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EVALUATION OF FLASH TEMPERATURE PARAMETER IN TMPTO-BASED NANO-LUBRICANTS

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Abstract

Flash Temperature Parameter (FTP) is the temperature at which a lubricant ceases to function effectively, leading to metal-to-metal contact, increased friction, wear, and possible equipment failure. This study explores the impact of TiO2 nanoparticles in trimethylolpropane trioleate (TMPTO)-based bio-lubricants on the Flash Temperature Parameter. A four-ball tester assesses the Anti-Wear Scar Diameter (AWSD) of TMPTO-TiO2 nano-lubricants at varying concentrations under controlled speed, load, and temperature conditions. The FTP is determined from the average AWSD measured on the bottom three balls. Results from Taguchi experiments and corresponding signal-to-noise ratios were used to rank the parameters. The combination of TMPTO base oil and TiO2 nanoparticles synergized to enhance FTP. FTP assesses a lubricant's performance under high load and temperature conditions, such as in rolling mills and cutting processes. This research may benefit specialty lubricant manufacturers. Further studies on the wear mechanisms of TMPTO-based nanolubricants and their potential for high-speed metal cutting applications are recommended.

Keywords: *Trimethylolpropane trioleate, Flash Temperature Parameter, ANOVA, Taguchi.*

1. Introduction

Flash Temperature Parameter (FTP) is critical in tribology and lubrication engineering. It is associated with the critical flash temperature (CFT), the threshold above which a lubricant fails to function effectively under the applied conditions. Beyond this temperature, the lubricant may lose its lubricating properties, leading to metal-to-metal contact, increased friction, wear, and potential equipment failure. The Flash Temperature Parameter (FTP) represents the heat from friction during sliding contact between surfaces. The Critical Flash Temperature (CFT) refers to the maximum temperature at which a lubricant can effectively maintain lubrication without breaking down or causing excessive wear. FTP is key in selecting lubricants for high-load or high-speed applications where friction-induced temperature rise is significant. It is influenced by load, contact surface speed, lubricant composition, thermal stability, and material properties.

Applying advanced additive technologies and chemical alterations can enhance vegetable-based lubricants' tribological behavior and overall efficiency. Continued research and innovation could enable vegetable-based lubricants to serve as sustainable alternatives to mineral-based oils, contributing to more eco-friendly lubrication solutions [1]. The Four Ball Tester is widely used to assess additive performance and synergy in lubricating oils, enhancing anti-wear and extreme-pressure properties to meet heavy metalworking industry demands [2-3].

Trimethylolpropane trioleate (TMPTO), a vegetable-based lubricant synthesized from oleic acid and trimethylolpropane, offers reduced environmental impact compared to mineral oils. Blending sulfurized vegetable oil-based additives with TMPTO improves tribological performance, demonstrated by higher weld loads, better load wear index values, and smaller anti-wear scar diameters. This additive combination enhances wear protection, durability, and component longevity in industrial applications [4-6].

When added to lubricating systems, various nanoparticles, including TiO2, boron nitride, and graphene, effectively reduce friction between surfaces. Friction reduction with nanoparticles depends on their size, concentration, dispersion, and interaction with lubricants and surfaces. Surface roughness and oil viscosity influence lubrication regimes and film thickness, which are key for selecting vegetable oil-based lubricants and optimizing additives to minimize friction, wear, and energy losses [7-13]. The tribological performance of TMPTO-based lubricants for high-speed drilling of Al-6061, evaluated using ASTM standards, showed high seizure load with sulfurized vegetable oils. A Taguchi-based experiment identified spindle speed, feed rate, and additive concentration as key torque

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factors, while feed rate primarily influenced thrust force [14].

This study evaluates the Flash Temperature Parameter of Trimethylolpropane Trioleate (TMPTO)-based oil blended with TiO2 nano-lubricant using anti-wear scar diameter measurements from a four-ball tester.

2. Materials and Methods

2.1 Lubricants

The base oil chosen for the formulation of the bio-lubricant is Trimethylolpropane Trioleate (TMPTO) due to its superior fatty acid composition, which enhances the lubricant's performance characteristics. The TMPTO was procured from Subhash Chemicals Pvt. Ltd., Pune. The physical properties of TMPTO, as provided in the supplier's catalogue, are presented in Table 1.

Table 1 Physical Properties of TMPTO Base Oil

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

TiO_2 nanoparticles, at concentrations of 0.5%, 1%, and 1.5% by weight, were uniformly dispersed in the TMPTO base oil using ultrasonication. The mixture was stirred appropriately to ensure thorough dispersion and stability of the prepared samples.

