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Research Article

The Application of Response Surface Methodology in the Investigation of the Tribological Behavior of Palm Cooking Oil Blended in Engine Oil

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The purpose of this study was to determine the optimal design parameters and to indicate which of the design parameters are statistically significant for obtaining a low coefficient of friction (COF) and low wear rate with waste palm oil blended with SAE 40. The tribology performance was evaluated using a piston-ring-liner contact tester. The design of experiment (DOE) was constructed by using response surface methodology (RSM) to minimize the number of experimental conditions and to develop a mathematical model between the key process parameters such as rotational speeds (200 rpm to 300 rpm), volume concentration (0% to 10% waste oil), and applied loads (2 kg to 9 kg). Analysis of variance (ANOVA) test was also carried out to check the adequacy of the empirical models developed. Scanning electron microscopy (SEM) was used to examine the damage features at the worn surface under lubricant contact conditions.

1. Introduction

Tribological Studies of Waste Oil Biolubricant. In the late 1800s, petroleum had been discovered and that led to the replacement of animal fats, vegetable oils, and mineral oils with synthetic oils. Petroleum oil gradually started to be the main lubricant base stocks and that was because of their low cost and superior performance. Lubricants are being used widely in all fields of manufacturing and industrial applications. Studies showed that more than thirty-eight million metric tons of oils was used for lubrication techniques in 2005 for different industrial applications in the United States (USA). Lubricants are commonly used to reduce overheating and friction in various engines, machinery, turbines, and gear.

The excessive usage of petroleum-based oils has significantly contributed to the environmental pollution and triggered awareness from the environmental sectors [1]. Besides that, the demands for fossil fuel and oil products are increasing in numerous areas. Based on the reported works, alternative oil should increase to cover about 36 billion gallons in 2022 [2]. In other words, there is a great demand for oil in the coming few years and high attention should be paid to find alternative resources. To overcome such issue, researchers start developing an alternative fuel and/or oil products from natural resources aiming to replace the fossil products which become the main goal of many researchers, environmental and government bodies especially in the developed countries such as Australia, US, and Europe.

In the current decade, there are a few attempts aiming to study the potential of using bio-oil such as sunflower oil, castor oil, soybean oil, and pollock oil as biofuel for diesel engines. Most of the works showed good and promising results. However, there is a tribological issue raised by most of the researchers in which biofuels deteriorate the engine components. On the other hand, currently there is an effort to try to use pure bio-oil as a lubricant. From 2010 until recently, several biolubricants have been investigated in different countries [3], for example, soybean oils (the USA and South America), rapeseed oil (Europe), and palm oil (Asia) [4–6]. Those studies are still at the initial stage and there are many issues and limitations that need to be addressed before using such oil [7]. Moreover, the literature highly recommends deep investigation on the performance and the potential of using biolubricants. Developing a friendly low cost biolubricant attracts the attention of researchers to use waste cooking oil as the main resources of lubricant.

Waste cooking oil can be considered the most promising bio-oil feedstock despite its drawbacks, that is, high free fatty acid (FFA) and water contents [8]. As reported by many researchers, biofuels produced from waste cooking oils have numerous advantages such as low pollution (CO_2, CO, and NO_x), low cost, and acceptable brake specific fuel consumption. An interest can be drawn to use the waste cooking oil as a lubricant. Kalam et al. [9] experimentally investigated the friction and wear characteristics of normal lubricants, which is an additive-added lubricant and waste vegetable oil-(WVO-) contaminated lubricants. The WVO-contaminated lubricants with amine phosphate as antiwear additive reduced the wear and friction coefficient and increased the viscosity; thus palm oil waste with a normal lubricant and amine phosphate additive could be used as a substitution for lubricant (maximum 4%). Based on the four-ball tribo testing result, the WVO-contaminated lubricant with the presence of antiwear additives showed promising results due to better thermal and oxidative properties of waste vegetable oils which consist of long chain saturated fatty acids [10]. Masjuki and Maleque [11] have experimented the effect of palm oil diesel (POD) fuel contaminated lubricant on sliding wear of cast iron against mild steel and investigated the sliding contact using the pin-on-disc type of friction and wear apparatus. Based on the results, the use of pure commercial (0% POD contamination) lubricant resulted in a moderate wear rate while pure POD 100% lubricant produced the highest wear rate compared to other contaminated lubricants.

2. Experimental Setup

2.1. Lubrication and Material Preparation. Base oil used in this experiment was SAE 40. Palm oil was chosen because it is commonly used in Malaysia. Volume concentrations of 0% and 10% waste oil were blended with base oil using magnetic stirrer and ultrasonic bath. For the preparation of waste cooking oil as biolubricant, the waste cooking oil underwent three types of processes: coarse filtering, dewatering, and fine filtering. Wear and friction performance for biolubricant were evaluated using a piston ring-liner contact tester and the material use was aluminium 6061 which is the common material for a piston ring. After the lubrication preparation had been completed, the details of lubricant compositions which are viscosity, density, and moisture content for all lubrication were determined.

2.2. Evaluation of Tribological Properties. Wear test involves making linear movements similar to the pair of cylinder-piston ring operating under real conditions. Figures 1–3 show the picture of the wear tester and setup. The type of material for specimen used in this experiment was aluminium 6061 which are the material commonly used for a piston ring.

