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Taguchi-Grey Optimization of Tribological Characteristics of Blended SAE 40 Lubricant

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Abstract

A high proportion of lubricants used in automobile engines are mineral-based oil. The depletion of oil reserves and the concerns (non-biodegradable, toxic and environmental issues) of mineral based lubricants prompted the research for a viable alternative. Vegetable oil has been proposed as a potential substitute for the mineral-base lubricants due to its natural and eco-friendly characteristics. In this study, optimization of tribological characteristics of blended SAE 40 produced from SN 500 mineral oil, Shea butter bio-base oil, and viscosity improver was carried out on pin-on-disc tribometer. Taguchi and Taguchi-grey relational method were used to optimize the load and sliding speed to obtain the minimum specific wear rate and coefficient of friction (COF) for the blended SAE 40. The optimum parameters using Taguchi's and Taguchi-grey relational analysis methods are 8 N load and 5 cm/s sliding speed. At this optimum condition, the minimum specific wear rate of 0.007 mm^3/Nm and minimum coefficient of friction of 0.001 were observed. The developed mathematical model was validated against the experimental results. Deviation of about 5% was obtained in the wear rate model using Taguchi model. Also, the correlation of about 89.77% was observed between the model developed using Taguchi-grey relational model and experimental values. This implies that the two models can be used to predict the tribological properties of blended SAE 40 lubricant.

1.0 Introduction

Bio-lubricants are generally seen as biodegradable, harmless, and eco-friendly lubricants obtain from renewable resources such as plant oils and animal fats (Chan et al., 2018). Using bio-lubricant in automobile engines is not feasible now, due to its low viscosity. There are also concerns about friction and wear of engine parts when blending bio-lubricant and mineral base oil. The engine load and speed has been reported to have significant effect on engine wear rate. These factors (i.e., engine load and speed) has to be optimized to give minimum wear rate and coefficient of friction in order to maximize the engine efficiency. The optimization techniques applied for engine analysis includes: artificial neural network (ANN), simplex method, Taguchi method, response surface method (RSM) and genetic algorithm (GA) (Ganapathy et al., 2009). The technique that gained attention for decades by researchers is the Taguchi's method, based on its accuracy in the optimization of single response parameter (Jena et al., 2020a). Some research findings on optimization are : Dzierwa et al. (2022) used Taguchi method to test steel elements tribological properties. The results showed that load was the major parameter influencing wear and coefficient of friction. Taguchi method was used for the optimization of hybrid carbon-epoxy composites by (Divya et al., 2021). It was established for the hybrid composite that the lowest specific wear rate and friction coefficient are 3 wt% $nSiO_2$. The performance of vegetable oil using Taguchi method in a milling operation was investigated by Afonso et al. (2022). The vegetable oil had lubricating properties similar to conventional cutting fluid. Singh (2022) used Taguchi method to investigate dry sliding wear in aluminum nanocomposites. It was found that 5-wt% TiO_2 + 5-wt% Y_2O_3 nanocomposite showed excellent tensile strength and micro hardness. Taguchi-Grey method was use to optimize the tribo properties under wet condition of worm gear by (Bhat et al., 2021). The optimal parameters were speed load 75 N, time 1800 s and speed 800 rpm. Kumar et al. (2022) optimized using Taguchi method, the wear properties of composite metal matrix. The weight fraction was found to have greatest impact on the wear behavior. Singh et al. (2015) optimized using Taguchi method the blends of pongamia oil as engine lubricant additive. The optimum result was 1st, 2nd and 3rd level for wear rate, pin weight loss, and friction coefficient. Chowdhury et al. (2014) optimized via Taguchi method to the production parameters of biolubricant. The optimum conditions were reaction time 3 h, temperature 60, molar ratio of actanol: free fatty acid = 2.5:1. To overcome the limitations of Taguchi's method, Grey analysis was employed as a method to relate multi-response optimization. The combine application of hybrid Taguchi-Grey method approach was used by Chougale et al. (2021) to optimize the process parameters of lubricant oil in worm gearbox. The optimum levels were determine as the lowest, intermediate levels of load, volume of oil respectively and oil Type B. Taguchi-Grey method was use to optimize the tribo parameters under wet condition of worm gear by (Bhat et al., 2021). The optimal parameters were speed load 75 N, time 1800 s and speed 800 rpm. Cesur et al. (2021) optimized via Taguchi method and ANN and model wear in rings of piston and liner of cylinder. The biodiesel fuel had a lower abrasion and friction coefficient. The Taguchi and Taguchi-Grey analysis method was adopted in this study to optimize the load and sliding speed for minimum coefficient of friction (COF) and specific wear rate using a SAE 40 blended lubricant. The blended lubricant here referred to a mixture of Shea butter bio-base oil, SN 500 mineral oil and viscosity improver. The test was carried out on the pin-on-disc tribometer. ANOVA statistical tool was used to evaluate the percentage contribution of the optimized parameters (i.e. load and sliding speed). Mathematical models developed was used to predict the coefficient of friction (COF) and specific wear rate.

1.1 Design of Experiments (DOE)

The fundamental principles of DOE are random sampling, blocking, duplication, orthogonality and factorial experimentation. The aim of DOE is resulting optimization with the minimum available data (Agrawal et al., 2020). In this study DOE was used to optimized load and sliding speed as control factors.