2.2 Test Balls

Tribological evaluation of the formulated lubricant was conducted using a four-ball tester with AISI 52100 steel balls of 12.7 mm diameter and hardness in the range of 64–66 Rc. The test balls were of EP grade and possessed a Young’s modulus of 200 GPa, 7.81 g/cm^3 density, and a Poisson’s ratio of 0.3, ensuring consistent and reliable test conditions.

2.3 Methodology

The critical flash temperature defines the point beyond which a lubricant loses its effectiveness under the specified operating conditions. Various models for calculating the flash temperature parameter (FTP) have been presented in the literature, with the authors selecting the equation proposed by Marcher [15]

$$FTP = \frac{P}{WSD^{1.4}} \tag{1}$$

P denotes the load applied during the four-ball tribotester test (in N). WSD represents the mean wear scar diameter measured across six stationary balls during a single test cycle. At a constant load, FTP decreases as the wear scar diameter increases and correlates with the heat generated due to friction. The mean wear scar diameter (WSD) of TMPTO blended with varying concentrations of TiO_2 additives was measured using a DUCOM TR-30L four-ball tester. A schematic diagram of a four-ball tribo-tester is shown in Figure 1. The test was performed for 60 minutes under a load of 392 N, a rotational speed of 1200 rpm, and a temperature of 75°C, following the wear-preventive standard ASTM D4172.

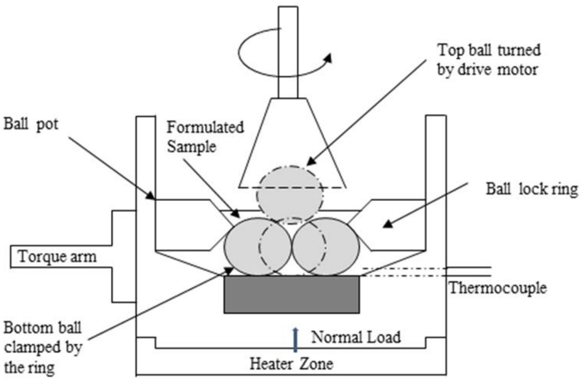

Figure 1 Schematic diagram of a four-ball tribometer

3. Experimentation: Magnesium-based nanocomposites

3.1 Selection of Factors and their levels

The experiments were designed following Taguchi’s methodology using an L9 Orthogonal Array (OA). The factors considered and their corresponding levels are presented in Table 2. The L9 OA was chosen to assess the influence of TiO_2 concentration, applied load, rotational speed, and temperature on the system's performance. The Flash Temperature Parameter (FTP) was determined using the average wear scar diameter (WSD) measurements.

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. (^{0}C)	35	45	55

3.2 Experimental Results

FTP (Flash Temperature Parameter) for a lubricant represents the minimum temperature at which the liquid begins to evaporate, posing a risk of auto-ignition in air. A high FTP is advantageous as it indicates the lubricant resists evaporation at lower temperatures, maintaining a sufficiently thick fluid film to minimize friction and prevent direct asperity contact. Consequently, friction-generated heat remains low. These conditions of reduced friction and lower temperatures can also signify boundary lubrication. High FTP values are beneficial, as they prevent evaporation, ensure a thicker fluid film, reduce friction, and minimize asperity contact. This helps control heat generation and supports boundary lubrication. Conversely, a low FTP suggests fluid film degradation, which can compromise lubrication performance. Hence, “larger is better” is set as an objective function for measurement of FTP. To assess the flash temperature parameter, the average wear scar diameter (AWSD) was measured on the surface of the lower three balls. A Taguchi [L_9] experiment was performed to identify the key parameters influencing the Flash Temperature (FTP). The scatter around the target value was assessed using the signal-to-noise ratio (S/N). The Taguchi loss function was applied, representing the Mean Square Deviation (MSD), which in turn was used to calculate the S/N ratios.

$$S/N = -10 \log (MSD) \tag{2}$$

Where MSD = Mean Square Deviation.

For Larger is better:

$$MSD = \frac{1/{K_1}^2 + 1/{K_2}^2 + 1/{K_3}^2 + \cdots\cdots\cdots\cdots 1/{K_n}^2}{n} \tag{3}$$

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

Table 3 Experimental results for FTP

Type of Oil	Load (N)	Speed (rpm)	Temp (^{0}C)	FTP N/mm$^{1.4}$	FTP N/mm$^{1.4}$	SN Ratios
Type A	392	400	35	971	946	59.60
Type A	588	600	45	1140	1143	61.14
Type A	785	800	55	1241	1206	61.74
Type B	392	600	55	1001	979	59.91
Type B	588	800	35	1354	1382	62.72
Type B	785	400	45	1683	1601	64.29
Type C	392	800	45	1040	1043	60.35
Type C	588	400	55	1419	1434	63.11
Type C	785	600	35	1836	1831	65.26