Table 1: Tribology test condition.

Test specifications	Values
Load, kg	2.0–9.0
Engine speed, rpm	200–300
Temperature, °C	Room temperature
Operating time, min	10 minutes per specimen

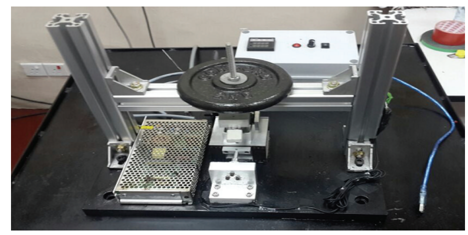

Figure 1: Piston ring reciprocating liner test machine, contact geometry, and test specimen.

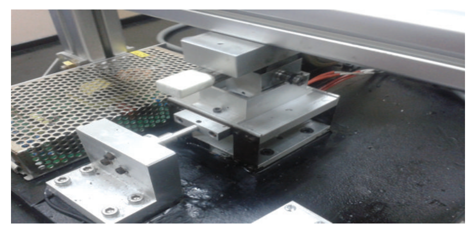

Figure 2: Lubricant bath for specimen facilitates the linear movement.

Normal loads were applied to the device by hanging weights on the bearing lever where the piston ring sample is attached in order to produce the desired loads. The load chosen was between 2.0 kg and 9 kg. Low engine-speed intervals (200 rpm and 300 rpm) were selected during testing because such conditions generate the greatest friction in engines, particularly during the first movement and at the top dead centre (TDC) [12]. The temperature used was the same as room temperature and the operating time was 10 minutes per specimen. The coefficient of friction (COF) was measured using ARDUINO Software and wear rate was determined via weight difference using weight scale with sensitivity 0.1 mg. Calculation of soefficient is shown in Figure 4. The test conditions are presented in Table 1.

2.3. Calculation of Coefficient of Friction and Specific Wear Rate. Consider

$$\mu_k = \frac{F_k}{N}, \tag{1}$$

where μ_k is coefficient of kinetic friction, F_k is applied force, and N is the load.

For specific wear rate evaluation,

$$\Delta w = (w_1 - w_2), \tag{2}$$

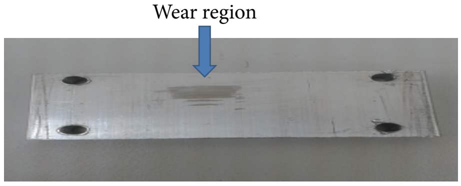

FIGURE 3: The wear region of a specimen.

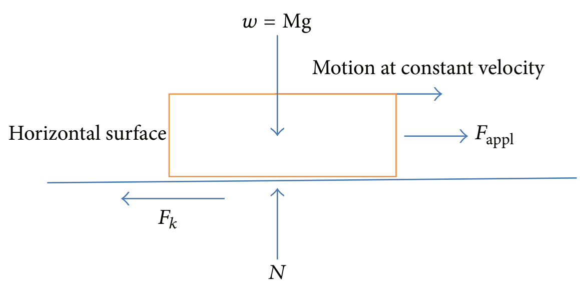

FIGURE 4: Coefficient of friction evaluation.

where Δw is weight loss of the specimen, w_1 is weight of the specimen before test, and w_2 is weight of the specimen after test.

Volume loss (ΔV) of the specimen is computed as per below:

$$\Delta V = \frac{1}{\rho}(w_1 - w_2), \quad (3)$$

where ρ is experimental density of the specimen.

The specific wear rate (w_s) of the specimen was calculated using the following equation:

$$w_s = \frac{\Delta V}{F_n \times s_s}, \quad (4)$$

where s_s is sliding distance and (m), F_n is normal load (N).

2.4. Design of Experiment (DOE)

2.4.1. Response Surface Methodology. The design of experiment (DOE) for this study was constructed using response surface methodology (RSM) to obtain the optimization for different parameters in the tribological behavior using Minitab software. RSM is the procedure to determine various relationships between process parameters and tribological criteria and explore the effect of these process parameters on the coupled responses Montgomery [13]. RSM techniques are based on the use of factorial design in which the main effect of the factor is defined as the variation in response caused by a change in the level of the factor considered, while the other ones are kept constant [14]. In order to study the effects of the tribological parameters, the two most important tribological criteria which are wear rate (WR) and coefficient of friction (COF) act as the response. Table 2 shows the suitable levels of the factors used to design the parameters for a tribological experiment while Table 3 shows the design values obtained from the Minitab.

TABLE 2: Process parameter and its level.

Parameter	−1	0	+1
Volume concentration (%)	0	5	10
Speed (rev/min)	200	250	300
Load (kg)	2	5.5	9

TABLE 3: Design values obtained from a Minitab.