1.2 Taguchi Method of DOE

Taguchi DOE studies control factors effects, reduce the number of experiments, and identify experimental conditions with orthogonal arrays (Sadriwala et al., 2019; Uslu et al., 2021). Based on Taguchi method, the two fundamentals' tools for DOE are signal-to-noise (S/N) ratio and orthogonal array (OA). To save cost and time of experiments, the OA functions as another form of factorial design that considers a chosen arrangement of several factors and several levels that depends on degrees of freedom, as calculated by equation 1 (Agrawal et al., 2020).

$$D.O.F. = 1 + \sum_{i=1}^{NV} (L_i - 1) \quad (1)$$

Where NV = number of independent variables

L_i= levels

D.O.F. =Degree of Freedom

While S/N ratio is a robustness measuring tool that minimize variability by reducing noise factors in a product or process. S/N ratio of higher values identify control factors levels that minimize noise factors (Uslu et al., 2021). Three categories of S/N ratio exist: smaller the better, nominal the better, and larger the better; that is dependent on the aim of the experiment and can be calculated by the equations below (Jena et al., 2020; Singh et al., 2015; Uslu et al., 2021). In this study, S/N ratios were generated for specific wear rate and COF as presented in equation 2. All control factors were varied simultaneously.

$$\frac{S}{N} = -log\frac{1}{n}(\Sigma_{i=1}^{n} y^2) \quad (2)$$

Where the observed response value is denoted by y, and n indicates number of replications. This is used where smaller value is desired. This study uses smaller the better criteria for the optimization of COF and specific wear rate via Taguchi method as shown in equation 3.

$$\frac{S}{N} = -log\frac{1}{n}\left(\frac{\mu^2}{\sigma^2}\right) \quad (3)$$

Where σ indicates the variance, and μ indicates mean. This criterion is best used for nominal variation as given in equation 4.

$$\frac{S}{N} = -log\frac{1}{n}\left(\Sigma_i^n \frac{1}{y^2}\right) \quad (4)$$

Where observed response value is denoted by y, and n indicates number of replications. In this study, larger the better was used to optimize grey relational grade.

For attaining maximum response, the S/N ratio of optimal conditions can be predicted, it can be estimated by using equation 5 (Chowdhury et al., 2014). In this study, the optimal COF and wear were predicted.

$$\frac{S}{N_{predicted}} = \frac{\bar{S}}{N} + \sum_{j=1}^{n}\left(\frac{S}{N_j} - \frac{\bar{S}}{N}\right) \quad (5)$$

Where $\bar{S}/N$ represents mean of all S/N ratios, S/N_j represents optimal level S/N ratio of each control factor, n stands for number of the process parameter that affects the process tangibly. (Jena et al., 2020) reported that Taguchi method is limited to problems where only a single response is optimized. This study involves optimization of more than a single response; therefore, Taguchi-Grey method can relate two different responses to generate a single response.

1.3 Grey Relational Analysis

Grey relational method optimizes more than one response problem, it identifies the important factors and their existing relationships (Jena et al., 2020; Rao & Rao, 2016). In grey relational analysis, when the "larger the better" criteria is use for optimization, then equation 6 will be used to optimize the original sequence as given by (Rao & Rao, 2016)

$$x_i(k) = \frac{y_i(k) - miny_i(k)}{maxy_i(k) - miny_i(k)} \quad (6)$$

However, if the "lower the better" criteria is use for optimization, then equation 7 will be used to optimize the original sequence as given by (Jena et al., 2020). The lower the better was applied to optimize specific wear rate and COF in this study.

$$x_i(k) = \frac{maxy_i(k) - y_i(k)}{maxy_i(k) - miny_i(k)} \quad (7)$$

Where $x_i(k)$ represents the normalize values for response, i=1,2,….m, $y_i(k)$ denotes actual reference sequence, $maxy_i(k)$ indicates highest value of $y_i(k)$, $miny_i(k)$ denotes lowest value of $y_i(k)$ of the response.

Grey relation coefficient (GRC) denoted as $\xi_i(k)$ presents the correlation joining expected output responses and actual experimental data. It follows that the GRC can be obtained using the equation 8 by (Jena et al., 2020; Rao & Rao, 2016). In this study GRC was obtained for COF and specific wear rate.

$$\xi_i(K) = \frac{\Delta_{min} + \Psi\Delta_{max}}{\Delta_{oi}(k) + \Psi\Delta_{max}} \quad (8)$$

Where;

$$\Delta_{oi} = \left||x_o(K) - x_i(k)|\right| \quad (9)$$

Δ_{oi} denotes the deviation sequences, $\Delta_o(k)$ represents the ideal sequence, Δ_{min} and Δ_{max} denotes the lowest and highest value of the deviation sequences Δ_{oi}, where $\Delta_{oi}(k)$ represents the deviation sequence actual starting point, and Ψ is called distinguishing coefficient whose value is between the range $0 \leq \Psi \leq 1$ depending on the experiment. The purpose of applying distinguishing coefficient is to dampen the effect of larger Δ_{max} values. Thus according (Jena et al., 2020b) Ψ = 0.5, similarly, in this study Ψ = 0.5.

1.4 Generation of Grey Relational Grade (GRG)

GRG is obtained via averaging the grey relationship coefficients as given in equation (10) below by (Jena et al., 2020; Rao & Rao, 2016). A higher value of GRG shows greater dependency between the ideal sequence $x_o(k)$ and the given sequence $x_i(k)$. Ideal sequence $x_o(k)$ in the experimental arrangement is then assumed as the best response. Appropriate weighting factor (β) is assigned to each response depending on relative magnitudes and summation of weighting factor is always equal to 1. In this study, equal weighting factor was attributed to the responses; 0.5 to COF, 0.5 to specific wear rate

$$y_o = \sum_{k=1}^{n} \xi_i(k)\beta y_i \ldots., \quad (10)$$

Where;

$\sum\beta = 1$

Higher GRG value implies closer optimal setting for the corresponding grouping of control parameters. The factor setting that gave the highest GRG value is regarded as optimal. In this study, GRG was obtained for the multiple response.

2.0 Methodology

2.1 Control Parameters

In this study, two control parameters having two levels were chosen. This selection was based on the maximum and minimum operating conditions of the tribometer. They factors considered and their levels are shown in Table 1. Minitab 19 software was used to generate the L4 orthogonal array as applied. The experimental runs are shown in Table 2, two columns load (N) and speed (cm/s), each consists of four levels of combination. Responses taken during the experiment were specific wear rate (mm^3/Nm), and COF.

