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RESEARCH

Statistical Models for Predicting Wear and Friction Coefficient of Valve Tappet Using ANOVA

Funsho Olaitan Kolawole[a,*], Aduramigba Toluwani Ayeni[b], Shola Kolade Kolawole[c], Olawale Samson Kolade[d], Adebayo Felix Owa[d]

[a] *Metallurgical and Materials Engineering Department, University of São Paulo, São Paulo, SP, Brazil,*
[b] *Department of Electrical and Electronic Engineering, Federal University, Oye-Ekiti, Nigeria,*
[c] *National Agency for Science and Engineering Infrastructure, Abuja, Nigeria,*
[d] *Department of Materials and Metallurgical Engineering, Federal University, Oye-Ekiti, Nigeria.*

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* Corresponding author:

Funsho Olaitan Kolawole
E-mail: fkopresido@yahoo.com

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A B S T R A C T

The focus of this study is to propose statistical models for predicting wear and coefficient of friction of the 16MnCr5 steel valve tappet using the analysis of variance (ANOVA). The 16MnCr5 steel valve tappet was fabricated from a steel strip and thermochemically treated by carburizing, quenching, and tempering. Under dry conditions, tribological tests were performed for 16MnCr5 steel valve tappet with a ball-on-plane configuration in a reciprocating slide using an Optimol SRV® v4 device. Subsequently, the results of the coefficient of friction (COF) and the wear rate were then analyzed using the ANOVA. Regression analysis was used to derive the predictive equations for both friction coefficient and wear rate. The applied load was found to be the most significant parameter affecting the COF and wear rate. The proposed statistical models has 88 - 92% percent reliability. These models can be beneficial for predicting the tribological operating conditions for the 16MnCr5 steel valve tappet to avoid premature failure within the tested load and temperature conditions.

1. INTRODUCTION

Every automobile manufacturer strives to reduce energy consumption in a passenger car through careful material selection, particularly in the internal combustion engine, where friction occurs. Improvement in the vehicle's environmental friendliness, reliability, durability, and energy efficiency is needed to reduce CO_2 emissions. The transportation sector consumes a lot of energy, accounting for 13.5% of global warming [1]. In addition, approximately 33% of the energy consumed by a passenger car is lost to friction, and 11.5% is lost in the engine [2,3]. Wear and friction reduction are the key factors to reducing energy losses in combustion engines, which can be achieved by surface treatments and coatings [4]. In the automotive industry, it is crucial to use materials that can withstand elevated temperatures in the internal combustion engine of an automobile vehicle. Combustion engines of an automobile are usually operated at elevated temperature conditions, between 25°C to 250°C, although some special need vehicles like racing cars can have operational temperatures above 300°C [2,5]. Tappets play a vital role as integral components within the internal combustion engine of an automobile. The advancement of internal combustion engines has resulted in the development of novel materials and designs capable of enduring elevated stress and temperature levels [6]. The utilization of valve tappets is in high demand across various modes of transportation, such as vehicles, trucks, motorcycles, and boats, as well as in equipment like lawnmowers and generators [6]. The 16MnCr5 steel is well-known for manufacturing high-stress components such as tappet valves, gears, shafts, crankshafts, connecting rods, and camshafts. Moreover, this steel has excellent hardenability and machinability [7,8]. In addition, the 16MnCr5 steel is renowned for its exceptional mechanical properties, excellent tribological properties, remarkable fracture and fatigue resistance, high corrosion resistance and oxidation resistance [9-11].

The wear properties of 16MnCr5 steel at room temperature were enhanced using the boronizing process [12]; also, the fracture of a gear shaft made from 16MnCr5 steel has been investigated to analyze the properties [13]. Several studies have been conducted to reduce friction and wear on various coatings for tribological applications and to predict their friction and wear behavior [14]. According to Jiang & Stack (2006), modeling is an effective tool that can be used to understand the tribological properties of certain materials. Researchers commonly use the statistical analysis of variance (ANOVA) to investigate which design parameter significantly affects the tribological behavior of a material [15-17].

The optimal combinations of the process parameters are predicted based on the analysis of variance (ANOVA). In addition, regression analysis was used to derive the mathematical models of the control factors and their interactions [16]. In general, it has been observed that several studies were conducted previously on several surfaces during tribological experiments. However, no study has been conducted on predicting friction and wear of 16MnCr5 steel valve tappet. Therefore, the present investigation employs the use of ANOVA and regression analysis methods to develop statistical models for predicting the wear and friction coefficient of 16MnCr5 steel valve tappet under room and elevated temperatures.