Experiment	Speed (rev/min)	Load (kg)	Volume concentration (%)
1	300	5.5	10
2	300	2	5
3	200	9	5
4	250	2	10
5	250	5.5	5
6	200	5.5	10
7	250	9	0
8	250	2	0
9	300	5.5	0
10	300	9	5
11	250	5.5	5
12	250	9	10
13	200	2	5
14	200	5.5	0
15	250	5.5	5

2.4.2. Mathematical Modelling Based on RSM. Response surface regression was used to construct a complete quadratic mathematical equation for wear rate and average COF. A second-order polynomial response surface empirical model can be developed as follows to evaluate the parametric effects on the various tribological criteria:

$$f(x) = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{i=1}^{n} \beta_{ij} x_i x_j + \varepsilon, \quad (5)$$

where $f(x)$ is the response which is wear rate (WR) and coefficient of friction (COF). It is created by various process variables of tribological parameters. β_0, β_i, β_{ii}, and β_{ij} are the regression coefficients for intercept, linear, quadratic, and interaction terms, respectively. x_i and x_j are the independent variables. Contour plots were obtained using the fitted model by keeping the least effective independent variable at a constant value while changing the other two variables [15]. A Box-Behnken design with three levels of variables was used for the current study. 15 tribology tests were conducted according to the design as shown in Table 3. To ensure that the quadratic mathematical models for the wear rate and average COF of the analysis were adhered to, all of the experimental data were checked through the residual plot to verify that the mathematical models displayed standard normal distribution.

Table 4: Properties of baseline oil.

Properties	SAE 40	Palm oil	Waste oil
Viscosity (mpa·s)	179.2	72.7	180.6
Density (g/cm^3)	0.8609	0.9033	0.9049
Moisture content (%)	0.19	0.24	0.28

Table 5: Properties of blended volume concentration for waste oil.

Properties	5% waste oil + SAE 40	10% waste oil + SAE 40
Viscosity (mpa·s)	192.1	169.6
Density (g/cm^3)	0.8632	0.8639
Moisture content (%)	0.14	0.19

3. Results and Discussion

3.1. Physicochemical Properties of Waste Cooking Oil in Base Lubricant. The data were used to evaluate the differences between base lubricant stock (SAE 40) and blended lubricant of palm oil and waste oil. Table 4 shows the properties of base oil (SAE 40), palm oil, and waste oil.

A good lubricant should have a high boiling point, adequate viscosity, low freezing point, high oxidation resistant, noncorrosive properties, and good thermal stability. The most important property of oil is viscosity. It indicates the resistance to flow and is directly related to temperature, pressure, and film formation. High viscosity indicates low resistance of flow [16]. Lubricants are generally less dense than water. If the density of an object is less than that of water, then that object will float. This is why if there is a moisture problem in the lube system, the water settles at the bottom of the sump and is drained out first whenever the plug is pulled or the valve is opened. The density of a lubricant fluid can provide indication of its composition and nature [17]. The presence of water does not only have a direct harmful effect on the machine components but it can also trigger the progress of oxidation up to tenfold increase and thus resulted in premature aging of oil [18]. Less moisture content in lubricating oil indicates rust and corrosion prevention. Table 5 shows the results of blended lubricant composition for 5% and 10% waste palm oil.

3.2. Analysis of the Developed Empirical Models and Regression Analysis. Table 6 represents the results of experiments conducted to investigate the tribological properties of waste cooking oil blended with SAE 40 engine oil for different factor variables.

The analysis of variance (ANOVA) and the F-ratio test were performed to justify the goodness of fit of the empirical models. The calculated values of F-ratio for lack of fit were compared to the standard values of F-ratio corresponding to their degrees of freedom to find the adequacy of different empirical models. The F-ratio was calculated as a ratio of mean sum of the experimental error [19].

Tables 7 and 8 represent the estimated regression coefficient and analysis of variance (ANOVA) for average COF for blended waste cooking oil with SAE oil. The fit summary recommends that the empirical model is statistically significant for the analysis of COF. The value of R^2 was more than 99.10% which means that the empirical model provides an excellent explanation of the relationship between the independent variables (factors) and the response (COF). Based on Table 7, the associated P value for the model was lower than 0.05 (95% confidence interval). This indicates that the model was considered statistically significant. Meanwhile, the lack of fit of P values for the average COF models was also significant as they were less than 0.05. Figure 5 shows the residual plot for coefficient of friction.

Tables 9 and 10 represent the estimated regression coefficient and analysis of variance (ANOVA) for the specific wear rate for blended waste cooking oil with SAE oil. The fit summary recommends that the empirical model was statistically significant for the analysis of COF. The value of R^2 was over 95.99% which means the empirical model provides an excellent explanation of the relationship between the independent variables (factors) and the response (WR). Based on Table 6, the associated P value for the model was lower than 0.05 (95% confidence interval). This indicates that the model was considered to be statistically significant. Meanwhile, the lack of fit of P values for the average COF models were not significant as they were more than 0.05. Figure 6 shows the residual plot for coefficient of friction.

The t values and P values in the estimated regression coefficient of wear rate in Table 10 denote the significant influence of each input variable in the models. The smaller numerical values of "P" and larger values of "t" signify that the related regression coefficient is highly significant [13]. Equations (6) are the empirical equation for the average COF and the wear rate for the lubricant as the functions of independent variables of speed (S), load (L), and volume concentration (VC) in coded units:

$$\begin{aligned} f(x), \mathrm{COF} = {} & 0.337598 - 0.000174S - 0.0064568L \\ & + 0.005517\mathrm{VC} + 0.000002S^2 \\ & + 0.004496L^2 + 0.000039\mathrm{VC}^2 \\ & - 0.0005SL - 0.000033S\mathrm{VC} \\ & + 0.000236L\mathrm{VC}, \\ f(x), \mathrm{WR} = {} & -0.783168 + 0.008006S - 0.117524L \\ & - 0.012697\mathrm{VC} - 0.000009S^2 \\ & + 0.000042L^2 + 0.002760\mathrm{VC}^2 \\ & - 0.000392SL - 0.000068S\mathrm{VC} \\ & + 0.001647L\mathrm{VC}. \end{aligned} \quad (6)$$

According to the COF model, the highest significant level was quadratic load, followed by linear load and lastly the interaction of speed and applied load, while, for specific average wear rate, quadratic volume concentration showed

Table 6: Experimental design and results (uncoded factors).