Table 1: Factors and levels for Taguchi DOE

Factors	Levels	
	I	II
Load (N)	8	3
Speed (cm/s)	15	5

Table 2: Taguchi L4 Orthogonal array experimental layout

Experiments	Load (N)	Speed (cm/s)
1	8	15
2	8	5
3	3	15
4	3	5

2.2 ANOVA

The percentage contribution of load and sliding speed was evaluated by ANOVA statistical analysis based on tribological responses of the blended SAE 40. Equations 11, 12 and 13 were used to compute R^2, predicted R^2 (Pred-R^2) and adjusted R^2 (Adj-R^2) values respectively (Uslu et al., 2021).

$$R^2 = 1 - \left[\frac{SS_{residual}}{SS_{residual} + SS_{model}}\right] \quad (11)$$

$$Adj.R^2 = 1 - \left[\frac{\left(\frac{SS_{residual}}{df_{residual}}\right)}{\left(\frac{SS_{residual} + SS_{model}}{df_{residual} + df_{model}}\right)}\right] \quad (12)$$

$$Pred.R^2 = 1 - \left[\frac{\sum_{i=1}^{n}(e-1)^2}{SS_{residual} + SS_{model}}\right] \quad (13)$$

$$e - 1 = \frac{e_i}{1 - h_{ii}} \quad (14)$$

The residuals denote the volume of variation not explained in response, model denotes amount of variation accounted by the model with the general model test for significance.

2.3 Correlation Equation

Regression analysis technique was used to establish a mathematical connection between some dependent and independent variables. In a multiple regression, expressing dependent variables as functions of independent variables is given by (Agrawal et al, 2020) as seen in equation (15).

$$Z = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + \cdots + a_nx_n \quad (15)$$

Z denotes dependent variable, a_o to a_n represents equation coefficients for linear relation and x_1 to x_n are independent variables. To judge fit quality of the linear model, the coefficient of determination R^2 was used. In this study, linear regression equation was employed to relate control factors (load and speed) and responses (specific wear rate and COF).

2.4 Production of Shea Butter Bio-lubricant

Crude Shea butter was purchased from a vendor in Kontagora, Niger state, Nigeria. It has a milky colour and it exist as semi-solid at room temperature.

2.4.1 Degumming of Crude Shea Butter

2000 cm^3 of crude Shea butter was weighed in a 2 L beaker. 20 ml of phosphoric acid was poured into 200 ml of water, the mixture added to oil. The resulting mixture was heated to 90^0C for 1 hour and kept overnight to separate into two layers. The dirt settled at the bottom layer. The upper layer formed the degummed crude Shea butter.

2.4.2 Determination of Free Fatty Acid (FFA)

Sample oil of 1 g was weighed in a conical flask. 25 ml of propa-2-ol was poured to sample to dissolve the oil. Phenolphthalein two drops were added to the mixture. KOH with a molarity of 0.1 was poured in the burette and titrated against the sample oil prepared. After the color changes from yellow to pink, the initial and final readings were recorded, and the total average titre value was calculated. The procedure was repeated twice to get two more solutions as outlined above. The acid value was evaluated using equation 16.

$$Acid\ value = \frac{(Molarity\ of\ KOH \times molar\ mass\ of\ KOH \times titre\ value)}{mass\ of\ oil} \quad (16)$$

The % free fatty acid value was obtained from equation 17 below:

$$\%FFA = \frac{Acid\ value}{2} \quad (17)$$

2.4.3 Esterification of Shea Butter Oil

A weighing balance was used to weigh 1900 g of Shea butter oil inside conical flask. The flask with sample oil was placed on a magnetic stirrer, the content was agitated and heated to 60^0C. On attaining this temperature, 167. 9 g of Methanol and 3.7 g of Sulphuric acid was added to the heated oil using equation 18 and 19:

$$Amount\ of\ methanol = 2.25 \times \%FFA \times mass\ of\ oil \quad (18)$$

$$Amount\ of\ H_2SO_4 = 0.05 \times \%FFA \times mass\ of\ oil \quad (19)$$

Where 2.25 and 0.05 are defined constants

The mixture was agitated for 1 hour at a temperature of 60^0C, then poured into a separating funnel and left to settle overnight. Methanol, water, and H_2SO_4 floated on top of denser oil due to differences in densities. The oil was drained in a clean conical flask. This procedure was carried out to lower the %FFA to ≤0.5%. The %FFA of the esterified oil was calculated as outlined in equation 2 after every 1 hour until the value drops to ≤0.5%.

2.4.4 First Trans-esterification Process of Esterified Shea Butter Oil

The trans-esterification method outlined by Tulashie et al., (2018) was followed in this study. Three stages were involved: Acid catalyzed reaction, Neutralization reaction, and Alkaline catalyzed reaction.

- **Acid Catalyzed reaction**

1000 ml of Shea butter was poured into a 2000 ml beaker and heated to 65^0C, 680 ml of Methanol was added and stirred at 550-600 rpm. The mixture initially was stirred continuously for 5 minutes with addition 1 ml 95% H_2SO4 and the temperature was maintained at 65^0C. The stirring continued for 2 hours at 550-600 rpm and the mixture was transferred to separating funnel. 2 hours after, the content in the separating funnel settled and the upper layer containing methanol and water was discarded.

- **Neutralization reaction**

10 g of NaOH was measured and dissolved in 90 ml of methanol to get a solution of Sodium methoxide. It was gradually poured into the acid treated mixture at 65^0C and the corresponding mixture was gently stirred for 5 minutes. The mixture was moved into a separating funnel, it stayed till daybreak and the glycerin was drained off.

- **Alkaline catalyzed reaction**

The solution collected from neutralization reaction temperature was raised to 65^0C, while the remaining sodium methoxide solution was gradually added and stirred. The stirring continued for 1 hour and the entire mixture was again moved into a separation funnel. The mixture stayed for 48 hours after which the Shea methyl ester was drained off. It was washed with warm distilled water.