2. METHODOLOGY

2.1 Design of experiment

The experimental design employed in this study utilized a full factorial design of experiment, incorporating two factors with varying levels (first factor – 6 levels and second factor – 4 levels), resulting in 24 levels of orthogonal arrays. The parameters and levels used are presented in Table 1, while the 24 orthogonal arrays are presented in Table 2. The selection of parameters and range was determined by considering the harsh operating conditions encountered by combustion engines in automobiles. To minimize the occurrence of experimental errors, the test was conducted on twice.

Table 1. Design parameters at six and four levels for valve tappet.

Load (N)	Temperature (°C)
5	25
10	150
20	200
30	250
40	
50	

Table 2. Design of experiment with L24 arrays for valve tappet.

S/N	Load (N)	Temperature (°C)
1	5	25
2	10	25
3	20	25
4	30	25
5	40	25
6	50	25
7	5	150
8	10	150
9	20	150
10	30	150
11	40	150
12	50	150
13	5	200
14	10	200
15	20	200
16	30	200
17	40	200
18	50	200
19	5	250
20	10	250
21	20	250
22	30	250
23	40	250
24	50	250

The valve tappets used in this study were manufactured using DIN 16MnCr5 steel. The valve tappets were carburized, quenched, and tempered to obtain a wear-resistant hardened surface layer (case thickness – 800 µm and core thickness – 400 µm). Fig. 1 shows the microhardness distribution along the cross-section. The hardness and Young's modulus of the 16MnCr5 steel valve tappet were determined using the nanoindentation technique. The nominal chemical composition of the valve tappet is presented in Table 3. The microstructure of these valve tappets is presented in Fig. 2, while the mechanical properties of the valve tappet are summarized in Table 4.

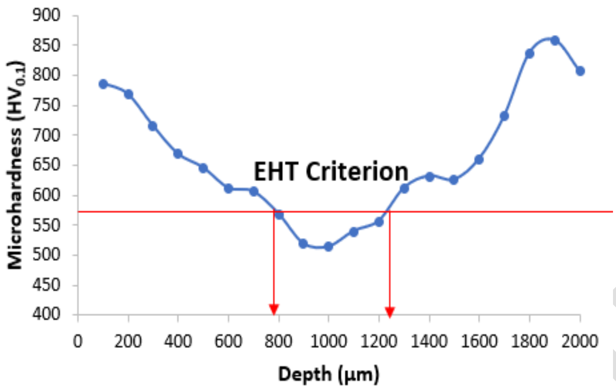

Fig. 1. Microhardness profile of tappet valve.

Table 3. Nominal chemical composition of the valve tappets (wt.%).

C	Mn	Si	Cr	P	S
0.14 – 0.19	1.05 – 1.30	0.4 max	0.85 – 1.10	0.025 max	0.035 max

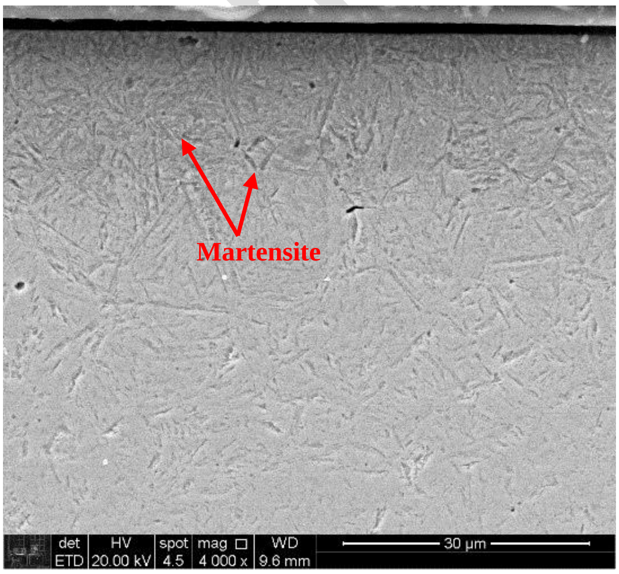

Fig. 2. SEM image of cross-section of tappet valve.

Table 4. Mechanical properties of the valve tappet.