Experiment	Speed (rev/min)	Load (kg)	Volume composition (%)	Coefficient of friction (μ)	Specific wear rate (mm^3/Nm)
1	300	5.5	10	0.09103	0.89984
2	300	2	5	0.26564	0.07589
3	200	9	5	0.06056	0.85635
4	250	2	10	0.23418	0.33661
5	250	5.5	5	0.09542	0.46867
6	200	5.5	10	0.09566	0.79715
7	250	9	0	0.06079	0.86458
8	250	2	0	0.25055	0.77947
9	300	5.5	0	0.09118	0.72354
10	300	9	5	0.06097	0.83164
11	250	5.5	5	0.09542	0.88928
12	250	9	10	0.06089	0.97986
13	200	2	5	0.26146	0.74241
14	200	5.5	0	0.09293	0.68133
15	250	5.5	5	0.09563	0.88928

Table 7: Analysis of variance for coefficient of friction (COF).

Source	DF	Seq SS	Adj SS	Adj MS	F value	P value
Regression	9	0.069229	0.069229	0.007692	462.37	0.000
Linear	3	0.058443	0.002365	0.000788	47.39	0.005
Square	3	0.010525	0.007339	0.002446	147.04	0.001
Interaction	3	0.000261	0.000261	0.000087	5.23	0.104
Residual error	5	0.000050	0.000050	0.000017		
Lack of fit	3	0.000050	0.000050	0.000050	3741.13	0.000
Pure error	2	0.000000	0.000000	0.000000		
Total	14	0.069279				

$S = 0.00407874$, PRESS = $*$, $R^2 = 99.93\%$, R^2 (pred) = $*\%$, and R^2 (adj) = 99.71%

DF: degrees of freedom; Seq SS: sequential sum of squares; Adj SS: adjusted sum of squares; Adj MS: adjusted mean squares.

Table 8: Estimated regression coefficients for COF.

Term	Coef	SE Coef	t-ratio	P value
Constant	0.337598	0.077232	4.371	0.022
Speed	−0.000174	0.000520	−0.335	0.760
Load	−0.064568	0.006435	−10.033	0.002
Volume composition	0.005517	0.002745	2.010	0.138
Speed $*$ speed	0.000002	0.000001	1.571	0.214
Load $*$ load	0.004496	0.000240	18.712	0.000
Volume composition $*$ volume composition	0.000039	0.000118	−2.790	0.761
Speed $*$ load	−0.000050	0.000018	−2.790	0.068
Speed $*$ volume composition	−0.000033	0.000012	−2.667	0.076
Load $*$ volume composition	0.000236	0.000117	2.023	0.136

the highest significance level, followed by interaction of speed and applied load and finally the linear load.

3.2.1. Effect of Control Parameters on Coefficient of Friction (COF) and Specific Wear Rate (WR). Figures 7(a), 7(b), and 7(c) represent the three-dimensional response surface plots and the contour plots of COF regarding speed, load, and volume composition. Based on Figure 7(a), as the load and speed increase, the value of COF increases. Figure 7(b) shows the relationship of volume composition and load by which the COF is gradually decreasing as the volume composition decreases. For Figure 7(c), concerning the volume composition, the coefficient of friction reduces to the lowest at a certain speed and then increases as the speed increases even

Table 9: Analysis of variance for wear rate.

Source	DF	Seq SS	Adj SS	Adj MS	F value	P value
Regression	9	0.456675	0.456675	0.009888	173.19	0.000
Linear	3	0.198500	0.198500	0.024624	431.29	0.000
Square	3	0.236568	0.236568	0.005015	87.84	0.000
Interaction	3	0.021607	0.000073	0.000024	0.43	0.742
Residual error	5	0.054272	0.000285	0.000057		
Lack of fit	3	0.051876	0.000285	0.000095	6486.86	0.000
Pure error	2	0.002396	0.000000	0.000000		
Total	14	0.510947				

$S = 0.0330377$, PRESS = ∗, $R^2 = 95.99\%$, R^2 (pred) = ∗%, and R^2 (adj) = 83.96%.

Table 10: Estimated regression coefficients for wear rate.

Term	Coef	SE Coef	t-ratio	P value
Constant	−0.783168	0.625581	−1.252	0.299
Speed	0.008006	0.004209	1.902	0.153
Load	0.117524	0.052127	2.255	0.109
Volume composition	−0.012697	0.022237	−0.571	0.608
Speed ∗ speed	−0.000009	0.000008	−1.085	0.357
Load ∗ load	0.000042	0.001946	0.022	0.984
Volume composition ∗ volume composition	0.002760	0.000954	2.894	0.063
Speed ∗ load	−0.000392	0.000144	−2.718	0.073
Speed ∗ volume composition	−0.000068	0.000101	−0.673	0.549
Load ∗ volume composition	0.001647	0.000944	1.745	0.179

more under low applied load conditions. Thus, volume composition had more significant effect than speed and load.

