Nigerian Journal of Technology (NIJOTECH)
Vol. 42, No. 4, December, 2023, pp.464 - 471
www.nijotech.com

Print ISSN: 0331-8443
Electronic ISSN: 2467-8821
https://doi.org/10.4314/njt.v42i4.6

BOX-BEHNKEN OPTIMIZATION OF PIN-ON-DISC WEAR TEST PROCESS PARAMETERS

AUTHORS:
B. N. G. Aliemeke[1,*], H. A. Okwudibe[2], A. I. Omoakhalen[3], and P. Major[4]

AFFILIATIONS:
[1,2,3,4]Department of Mechanical Engineering, Auchi Polytechnic, Auchi, Edo State, Nigeria

***CORRESPONDING AUTHOR:**
Email: aliemekebng@auchipoly.edu.ng

ARTICLE HISTORY:
Received: 11 July, 2023.
Revised: 20 December, 2023.
Accepted: 20 December, 2023.
Published: 12 February, 2024

KEYWORDS:
Optimization; Box-Behnken Design; Full factorial; Mathematical model, Test parameters; Statistical NOVA; Wear rate

ARTICLE INCLUDES:
Peer review

DATA AVAILABILITY:
On request from author(s)

EDITORS:
Chidozie Charles Nnaji

FUNDING:
None

Abstract
The Full factorial and Box-Behnken Designs for determination of optimal values of wear rate using pin –on-disc wear test parameters have been successfully carried out. The parameters used are track diameter of the disc, mass difference of specimen before and after the test and speed of the disc. The mathematical model developed for the "smaller-the-better" wear rate response by the Full factorial and Box-Behnken Design methods were adjudged adequate with a p-value of 0.025 and 0.046 respectively. Also, the adjusted R^2 values of the Factorial and Box-Behnken Designs were determined to be 0.89 and 0.69 respectively. The statistical ANOVA analysis carried out on the Box-Behnken Design showed that the track diameter and the mass difference were significant with a p-value of 0.041 and 0.007 respectively. Contour plots and response surface plot developed for the factorial method and the Box-Behnken Design displayed appreciable level of similarity. It was noticed that a reduction of wear was occasioned by an increase in track diameter and speed of the disc.

1.0 INTRODUCTION
Engineering materials in the course of their operations within engine system encounter some adverse conditions such fatigue and wear. These conditions are bound to happen so long as the components are involved in the running of the engine or facility system [1]. Wear may be seen as a kind of damage or loss of material in a component. It could also connote the change in geometry in a material as a result of deformation undergone during engine working process or mechanical shaping process [2]. The technical and economic consequences caused by wear cannot be overemphasized. So much so that material and design engineers have got to work extra ordinarily to accommodate its effect in a manufacturing operation. In the recent past the cost of component wear has been estimated to be up to four percent of the Gross National Product of a developed nation [3]. Abrasive wear challenges are observed virtually in every area of engineering so it finds expression in the determination of the lifetime of component parts in machines. This is evident in the application of dies and moulds in foundry engineering, car assembly in automobile and earth moving equipment in construction industry [4].

The manifestation of wear is noticeable in material appearance and surface profile. It actually results from the relative movement between a component surface

----
HOW TO CITE:
Aliemeke, B. N. G., Okwudibe, H. A., Omoakhalen, A. I., and Major, P. "Box-Behnken Optimization of Pin-On-Disc Wear Test Process Parameters", *Nigerian Journal of Technology*, 2023; 42(4), pp. 464 – 471; *https://doi.org/10.4314/njt.v42i4.6*

and an interacting body. It is tagged progressive as it increases with constant working operation and increased motion which causes detachment of material from the surface [5]. Wear failures could be as a result of the material sensitivity to the surface changes as a result of wear. Surface defects caused by material imperfections could lead to outright failure wear. Examples of wear failures occur in automobile valves which wear as result of galling, and cracked structural components whose wear nature could lead to reduction of fatigue life [6].