Materials	Hardness (GPa)	Young's Modulus (GPa)	H/E	H^3/E^2 (GPa)
Valve tappet	11.04 ± 1.91	199.79 ± 4.31	0.055	0.034

2.2 Tribological testing

Dry tribological tests were performed for valve tappets with a ball-on-plane configuration in a reciprocating slide using an Optimol SRV® v4 device. The tests were performed for different loads (5, 10, 20, 30, 40, 50N) and temperatures (25, 150, 200, and 250°C) for 30 minutes, 10 Hz of reciprocating frequency, and a stroke length of 2 mm. The contact body used was AISI 52100 steel sphere balls. The tests were performed in triplicate for each test condition to ensure repeatability. The wear volumes were measured using the 3D coherence correlation interferometry (CCI) - Taylor Hobson profilometer.

2.3 Analysis of variance

The COF and wear rate results obtained from the reciprocating tribological test were tabulated into the 24 L orthogonal arrays created in Table 2. The results were then analyzed by ANOVA and Regression using Minitab® 21.4 statistical software. The ANOVA is a statistically based analysis usually used for detecting differentials in groups of tested data. The ANOVA helps test the main factors' significance and interactions by comparing the mean squared value against the estimated experimental errors.

3. RESULTS AND DISCUSSION

3.1 ANOVA for COF and wear rate

ANOVA was performed using two parameters at 6 levels and 4 levels for load and temperature, respectively, producing a 24 levels orthogonal array. Tables 5 and 6 summarize the ANOVA results for COF and wear rate, which indicate a degree of freedom (DOF) of 5 for load and 3 for temperature for both COF and wear rate. The F and P valves for the load are 1.17 and 0.369, respectively. The higher F value of the load compared to the temperature indicates that the load has a higher contribution to the COF than the temperature, as seen in Table 5. Similarly, the F value for the load was higher than that of the temperature. The F and P values for the load are 1.89 and 0.419, respectively. The higher F value of the load compared to the temperature indicates that the load has a higher contribution to the wear rate compared to temperature, as seen in Table 6. The difference between the F value of the load and temperature for the COF and wear is insignificant; therefore, it will be proper to mention that both load and temperature had almost equal contributions to the COF and wear of the valve tappet. A decrease in the COF was observed as the load increased at every level of increased temperature. This was probably due to increased deformation as the load increased, thereby reducing the COF at every increased temperature level. In the case of both the COF and wear rate, the load contributed more, implying an increase in load decreases the COF while increasing the wear rate, mainly because of an increase in deformation. The combined effect of both load and temperature increases the COF and wear rate of the valve tappet, which increases the adhesive and abrasive wear mechanisms, making the valve tappet wear out quickly as the temperature increases. The results in Table 6 show that the wear rate increases with an increase in temperature. Deformation at elevated temperatures will result in the oxidation of the surface, increasing the asperity conditions.

Table 5. ANOVA for COF of valve tappet.

Source	DOF	Sum of squares	Mean square	F value	P value
Model	8	1.531	0.1914	1.15	0.39
Load	5	0.9759	0.1952	1.17	0.369
Temperature	3	0.5552	0.1851	1.11	0.377

Table 6. ANOVA for wear of valve tappet.

Source	DOF	Sum of squares	Mean square	F value	P value
Model	8	1464.9	183.1	1.04	0.452
Load	5	922.2	184.4	1.04	0.428
Temperature	3	542.7	180.9	1.02	0.409

3.2 Regression analysis for COF and wear rate

The results of the experimental investigations on COF and wear rate were confirmed and validated using statistical models. The fittings were performed through nonlinear bivariate regression models using full factorial design of experiment involving two dependent variables/factor (response) and an independent variable (predicator) at six different load levels and four different temperature levels. The models were built at α = 0.05 (95% confidence level, significance, and goodness of fit). Table 7 and 8 summarize the results obtained from the regression analysis for COF and wear rate, respectively. Equations (1) & (2) are the statistical models obtained by regression analysis for COF and wear rate, respectively, where L is Load (N), and T is Temperature (°C).

$$COF = 1.264 - 0.00044L - 0.00036T \quad (1)$$

$$Wear\ rate = 30.25 - 0.164L - 0.0089T \quad (2)$$

Table 7. Regression for COF of valve tappet.

Term	Coefficient	SE Coefficient	t-value	p-value
Constant	1.264	0.238	5.31	0
Load	-0.00044	0.0056	-0.08	0.939
Temperature	-0.00036	0.00107	-0.34	0.738

Table 8. Regression for wear of valve tappet.