Figures 8(a), 8(b), and 8(c) represent the three-dimensional response surface plots and the contour plots of wear rate regarding speed, load, and volume composition. Based on Figure 8(a), as the load and speed increase, the value of specific wear rate increases. Meanwhile Figure 8(b) shows the volume composition and load by which the specific wear rate gradually increases as the volume composition increases. For Figure 8(c), concerning the volume composition and load, the specific wear rate gradually increases as the volume composition increases. Thus, volume composition had more significant effect than speed and load.

3.3. Multiobjective Optimization Using Response Surface Methodology. The main advantage of using response surface methodology (RSM) is that the response can be optimized by controlling the input parameters [20]. The performances of wear and coefficient of friction depend not only on the lubricant properties but also on the sliding conditions of material under lubricant contact condition. In this study, the optimization was carried out in order to determine the minimum wear and friction of the blended waste oil with SAE 40 contact with aluminium 6061. Optimization of the process parameters was carried out using RSM optimization technique. Desirability for the whole process of optimization was calculated to show the feasibility of optimization to examine whether all parameters are within the working range or not. The goal was to minimize COF and WR. Table 11 shows the target value and the upper value for both response, average COF, and wear rate.

Table 11: Target value and upper value of average COF and wear rate.

Response	Target value	Upper value
Average COF	0.0605	0.2656
Wear rate ($\times 10^{-3}$ mm^3/Nm)	0.68133	0.97986

Figure 9 exhibits the optimization plot for both COF and WR responses. The optimum value shown in the plot is 0.0717 μ for COF and 0.7380 for WR. The relevant parameters such as speed, load, and volume composition are 200 rev/min, 6.3712 kg, and 0.2020% of volume composition respectively. The composite shown in the plot is 0.87250.

3.4. Surface Texture Analysis. There are various types of wear in mechanical systems such as abrasive wear, adhesive wear, fatigue wear, and corrosive wear. Since the lubricant regime occurred in this experiment was boundary lubrication, thereby, abrasive wear, adhesive wear, fatigue wear, and corrosive wear were observed in the wear regions [21]. All these wear mechanisms were found in this experiment but most of the wear phenomena were abrasive and adhesive wear. The

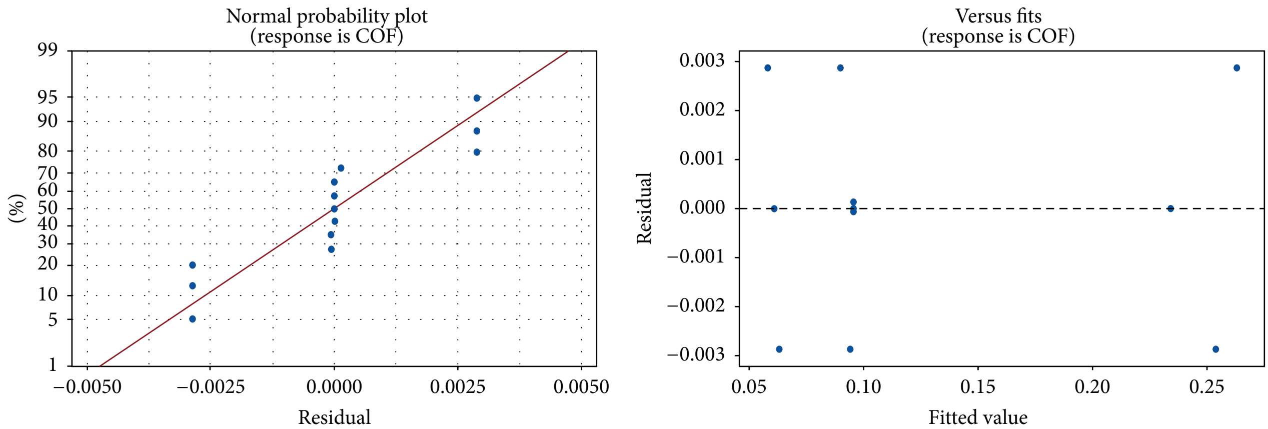

Figure 5: Normal probability plot and versus fits for average COF.