Various optimization tools have been employed to determine optimal levels of factors affecting wear of components. Taguchi design had been deployed to find the optimal levels of parameters such as speed, load, time for wear and sliding speed in the determination of the wear rate of aluminium alloy [7]. The work showed that the speed in rpm is the most influential parameter in the Pin on Disc wear experiment. A speed of 1500rpm brought about a wear rate of 0.015g/mm on the aluminium silicon alloy. Using mild steel for the same set of parameters yielded a wear rate of 0.005g/mm for an influential parameter of speed of 1412rpm. Taguchi design experiment has displayed appreciable level of dexterity in handling optimization of various process parameters and mechanical properties. Other optimization tools such as Full Factorial Design, Genetic algorithm, artificial neural network and Particle Swarm have been very useful over the years. Another emerging optimization tool showing high level importance is the Response Surface Methodology [8].

Box-Behnken design is a type of Response Surface Methodology that has been known to play a great role in the optimization of process parameters. It applies the second order quadratic equation model in determining optimal values of process and response parameters. It is found to be effective in various fields of study. Its impact has been felt in engineering, medical and pharmaceutical sciences. The model was applied in [9] to determine the efficiency of some certain drugs yield. It was discovered in the study that the phospholipids is very effective in improving solubility of water and enhanced bioavailability. The second order model was also applied in the determination of optimal values of squeeze casting parameters by [10].

This study is geared towards optimizing the effective wear parameters operational in a pin-on-disc wear test experiment using Full factorial and Box-Behnken Design analysis. The parameters investigated are track diameter of the disc, mass difference and speed of the disc in rpm.

2.0 MATERIALS AND METHODS

The materials used in this work are aluminium alloy specimen, variable weights, stop watch and Design Expert Software. The Pin-on-disc wear test machine shown in Figure 1 was used for the wear rate experiment . The Design Expert Software was used to perform the optimization of the Pin-on-Disc parameters. The software created the Design of Experiment platform applied in the wear analysis. It was used in carrying out the Factorial linear model and the Box-Behnken Design nonlinear model as well.

Figure 1: Pin-on-Disc wear test machine (Manufactured in Auchi Polytechnic)

2.1 Method

The experiment was conducted by mounting the aluminium alloy specimen pin on the lever arm so as to be directly on the circular disc. A weight of 2kg was placed at the load holder to complete the contact action between the pin and the disc. The weight of the specimen pin was taken before and after each experiment. The disc rotated with a speed range of between 1000 and 1500rpm during the experiment. As the disc rotates in contact with the specimen pin there exists a detachment of material particles from the contact surface of the pin. The pin-on-disc wear test machine has an in-built weighing balance that helps in recording the amount of the wear or lost material.

2.2 Determination of Wear Rate

The wear rate of the material was determined by using equation (1) obtained from [11]

$$W_r = \frac{M_i - M_f}{S_d} \quad (1)$$

Where; M_i: Initial mass of specimen; M_f: Final mass of specimen; S_d: Sliding distance; W_r: Wear rate.

The sliding speed is the product of the angular speed in radians and the track radius. While the sliding distance in the wear experiment is the product of experimental time taken in seconds and the sliding speed.

2.3 Design of Experiment (DOE)

The Design of experiment is the platform used in specifying the number of trials and conditions required for a particular experimentation. It is targeted at product quality and determination of actual number of experiments to be conducted [12]. The experimental layout was created for the Factorial model and the Box-Behnken Design model. The layout had columns for standard and run orders on which the experiment was conducted using the various parametric conditions as stipulated by the DOE.

2.4 Full Factorial Model

The Full factorial model is the linear model applied in this study. It was applied because of its ability to economically conduct fewer numbers of experimental runs while still targeting high quality product [12]. The model contained three parameters and a range of a maximum and minimum value. This means that a maximum of 2^3 experiments were considered in this study. In conducting the experiment a column for the response parameter was created for each experimental run. The outcome of the Factorial experimentation model is shown in Table 1. The three process parameters are track diameter, speed of disc and mass difference while the response parameter is the wear rate.