2.4.5 Double Transesterification with trimethylopropanol (TMP)

The double trans-esterification method outlined by (Agrawal et al., 2017) was followed in this study. Shea methyl ester was trans-esterified with trimethylopropane (TMP) and sodium methoxide (in 30% methanol) as catalyst. The Shea methyl ester-to-TMP molar ratio was 4:1, the catalyst used was 0.8% w/w of the total reactant and the reaction was maintained at a temperature of 110^0C for 3 hours in oil bath together with the stirrer. The reaction occurred under vacuum condition to hinder a backward reaction. TMP and oil methyl esters reacted with sodium methoxide catalyst at 110^0C under vacuum conditions, to produce TMP tri-esters that was considered as bio-lubricant. Methanol was continuously being removed from the reaction mixture.

2.5 Blending SAE 40

One of the mineral base oils used in the industry (SN 500 mineral oil) was obtained from ABY lubricants Kano, Nigeria. The most critical parameter for SAE 40 mono grade lubricant is the viscosity at 100^0C should lie between 12.5 - 16.3 cSt. The SN 500 mineral oil was blended with Shea butter bio-lubricant and viscosity improver in the ratio 7.5:1.5:1.0 v/v to produce SAE 40. The mixing ratio was based on the viscosity difference of base oils at room temperature. Then, a conventional SAE 40 was purchase from a local vendor in Zaria and used as a reference fluid. The SAE 40 produced was referred here as blended lubricant, and the conventional SAE 40 was referred to as conventional lubricant. The physicochemical properties of blended lubricant and conventional lubricant are presented in Table 3. ASTM standards D445, D2270 and D2004 were used to determine kinematic viscosity, viscosity index and density respectively. ASTM D97 and D93 were used to determine pour and flash point respectively.

2.6 Preparation of Pin and Disc Specimens

Anton-Paar pin-on-disc tribometer was used in this study to examine COF and specific wear rate. The machine has a maximum loading 10N and maximum disc rotating speed 15 cm/s. The samples used in this study were made from stainless steel and aluminum alloy and their physical properties are presented in Table 4. The pin sample is of dimension 6mm and ball geometry, the disc samples were 220mm diameter and 7mm thick. The same size and shape of disc was used throughout the experiment to present uniformity in measurements. The surfaces of the disc specimens were cleaned to remove dirt and debris before the experiment starts. The schematic image of the pin-on-disc setup and tribometer are shown in figures 1 and 2 respectively.

Table 3: Physico-chemical properties of blended lubricant and conventional lubricant

S/N	Property	Blended lubricant	Conventional lubricant
1	Kinematic Viscosity @ 40°C, cSt	93.91	130
2	Kinematic Viscosity @ 100°C, cSt	14.40	13.5
3	Density, g/cm^3	0.95	0.89
4	Viscosity index	158	99
5	Pour point °C	-7.9	-17
6	Flash point °C	230	270

Table 4: Physical properties of the pin and disc specimens

Property	Pin sample	Disc samples
Name	Stainless steel	Aluminium alloy A356
Manufacturing process	As-supplied	Machined, Ground and Polished
Surface finish	Mirror-finish	Mirror-finish
Test position and motion	Upper and rotating	Lower and stationary
Diameter, (mm)	6	22
Elastic modulus, (gpa)	200	
Hardness value, hv, (kg/mm^2)	600-800	70-105
Tensile strength, (n/mm^2)	500-1500	234
Poisson's ratio	0.3	0.33
Compression strength, (n/mm^2)	1000	185

2.7 Experimental Procedure

The computer was boot on and the Anton Paar's tribometer software was launched. The wet experiment was selected, the sliding speed =5 cm/s, load = 3 N and sliding distance =50 m was specified on the software. Then the disc specimen was secured to the disc sample holder on the tribometer. 2 ml of sample lubricant was evenly spread on the polished disc surface. Then the loading arm was loaded with a dead load =3 N. The loading arm was lowered until the pin made contact with the wet surface of the disc. Then the Ok button on the computer software was clicked to begin the experiment. The experiment stopped automatically as soon as the sliding distance was reached and the tribological properties were generated by the software and stored on the computer.

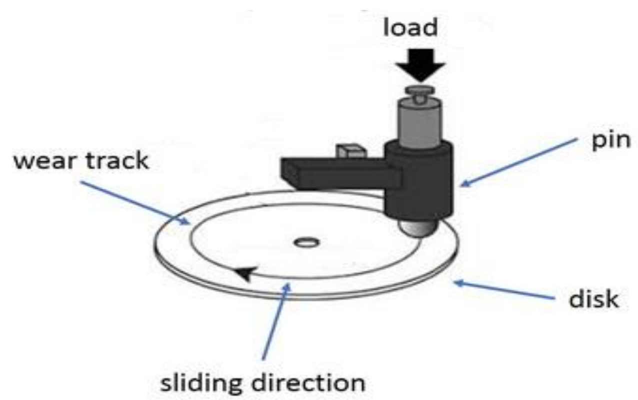


Figure 1: Schematic diagram of Pin-on-disc apparatus.

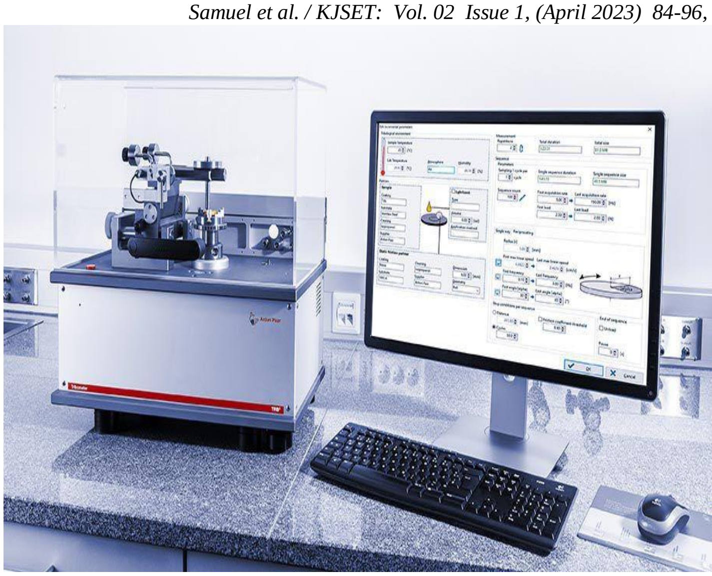


Figure 2: Pin-on-disc tribometer.

