations and K is the observed data.

4.2.1 Analysis of Coefficient of Friction

The friction coefficient under lubricated conditions is directly recorded from four-ball tester. The tests were replicated to allow the analysis of the variance of the results. Using MINITAB, Taguchi Design Software, S/N ratios were calculated for the coefficient of friction, as shown in Table 3.

Table 3 Experimental results for Coefficient of Friction

Type of Oil	Load (N)	Speed (rpm)	Temp (^{0}C)	COF (μ_1)	COF (μ_2)	SN Ratios
Type A	392	400	35	0.078	0.074	22.38
Type A	588	600	45	0.075	0.077	22.38
Type A	785	800	55	0.085	0.082	21.56
Type B	392	600	55	0.060	0.061	24.44
Type B	588	800	35	0.073	0.068	23.03
Type B	785	400	45	0.071	0.072	23.10
Type C	392	800	45	0.080	0.100	20.86
Type C	588	400	55	0.085	0.087	21.31
Type C	785	600	35	0.091	0.089	20.96

The parameters were ranked and presented in Table 4, indicating their respective positions. In this table, the Delta value represents the proportionate change in the signal-to-noise (S/N) ratio. The analysis of variance results is displayed in Table 5, providing further insights into the study.

Table 4 Response Table for S/N ratios (for CoF)

Level	Type of Oil	Load (N)	Speed (rpm)	Temp. (°C)
1	22.11	24.19	22.99	23.16
2	23.52	22.96	23.63	23.75
3	24.44	22.91	23.45	23.16
Delta	2.33	1.28	0.65	0.59
Rank	1	2	3	4

Table 5 Analysis of Variance for Coefficient of Friction

Source	DF	Adj SS	Adj MS	% Cont.
Type of Oil	2	0.000508	0.000254	68.37
Load	2	0.000166	0.000083	22.34
Speed	2	0.000035	0.000018	04.71
Temperature	2	0.000034	0.000017	04.58
Error	0			
Total	8	0.000743		

The analysis of variance demonstrates that the type of oil, specifically the concentration of TiO_2 nano additive, has the most significant impact on reducing the coefficient of friction. Following this, load, speed, and temperature factors also contribute to the overall reduction within the selected range of parameters. To visualize the relationship between the signal-to-noise (S/N) ratios and the various parameters, a main effect plot has been presented in Figure 2.

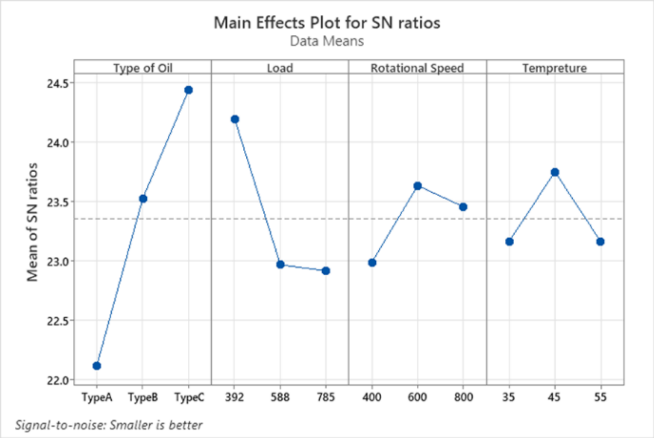

Fig. 2 The Main effect plot for S/N ratios (Friction)

4.2.1 Analysis of Wear

Average wear scar diameter (AWSD) was directly measured on the surface of the lower three balls through a machine vision system interface with four ball tester. The experiments were conducted in duplicate to enable variance analysis.

Table 6 Results for Wear experiments

Type of Oil	Load (N)	Speed (rpm)	Temp. (^{0}C)	WSD$_1$ (mm)	WSD$_2$ (mm)	SN Ratios
Type A	392	400	35	0.523	0.533	5.55
Type A	588	600	45	0.623	0.622	4.12
Type A	785	800	55	0.721	0.730	2.79
Type B	392	600	55	0.512	0.520	5.75
Type B	588	800	35	0.551	0.543	5.24
Type B	785	400	45	0.580	0.601	4.57
Type C	392	800	45	0.498	0.497	6.06
Type C	588	400	55	0.533	0.529	5.50
Type C	785	600	35	0.545	0.540	5.31

Table 7 Response Table for S/N ratios (Wear)

Level	Type of Oil	Load (N)	Speed (rpm)	Temp. (^{0}C)
1	4.150	5.786	5.206	5.366
2	5.187	4.952	5.059	4.919
3	5.625	4.224	4.697	4.677
Delta	1.474	1.562	0.509	0.689
Rank	2	1	4	3

Table 8 Analysis of Variance for Wear

Source	DF	Sum of Squares	Adj. MS	% Contribution
Type of Oil	2	3.4396	1.7198	41.70
Load	2	3.6633	1.8316	44.41
Speed	2	0.4120	0.2060	04.99
Temperature	2	0.7334	0.3667	08.89
Error	0			
Total	8	8.2483		100.00

Tables 7 and 8 illustrate the ranking and contribution of individual parameters in determining wear. Meanwhile, Figure 3 presents a main effect plot for SN ratios. The analysis reveals that wear scar diameter tends to increase with load, rotational speed, and temperature, but it decreases as the concentration of TiO$_2$ in TMPTO base oil increases. Based on the ANOVA analysis, it is evident that Load accounts for approximately 44% of the wear increase, while the type of oil (specifically, TiO2 concentration) contributes to approximately 42% of the wear reduction.

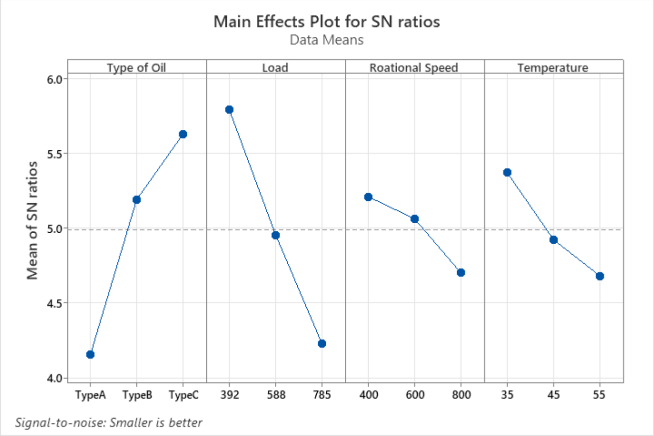

Fig. 3 The Main effect plot for S/N ratios (Wear)

5. Conclusion

The study highlights the effectiveness of TiO$_2$ nano additives in reducing friction and wear and suggests the potential of TMPTO-based oil with additives for industrial applications.

TiO$_2$ nano additive significantly reduces the coefficient of friction and wear scar diameter in the four-ball Anti-wear (AW) test. The use of Taguchi's design of experiments approach successfully facilitated the analysis of the frictional characteristics of TMPTO-based nano lubricants. The TiO$_2$ nano additive significantly reduces friction coefficient, followed by load, speed, and temperature.

Load and the type of oil contribute over 40% to the reduction of wear, while temperature contributes 8.89% and speed contributes 4.99%. TMPTO-based oil with additives is an environmentally friendly lubricating oil suitable for extensive use in the heavy metalworking industry. Future investigations should focus on exploring TMPTO-based oil with different additives and studying their synergistic effects.

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