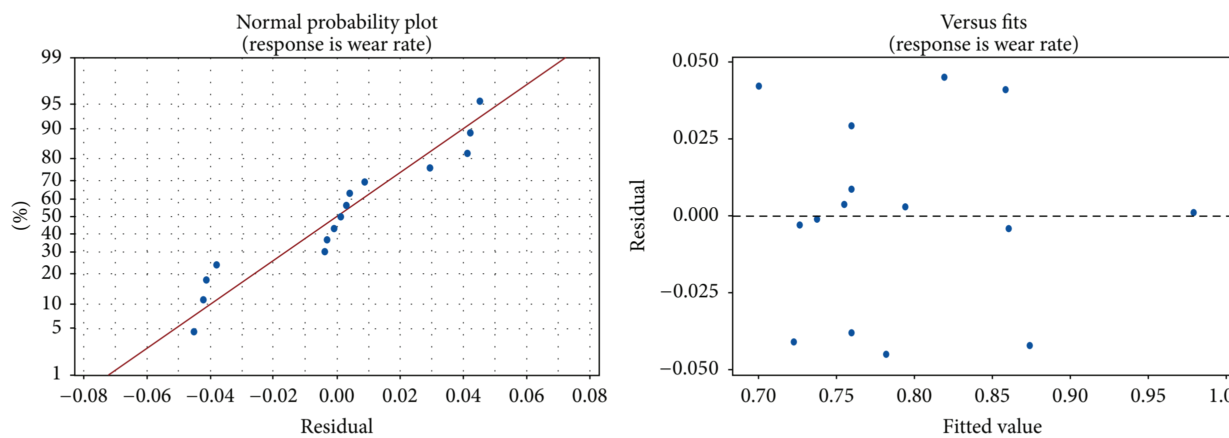

Figure 6: Normal probability plot, versus fits, histogram, and versus order for wear rate.

major wear mechanisms that can be found in the specimen were observed to be wear grooves that resulted from abrasive wear because the asperities on the hard surface of the liner samples touched the soft surface of the ring samples and had a close relationship with the thickness of lubricant film. The SEM images of the aluminium plate shown used various types of volume concentration of waste cooking oil blended with engine oil. Referring to Figure 10, it was found that the wear decreases at 5% concentration compared to SAE 40 and wear started to increase when 10% waste oil concentration was used. This is due to the 5% concentration of waste oil that showed the highest viscosity results compared to 10% concentration because high viscosity (thick) engine oil helps to maintain a barrier between moving part and also drag the movements between two contact surfaces.

4. Conclusion

As conclusions, the study examined the effects of various control parameters, namely, speed, load, and volume composition on the responses of coefficient of friction and wear rate. The following conclusion can be derived based on the results obtained:

(i) The correlations between the control parameters (speed, load, and volume composition) and responses (specific wear rate and coefficient of friction) of waste oil added with standard lubricant were successfully developed using RSM. The model showed that the speed, load, and volume composition have a significant effect on coefficient of friction (COF) and specific wear rate (WR). According to the COF model, the highest significance level was quadratic load, followed by linear load and lastly the interaction of speed and applied load, while for specific average wear rate, quadratic volume concentration showed the highest significance level, followed by interaction of speed and applied load, and finally the linear load.

(ii) The predicted optimized volume composition for the input variables to produce the lowest response of specific wear rate and average COF in the range tested for waste oil blended with SAE 40 was speed (200 rev/min), load (6.3712 kg), and volume composition (0.2020%).

(iii) According to SEM analysis on the worn surfaces, the maximum wear occurred at 10% concentration of