2.7.1 Friction and Wear Analysis

A load cell mounted on the pin-holding lever arm of the tribometer was used to measure the force of friction. The friction coefficient is evaluated using equation 20 given by (Syahrullail, 2014). The wear rate of the pin is measured by LVDT sensor and reported directly on the display monitor. The computation of specific wear rate was by the software using equation 21 by (Hanief & Mushtaq, 2020)

$$\mu = \frac{F}{N} \quad (20)$$

Where, F denotes the force of friction, μ denotes friction coefficient and N denotes the load acting normally.

$$Specific\ Wear\ Rate = \frac{Wear\ volume}{Load \times Sliding\ distance} \quad (21)$$

2.7.2 Wear scar diameter (WSD)

The WSD of the disc was measured at the stop of each experiment with a trinocular stereo zoom microscope attached to the pin-holding lever arm. A lens with 20,000 magnification was focus on the worn disc, until a clear image was caught on the display monitor.

3.0 Results and Discussion

3.1 Prediction of Control Factors

The experimental results for COF and specific wear rates (WR) with respect to the control factors are shown in Table 5. For each control factor at each level, the response table displays the average characteristic of the desired response in S/N ratios. Table 6-7 shows the S/N response tables for specific wear rate and coefficient of friction.

Table 5: Experimental output for specific wear rate and coefficient of friction

WR mm^3/Nm	COF	S/N WR	S/N COF
0.008366	0.095	41.5496	20.4455
0.007219	0.001	42.8305	60.0000
0.021620	0.099	33.3029	20.0873
0.015250	0.113	36.3346	18.9384

From Table 6, the minimum specific wear rate occurred at level 1 of load, i.e. 8 N, and level 2 of speed, i.e. 5 cm/s. This is because they gave the lowest S/N ratio 34.82 and 37.43 respectively. Based on the rank, load strongly influences the specific wear rate. Therefore, operating the lubricant blend at 8 N and 5 cm/s decreases the signal. It means more separation between the two metals in contact during the test leading to low wear rate 0.007219 mm^3/Nm as given in Table 5. Lower wear rate implies less material loss from contacting machine parts. This enables the machine to reach it useful service life.

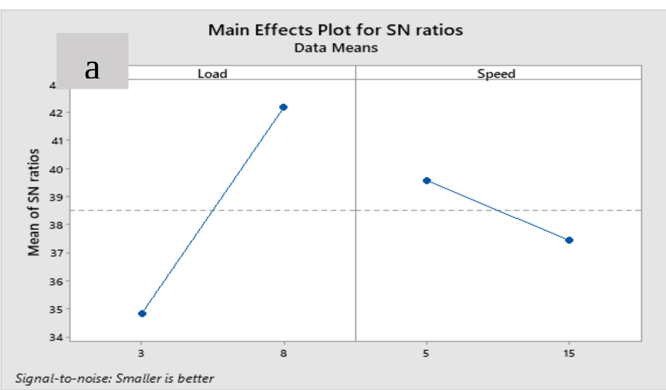
Table 6: S/N response table for specific wear rate

Level	Load	Speed
1	34.82	39.58
2	42.19	37.43
Delta	7.37	2.16
Rank	1	2

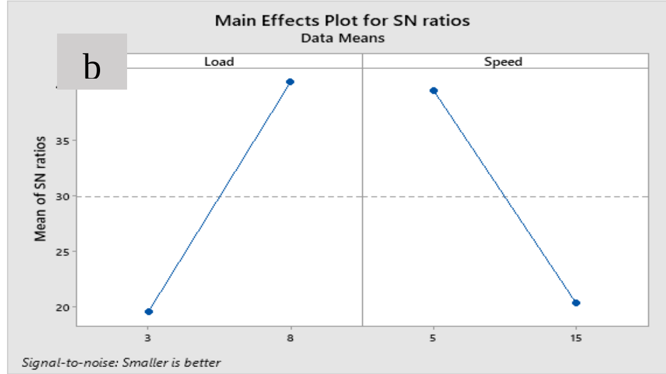
Table 7: S/N response table for coefficient of friction

Level	Load	Speed
1	19.51	39.47
2	40.22	20.27
Delta	20.71	19.20
Rank	1	2

From Table 7, the minimum COF occurred at level 1 of load, i.e. 8 N, and level 2 of speed, i.e. 5 cm/s. Reason being that they gave the lowest S/N ratio 19.51 and 20.27 respectively. Similarly, by ranking, load also has a strong influence on coefficient of friction. Therefore, operating the lubricant blend at 8 N and 5 cm/s lowers the signal levels. It means more separation between the two metals in contact during the test leading to low COF 0.001 as given in Table 5. Lower values of COF imply less energy loss, more machine efficiency and less material loss due to wear in contacting parts of machine. From Figure 3, 8 N load and 5 cm/s sliding speed shows minimum specific wear rate and minimum COF respectively when the responses were considered individually. These control factors combination provides more separation between metal to metal in contact. As load decreases, the frictional force decreases, as a result the COF and specific wear rate becomes minimum. Higher sliding speed favours formation of tribolayer. This is because as sliding velocity increases temperature also increases which reduces viscosity and favours formation of an oxide layer on the outer periphery when aluminum is used. This is also attributed to the fatty esters and polarity introduced into the blended SAE 40 by the Shea butter bio-base oil. The ester ends of fatty acids provided by the Shea butter bio-base oil, contributes to a mono-molecular layer formation on the metallic surface. The polarity of the esters end provides strong attraction of the tribolayer to the metallic surface. The long fatty acid chain forms a sliding layer that hinders direct metal surfaces contact, pits and asperities forming on the metal surface. This findings is consistent with observations by (Bahari, 2017; Salih et al., 2013). In this study, minimum specific wear rate and COF were observed at higher load and lower sliding velocity. A similar trend was also observed by (Singh et al., 2015), where load had significant effect on specific wear rate and COF. The optimum result for all the responses via Taguchi's method were obtained at Load$_1$Speed$_2$. This implies the first level of load i.e.8 N, and second level of speed, i.e. 5 cm/s.