Term	Coefficient	SE Coefficient	t-value	p-value
Constant	30.25	7.46	4.06	0.001
Load	-0.164	0.176	-0.94	0.36
Temperature	0.0089	0.0334	0.27	0.793

The tested values were substituted into the statistical models, and the results were compared with the experimental results obtained during the tribological test, summarized in Table 9. Fig. 3 and 4 show the plot of a comparison between experimental and statistical for the friction and wear models, indicating a fair match between them. The average error obtained between the experimental and the models was approximately 8 - 12 %. This implies that the proposed models had 88 - 92% reliability.

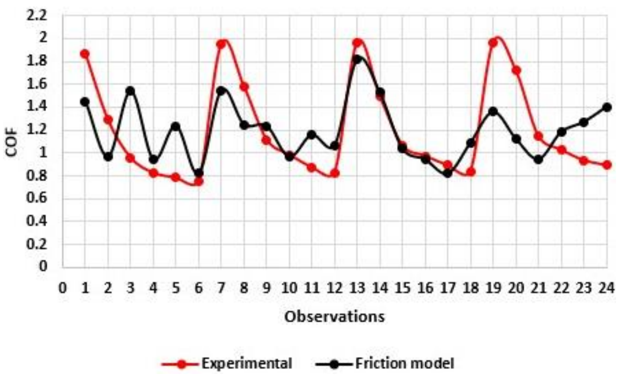

Fig. 3. Comparison between experimental and statistical friction model.

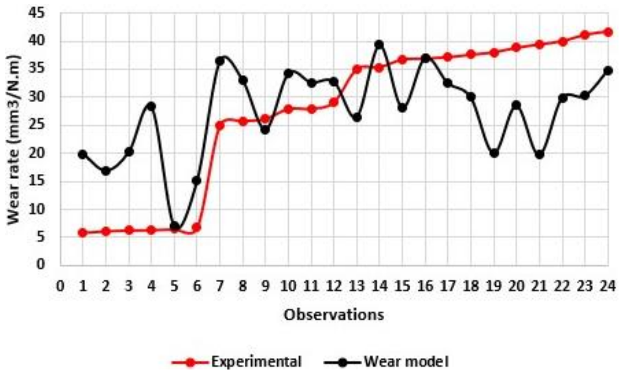

Fig. 4. Comparison between experimental and statistical wear rate model.

Table 9. Comparison between experimental values and statistical models.

Run order	COF Experimental	Friction model	Wear rate Experimental	Wear rate model
1	1.865	1.452898	5.90	19.88875
2	1.286	0.966558	6.17	16.92542
3	0.956	1.54155	6.31	20.24125
4	0.825	0.942495	6.37	28.27208
5	0.784	1.237482	6.52	6.94375
6	0.755	0.820591	6.69	15.20208
7	1.951	1.548986	25.00	36.50042
8	1.577	1.248784	25.74	33.00625
9	1.115	1.235894	26.15	24.27375
10	0.984	0.96497	27.93	34.25542
11	0.875	1.160133	27.97	32.65375
12	0.829	1.066621	29.11	32.77875
13	1.965	1.81991	35.00	26.51875
14	1.491	1.527145	35.36	39.28375
15	1.065	1.036007	36.71	28.14708
16	0.973	0.943129	36.89	37.03875
17	0.891	0.819003	37.13	32.53208
18	0.840	1.088462	37.58	29.99542
19	1.963	1.359386	38.00	20.01375
20	1.718	1.124658	38.81	28.49958
21	1.145	0.944717	39.40	19.70875
22	1.027	1.181974	39.98	29.87042
23	0.935	1.270626	41.11	30.22292
24	0.893	1.403019	41.72	34.77708

The COF residual plots are shown in Fig. 5 (a-b). These plots are normally used to justify the acceptability of the analysis. A normal probability plot shows the data distribution and justifies the data set's normality. The normal probability plot of Fig. 5a shows that the plot approximately follows a straight line. Hence, the data set forms an acceptable model. While the histogram plot, on the other hand, justifies the distribution of univariate data by showing the skewness, scale, and location of the data set as seen in Fig. 5c. The versus order plot shows the scatter data in which observation order is plotted on the x-axis and residuals are on the y-axis (Fig. 5d). The versus fit plot in Fig. 5b indicate that the observed data may exhibit a scattered pattern in relation to the residuals.