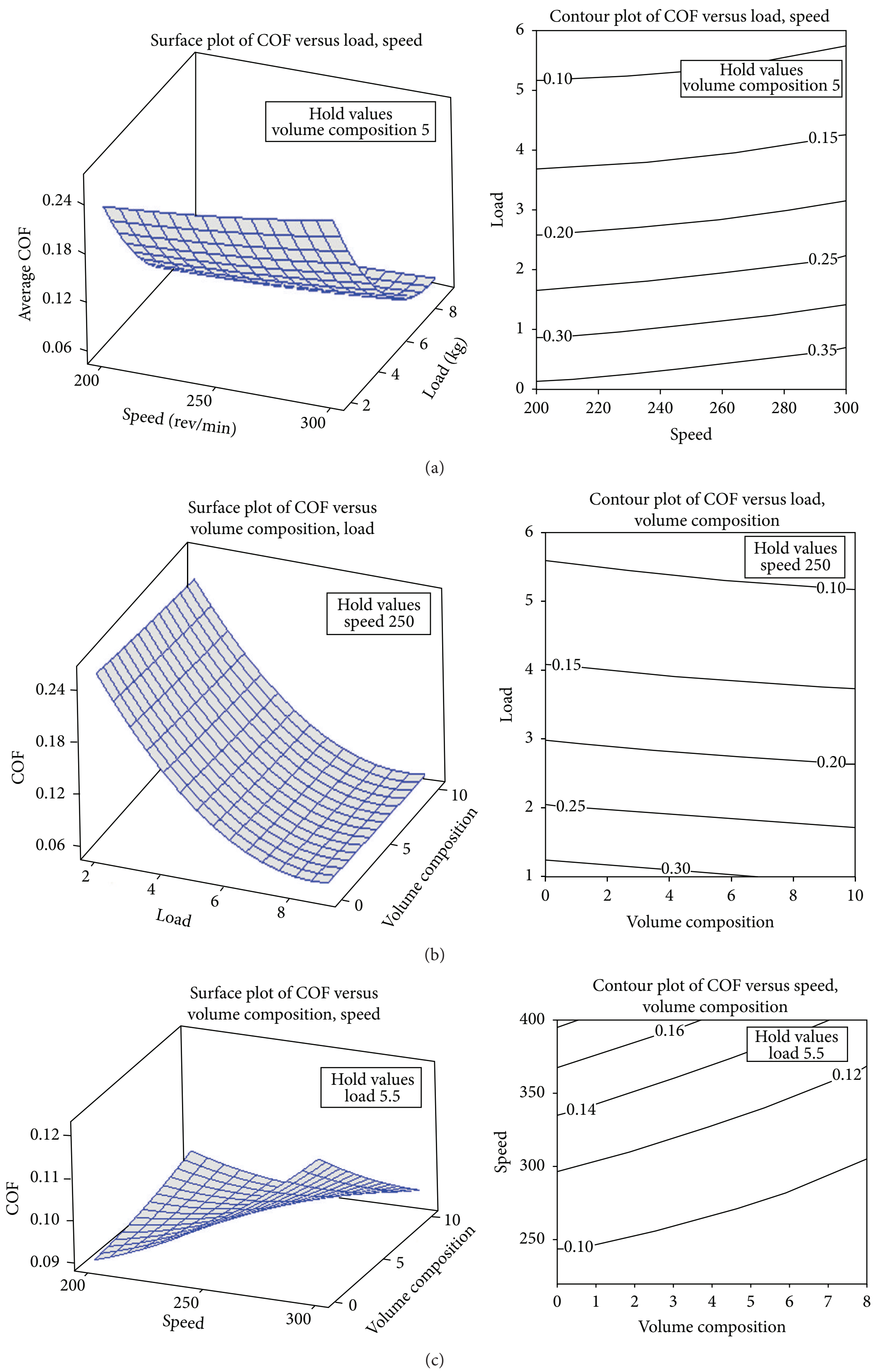

FIGURE 7: (a) Influence of load and speed on COF. (b) Influence of volume composition and load on COF. (c) Influence of volume composition and speed on COF.

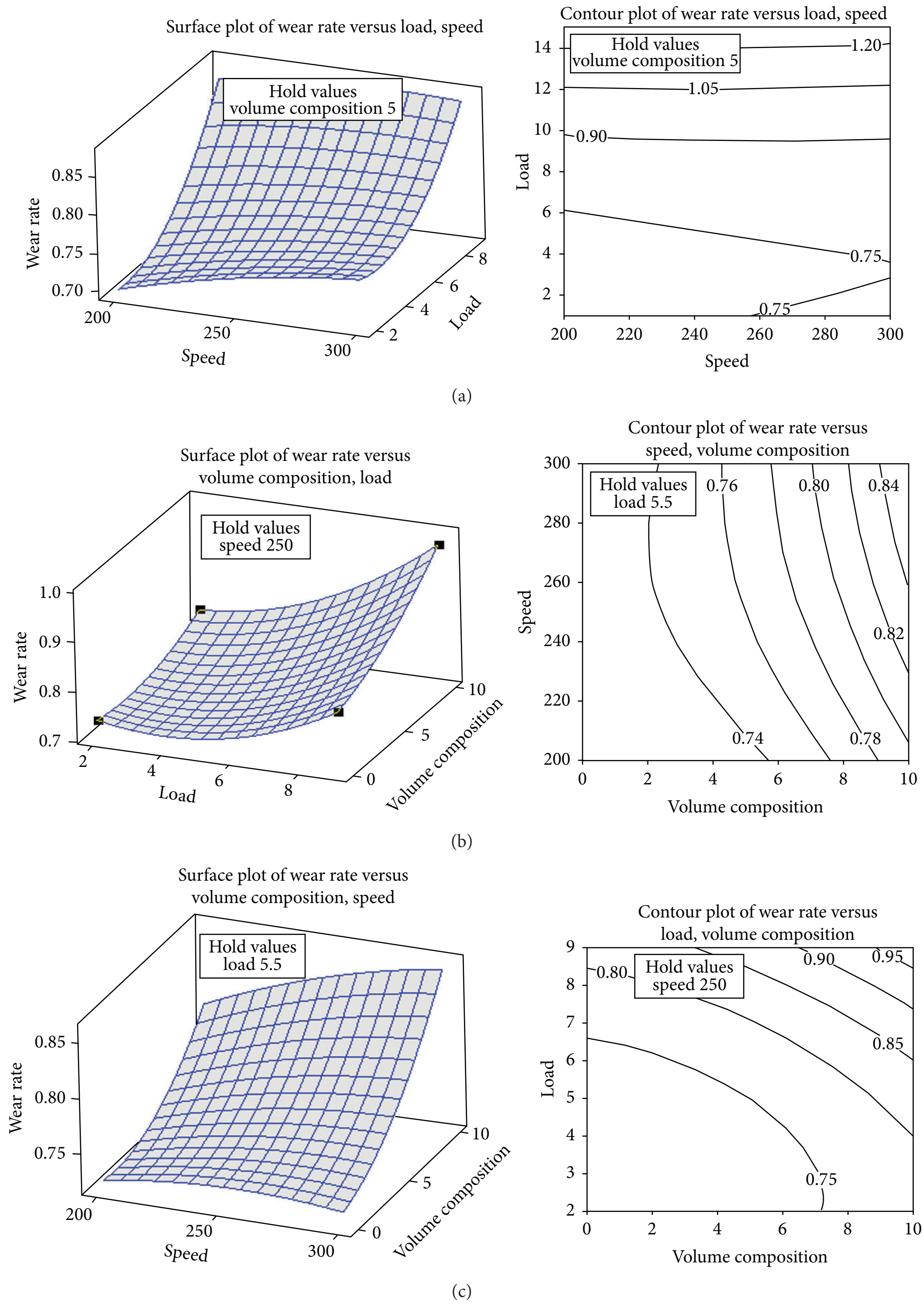

Figure 8: (a) Influence of load and speed on specific wear rate. (b) Influence of volume concentration and load on specific wear rate. (c) Influence of volume composition and speed on specific wear rate.

waste oil while minimum wear occurred at 5% concentration of waste oil. This shows that waste cooking oil has antiwear characteristics in the small amount of waste cooking oil and also means that using waste cooking oil as an additive to the engine oil will not have any severe wear causing premature failure.