(a) Specific wear rate



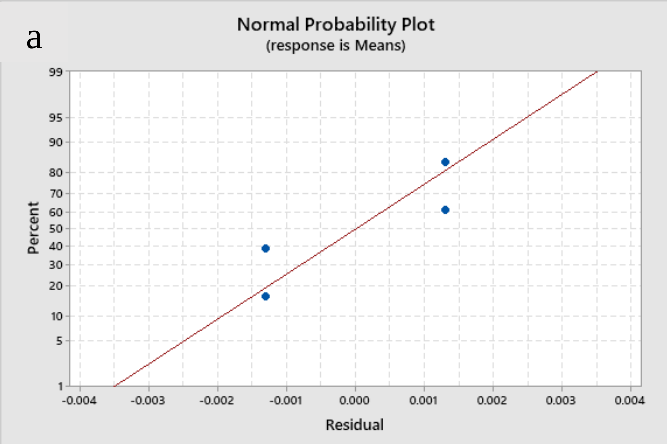
(b) Coefficient of friction (COF)

Figure 3: Main effects plots of S/N ratios.

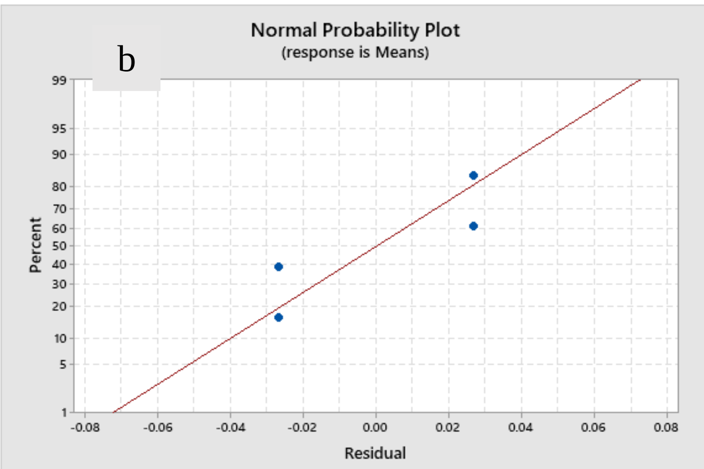
Figure 4 displays the normal probability plot for specific wear rate and COF. The figures obtained depicts that most of the plots obey a straight-line pattern. Residuals which measure the differences between the predicted and the actual value was shown on the x-axis. Not much difference was observed in the residual values that was up to 0.004. This is regarded as significant because values are < 0.05 as supported by (Sadriwala et al., 2019)

3.2 ANOVA Analysis

From Table 8, the load having (84%) influenced the specific wear rate significantly and speed (10%) was least. Several factors contributed to the wear of parts during contact, but specifically is the depletion of tribolayer between the contacting surfaces. This implies that depletion of tribolayer on metallic surfaces is more sensitive to load than speed. Therefore, in automobile applications that involves very high loads, extreme pressure additives that minimizes the depletion of the tribolayer should be included in the SAE 40 formulation. This finding justified the inclusion of Shea butter bio-base oil in the SAE 40 formulation. The polar groups present in the Shea butter bio-base oil forms strong attraction to metallic surfaces. From specific wear rate given by equation 21, load applied is indirectly proportional to specific wear rate. This direct relationship between load and specific wear rate is the reason behind the significant contribution by load in the ANOVA analysis.



(a) Specific wear rate



(b) Coefficient of friction (COF)

Figure 4: Normal probability plot.

From Table 9, it was observed that significant contribution to COF was given by load (43%), speed (20%) with error accounting for (37%). Load contributed more as compared to sliding speed. The load and pressure acting on a lubricant has a direct relationship. Pressure acting on lubricant fluid reduces the intermolecular distance between the atoms. The farther the atoms, the lower the viscosity and the higher the COF. Therefore, in automobile applications that involves very high loads, more anti-friction additives should be included in the SAE 40 formulation to reduce the coefficient of friction. However, long fatty acid chain of Shea butter bio-base oil makes more atoms available and reduce the inter-atomic distance. From equation 20 of coefficient of friction; there is a direct relationship between COF and frictional force. Frictional forces are a function of load, this buttress the fact why load has more influence on the coefficient of friction. This study is consistent with observations by (Singh, 2015).

Table 8: Specific wear rate ANOVA table

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pct (%)
Load	1	0.000113	0.000113	0.000113	16.61	0.153	84
Speed	1	0.000014	0.000014	0.000014	2.07	0.387	10
Residual Error	1	0.000007	0.000007	0.000007			5
Total	3	0.000134					100

Table 9: COF ANOVA table

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pct (%)
Load	1	0.003364	0.00336	0.003364	1.15	0.477	43
Speed	1	0.0016	0.0016	0.0016	0.55	0.594	20
Residual Error	1	0.002916	0.00292	0.002916			37
Total	3	0.00788					100

3.4 Correlation of Specific Wear Rate and COF

Relationship between specific wear rate and the control factors (load and sliding speed), using Taguchi method was found to be:

$$\text{Specific wear rate} = 0.01311 + 0.00532\text{load}^3 - 0.00188\text{Speed}^5 - 0.00532\text{load}^8 + 0.00188\text{Speed}^{15} \quad (22)$$