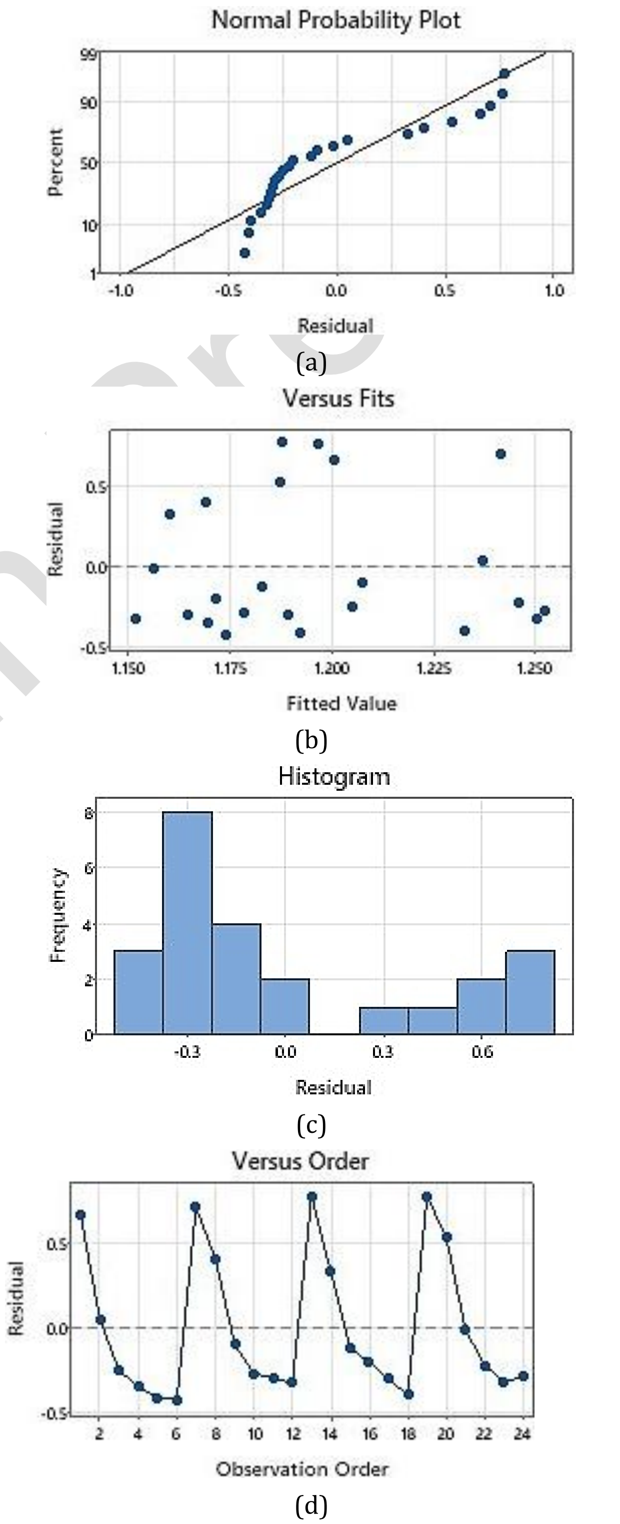

Fig. 5. Residuals plots for COF (a) Normal probability plot, (b) Versus fits, (c) Histogram, (d) Versus order.