4. Discussion

The average wear scar diameter (AWSD) from the bottom three balls was measured based on the test results obtained using the four-ball tester. The flash temperature parameter was then calculated from the AWSD using equation (1). To ensure statistical reliability, the tests were repeated for variance analysis. The signal-to-noise (S/N) ratios were calculated using MINITAB Taguchi Design Software, as presented in Table 3. The parameters were ranked and shown in Table 4, with their respective positions. The Delta value represents this table's proportional change in the S/N ratio. The response table for S/N ratios shows the influence of four parameters—Type of Oil, Load, Speed, and Temperature—on the signal-to-noise ratio for FTP. Load has the highest Delta value (3.81), indicating it has the most significant impact on the S/N ratio, followed by Type of Oil (2.07), Temperature (0.95), and Speed (0.74). The ranking confirms that Load is the most influential factor, while Speed has the least impact. Higher S/N ratios are generally preferred, indicating better performance with lower variability. Further insights into the study are provided by the analysis of variance results shown in Table 5.

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

Level	Type of Oil	Load (N)	Speed (rpm)	Temp. (^{0}C)
1	60.84	59.96	62.35	62.54
2	62.31	62.33	62.11	61.93
3	62.91	63.77	61.61	61.59
Delta	2.07	3.81	0.74	0.95
Rank	2	1	4	3

Table 5 Analysis of Variance for FTP

Source	DF	Adj SS	Adj MS	% Cont.
Type of Oil	2	168654	84327	22.99
Load	2	488850	244425	66.65
Speed	2	30435	15217	04.15
Temperature	2	45539	22769	06.21
Error	0			
Total	8	733477		100

The ANOVA table for FTP reveals that Load is the most influential factor, contributing 66.65% to the variation in the response variable, followed by Type of Oil at 22.99%. Temperature and Speed have lesser impacts, contributing 6.21% and 4.15%, respectively. The absence of an error term suggests either a perfect data fit or no replication. Load plays the dominant role, while Speed and Temperature have minimal influence on the response variable. A main effects plot has been presented in Figure 2 to illustrate the relationship between the signal-to-noise (S/N) ratios and the various parameters.

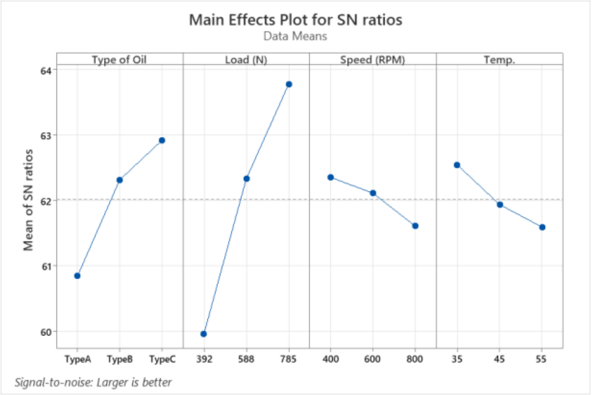

Figure 2 The Main effect plot for S/N ratios (FTP)

The main effects plot (Fig. 2) indicates that Type C oil, the highest load (785 N), the lowest speed (400 RPM), and the lowest temperature (35°C) result in the highest S/N ratios, suggesting optimal performance. Load has the most significant positive impact, followed by oil type, while increasing speed and temperature reduce the S/N ratio. Higher S/N ratios indicate better performance with lower variability, making these conditions ideal for optimization.

5. Conclusion

In conclusion, the study demonstrated that the load, type of oil, temperature, and speed significantly influence the Flash Temperature Parameter (FTP). Among these, load was identified as the most influential factor, contributing 66.65% to the variation in FTP values, followed by the type of oil at 22.99%, while temperature and speed exhibited minimal influence with 6.21% and 4.15% contributions, respectively. The response analysis revealed that a higher load, Type C oil (1.5% TiO_2 concentration), lower speed (400 RPM), and lower temperature (35°C) resulted in the highest signal-to-noise (S/N) ratios, indicating optimal tribological performance. Using TMPTO blended with TiO_2 nanoparticles improved anti-wear properties, as reflected in the reduced wear scar diameter and enhanced FTP values. The findings suggest that optimized lubrication conditions can be achieved by carefully selecting load and additive concentration, making TMPTO-based nano-lubricants effective for high-load, high-speed applications where friction and wear control are critical. Further research with a broader range of nanoparticle types and concentrations could provide deeper insights into enhancing lubrication efficiency and sustainability.

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