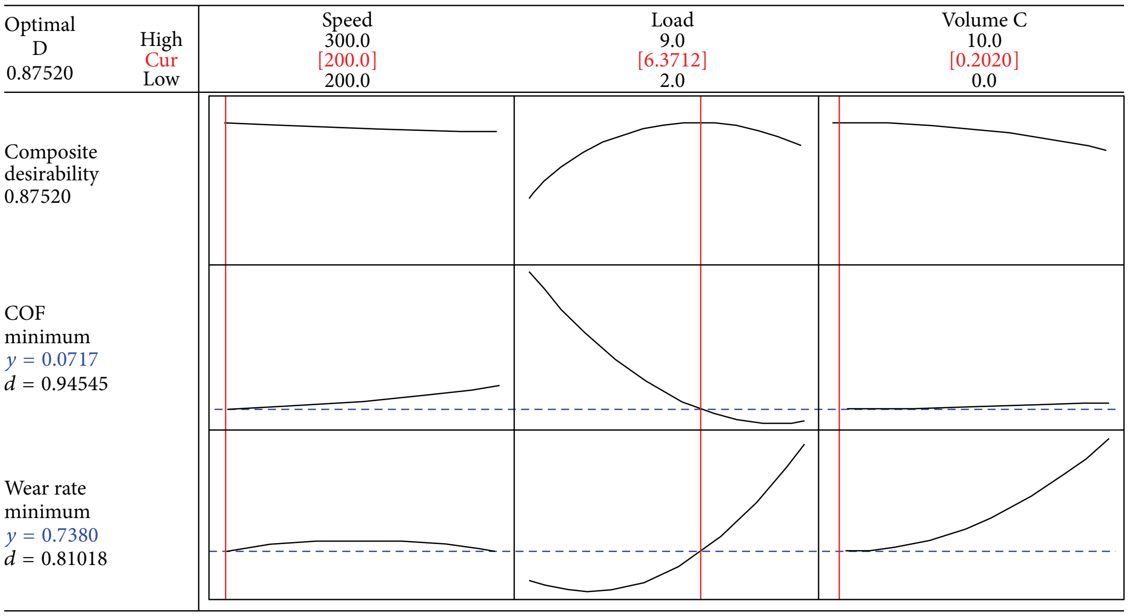

FIGURE 9: Optimal conditions for control variables on the wear and friction responses of blended waste oil with SAE.

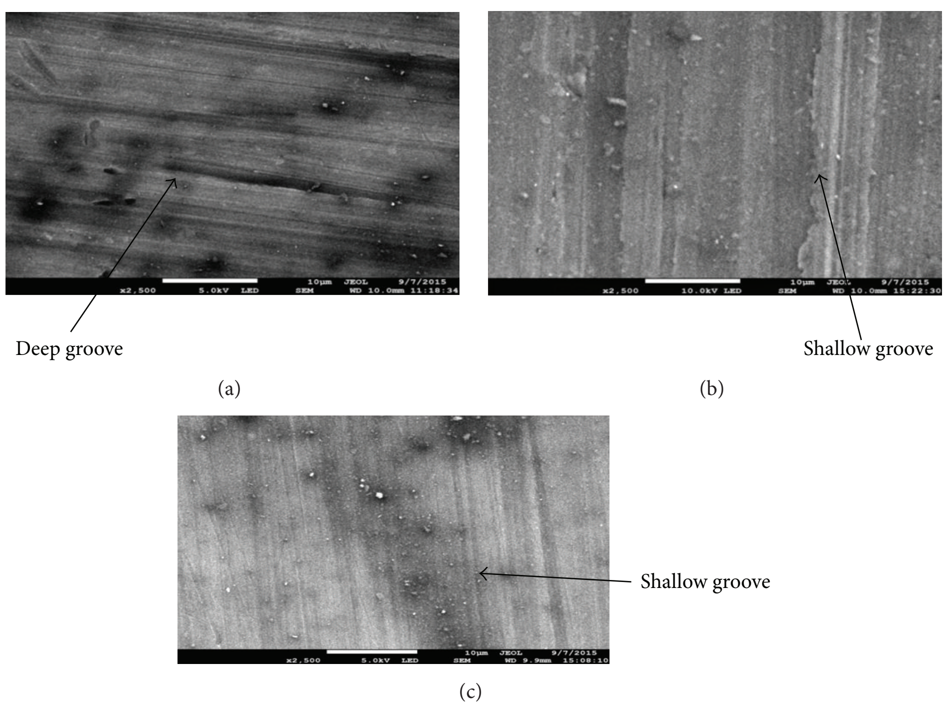

FIGURE 10: SEM images of the surface of aluminum plate for different volume concentrations of biolubricant; (a) 10% waste oil; (b) SAE 40; and (c) 5% waste oil.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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