$R^2 = 94.92\%$

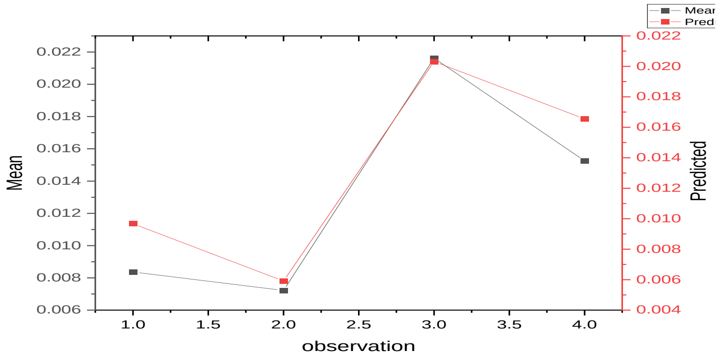
Similarly, the relationship between COF and the control parameters (load and sliding speed) using Taguchi method was found to be:

$$COF = 0.0770 + 0.02930load^3 - 0.0200Speed^5 - 0.0290load^8 + 0.0200Speed^{15} \quad (23)$$

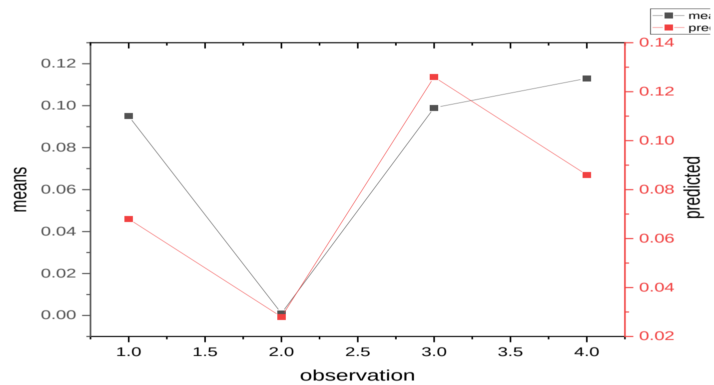
$R^2 = 62.99\%$

3.5 Model Validation

Comparison between the predicted values and actual were drawn from the experimental runs in Table 2 to validate the model generated. Fig. 5 (a) shows the specific wear rate actual and predicted plot applying the Taguchi method, and fig. 5 (b) shows the COF actual and predicted plot using the Taguchi method.



(a) Specific wear rate



(b) Coefficient of friction (COF)

Figure 5: Actual and predicted values.

The differences between the predicted and actual values are approximately 5%. This shows the model generated is significant. This implies that including Shea butter bio-base oil in the SAE 40 formulation did not affect performance predictability. Therefore, there is compatibility of Shea butter bio-based oil and mineral base oil. From figure 5 (a), the model for specific wear rate shows a close consistency between the predicted and actual value marked by an R^2 of 94.92%. This was supported in Table 10, as the difference between the actual and predicted values is 0.4377. From fig.5 (b), the model for COF was good with an R^2 of 62.99%, though not as fitting as in specific wear rate. This was supported in Table 10, as the difference between actual and predicted value is 10.1758. This can be attributed to residual error.

Table 10: Results of the predicted and experimental S/N values of specific wear rate and COF

	Optimum control factors	
	Predicted value	Experimental Value
Level	Load(II)speed(I)	Load(II)speed(I)
S/N ratio for specific wear rate	33.7406	33.3029
S/N ratio for COF	9.91146	20.0873

Equation 24 was used to determine the confidence interval of the predicted mean for the experiment, as given by (Y. Singh, 2015).

$$CI = \pm \left[\frac{F(1,\eta_2)XV_e}{N_e}\right]^{0.5} \tag{24}$$

Where F(1, η_2) = F value at required confidence interval at DOF 1,

CI = confidence interval,

N_e = Number of replications

V_e = Error variation from ANOVA.

The calculated confidence level for specific wear rate = ±0.01065dB

The calculated confidence level for COF =± 0.1073dB

For the predicted mean of the experiment the 95% confidence interval was shown in table 11

3.6 Grey Relational Analysis

To overcome the limitations of Taguchi method, grey relational analysis in tandem with Taguchi method was applied. Initially the responses were normalized according to smaller the better optimization criteria in equation 7 as shown in Table 12

Table 11: Confidence interval values for specific wear rate and COF

Parameters	Maximum value	Minimum value
Specific wear rate	0.02376	0.00247
COF	0.1586	-0.0046

Table 12: Normalized output responses

S/N	Wear rate	COF
1	0.920352753	0.160714286
2	1	1

3	0	0.125
4	0.442330394	0

The grey relational coefficients were computed using equation 8, afterwards the grey relational grade was determined using equation 10 and results presented in Table 13.

Table 13: Grey relational grade and rank

S/N	Load	Speed	GRG	Rank
1	8	15	0.617963462	2
2	8	5	1	1
3	3	15	0.348484848	4
4	3	5	0.403035376	3

From Table 13, experiment 2 was found to have the highest GRG (1) and the control factors levels became the optimal setting. The highest GRG was determined as the optimal factor setting and thus ranked 1. From Table 13, as observed the optimal control factor setting for combine response for this study was the first level of load i.e. 8 N and second level of speed i.e. 5 cm/s. These factors settings will produce a single combine effect of minimum specific wear rate and minimum coefficient of friction on the blended SAE 40 as supported by data in Table 5.

Table 14: GRG S/N response table

Level	Load	Speed
1	8.525	3.947
2	2.090	6.669
Delta	6.434	2.722
Rank	1	2

From Table 14, the combine minimum specific wear rate and minimum COF occurred at level 1 of load, i.e. 8 N, and level 2 of speed, i.e. 5 cm/s. This is because they gave the highest S/N ratio 8.525 and 3.947 respectively. Based on the rank, load strongly influences specific wear rate. Therefore, operating the lubricant blend at 8 N and 5 cm/s increases the grade number to 1 as shown in Table 13. It means more separation between the two metals in contact during the test leading to low wear rate 0.007 mm^3/Nm and low COF 0.001 as presented in Table 5.