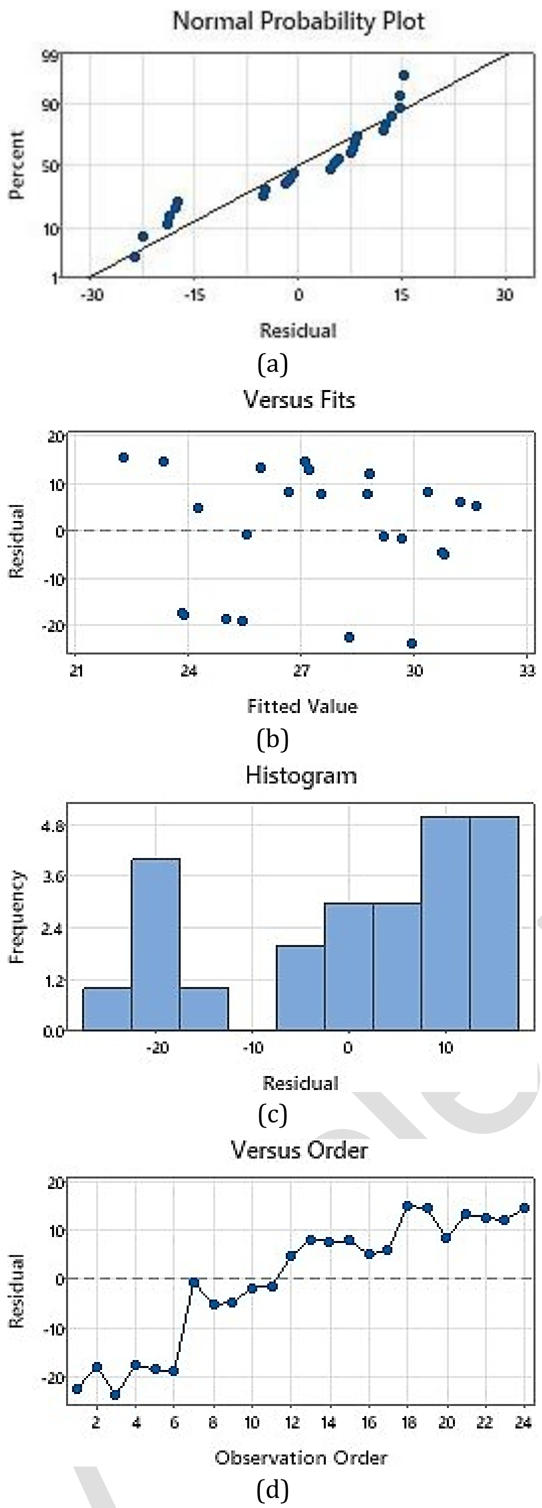

Fig. 6. Residuals plots for wear rate (a) Normal probability plot, (b) Versus fits, (c) Histogram, (d) Versus order.

The wear rate residual plots are shown in Fig. 6 (a-b). The normal probability plot of Fig. 6a shows that the plot approximately follows a straight line. Hence, the data set forms an acceptable model. The versus fit plot in Fig. 6b indicate that the observed data may have exhibited scattered pattern in relation to the residuals. On the other hand, the histogram plot in Fig. 6c, justifies the distribution of univariate data by showing the skewness, scale, and location of the data set. The versus order plot shows the scatter data in which observation order is plotted on the x-axis and residuals are on the y-axis (Fig. 6d). Furthermore, it is evident from both Fig. 5 & 6 that the observed data exhibit no correlation with the residuals.

The surface plots for COF and wear rate are presented in Fig. 7 & 8. The surface plot is used whenever a predictor variable is kept constant such that two predictor variables interact. The surface plot shows the influences of the load and temperature on the COF and wear rate.

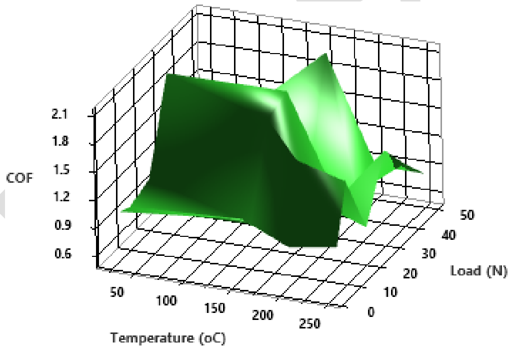

Fig. 7. COF surface plot as a function of load and temperature.

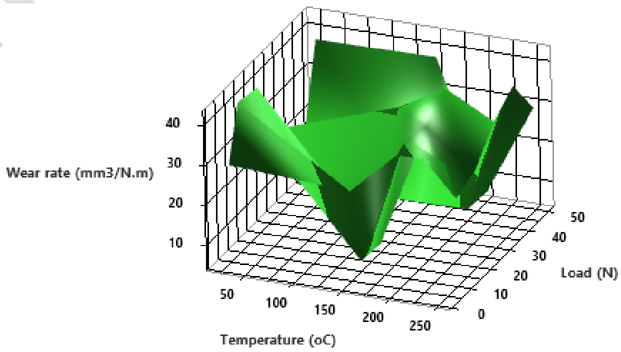

Fig. 8. Wear rate surface plot as a function of load and temperature.

4. CONCLUSION

In conclusion, the applied load is the most significant parameter that affects the COF, while temperature is the most significant parameter that affects the wear rate. The statistical models proposed have approximately 88-92% effectiveness. The equation models are limited to the tested parameters and range under the deformation region. These models can be beneficial for predicting the tribological operating conditions for the 16MnCr5 steel valve tappet to avoid premature failure.

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