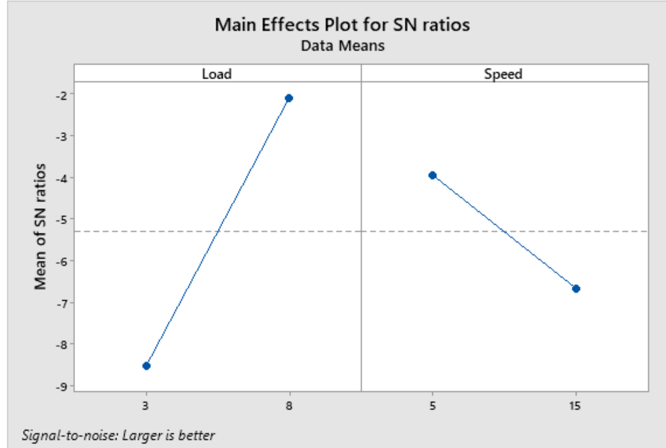


Figure 6: Main effects plots for S/N ratios of GRG.

From Figure 6, 8 N and 5 cm/s shows minimum specific wear rate and minimum COF, because it provides separation between metal to metal in contact.

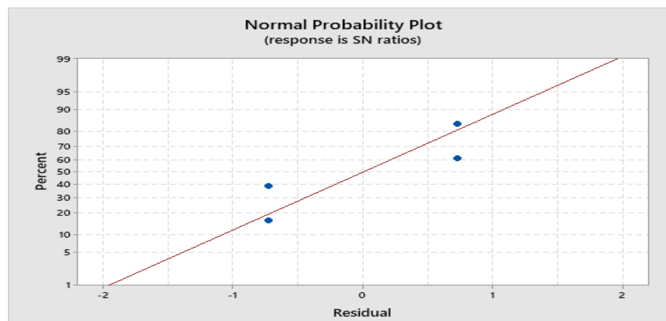


Figure 7: Normal probability plot of GRG.

Figure 7; displays the normal probability plot for the combine effect of minimum specific wear rate and COF.

Table 15: ANOVA table for GRG

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pct (%)
Load	1	0.18768	0.18768	0.18768	7	0.23	72%
Speed	1	0.04765	0.04765	0.04765	1.78	0.41	18%
Residual Error	1	0.02681	0.02681	0.02681			10%
Total	3	0.26214					100%

From Table 15, the load (72%) had significant influence on combine response and sliding speed (18%) was least. Due to the combine effect, the percentage of load in the GRG (72%) was lower than when considering specific wear rate alone by Taguchi method (84%) in Table 8. It was also higher than when considering COF alone by Taguchi method (43%) in Table 9. Therefore, GRG provides optimization of more than one output response. Similarly, because of the combine effect, the speed for the GRG (18%) is higher than when considering specific wear rate alone by Taguchi method (10%) in Table 8, and lower than when considering COF alone by Taguchi method (20%) in Table 9.

3.7 Correlation for GRG

The relationship between combine response and the control parameters i.e. load and sliding speed was found to be:

$$Combine\ respone = 0.5924 - 0.2166\,Load3 + 0.2166\,Load8 + 0.1091\,Speed5 - 0.1091\,Speed15 \quad (25)$$

$R^2 = 89.77\%$

With a percentage error of 10.23%, it can be observed from equation 25 that load8 and speed5 have the greater influence on the single combine response when the two responses were combined together.

3.8 Validation of Model for GRG

The difference between the predicted and the actual values is approximately 5%. Thus, the model generated for the single combine response is significant. This implies that including Shea butter bio-base oil in the SAE 40 formulation, and optimizing two output responses simultaneously did not affect performance predictability of the lubricant. The performance of the Shea butter bio-based oil and mineral base oil are similar.

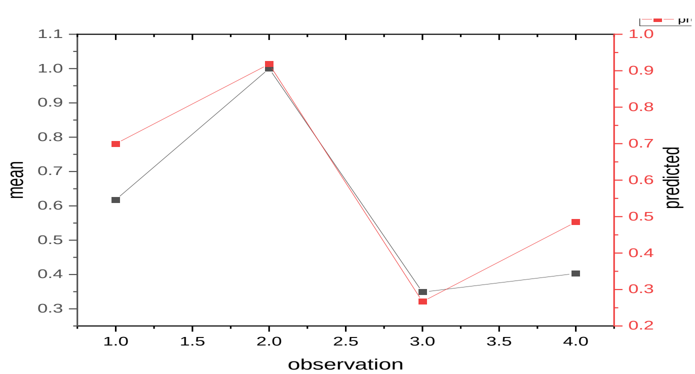


Figure 8: Actual vs. Predicted plot for GRG.

4. Conclusion

In this study, optimization of tribological characteristics of blended SAE 40 (mineral base oil and Shea butter bio-base oil blend) using Taguchi-Grey method was investigated. From the results the following conclusions were drawn:

1. The minimum specific wear rate and coefficient of friction were obtained at 8 N load and 5 cm/s sliding speed.
2. The ANOVA results showed that load had a dominant effect of about 84% on the specific wear rate and 43 % on the coefficient of friction using the blended lubricant. The effect of the sliding speed as well as the interaction between the load and the sliding factor are not significant especially on the specific wear rate.
3. The model generated for the specific wear rate using the blended lubricant has R^2 value of 94.92%. This implies that the model can be used to predict the wear rate at different load and speed for the blended lubricant.
4. The relative contribution of the load to sliding speed for minimum coefficient of friction was observed to be 2.15 as compared to 8.4 for minimum specific wear rate. Thus, the model generated for coefficient of friction has R^2 value of 62.99%.
5. Both the Taguchi and Taguchi-grey relational analysis showed the optimal combination of 8 N load and 5 cm/s sliding speed gave the minimum specific wear rate and minimum coefficient of friction. This implies that either of the two models can be used to optimize the tribological properties of the blended SAE 40 (mineral base oil and Shea butter bio-base oil blend)

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