2.5 Box-Behnken Design

The Box-Behnken Design is an experimental layout of Response Surface Methodology (RSM) created to optimize process parameters and their levels. It is a non linear model developed to help in the estimation of responses by applying the second order quadratic response model [13]. The nonlinear model is reputed for handling minimum of 3 process factors and 3 levels. Also, the Box-Behnken Design model reserves the ability of applying fewer number of runs compared to the Central Composite Design (CCD) of the Response Surface Methodology. A total number of 17 experimental runs were specified by the Design Expert Software. The experimental matrix contained columns for the run orders and standard orders. The standard order which was prescribed by the Design Expert Software was used for randomizing the experimental order. The randomization effects helped in eliminating statistical selection bias and form a foundation for equality of test treatments. The Box-Behnken Design experimentation is shown in Table 4.

3.0 RESULTS AND DISCUSSIONS

The experimental and statistical analysis for the Full factorial and Box-Behnken Designs are shown in this section. Also, contained in this section are the contour and surface designs of the models considered. The wear response parameter was targeted at the smaller-the-better.

3.1 Full Factorial Design Analysis

The Design of experiment for the full factorial model is shown in Table 1. It is composed of 2^3 randomised runs and a column for calculated wear rate response value. The wear rate values obtained are close to the values obtained in [14] which shows that the parametric values applied are within the ambits of pin-on-disc wear test experimentation.

Table 1: Design of Experiment for the Full Factorial model

Standard	Run	Track diameter, D(mm)	Speed, N(rpm)	Mass difference, M(mg)	Wear rate, Wr(mg/mm)
5	1	50	1100	13000	5.90
7	2	50	1500	13000	5.70
1	3	50	1100	3000	5.60
8	4	90	1500	13000	5.50
4	5	90	1500	3000	5.80
2	6	90	1100	3000	4.80
6	7	90	1100	13000	4.90
3	8	50	1500	3000	5.40

Table 2: ANOVA Result for the Factorial experiment

Source	Sum of Squares	df	Mean square	F-value	p-value
Model	1.12	6	0.1867	9.33	0.0245
A-D	0.320	1	0.3200	16.00	0.1560
B-N	0.180	1	0.1800	9.00	0.0248
C-M	0.020	1	0.0200	1.00	0.0500
DN	0.500	1	0.5000	25.00	0.1257
DM	0.080	1	0.0800	4.00	0.0295
NM	0.020	1	0.0200	1.00	0.5000
Residual	0.0200	1	0.0200		
Cor Total	1.14	7			

The Adjusted Coefficient of determination(Adj R^2) and Coefficient of determination(R^2) values were calculated to be 0.8772 and 0.9525 respectively. The p-values of less than 0.05 as shown in Table 2 indicate that the parameters are significant as can be seen in speed, mass difference and the interaction between track diameter and mass difference. The adequate precision value was 8.3152. The determined values indicate that the developed model is adequate. The model is significant with a p-value of 0.0245. The developed model obtained by multiple linear regression is as given in equation (2)

$$W_r = 9.7025 - 0.08325D - 0.0032N + 0.00012M + 0.00006DN - 0.000001DM - 0.0000005NM \quad (2)$$

Where D: Track diameter in mm; N: Speed in rpm; M: Mass difference in mg; W_r: Wear rate.

The predicted and actual values are shown in Figure 2. It is evident that the predicted values and actual values obtained from the Design of experiment are very close as can be seen from the diagonal line, which shows that the distribution is normal. Also, there is no noticeable outlier in the distribution shown in Figure 2 which also confirms that the predicted and actual values were very close.

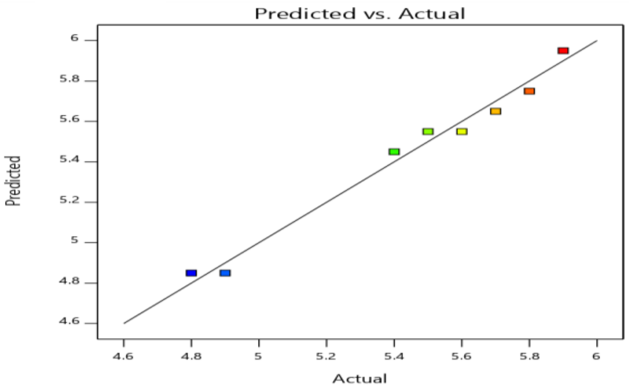

Figure 2: Predicted and actual values for the factorial experiment

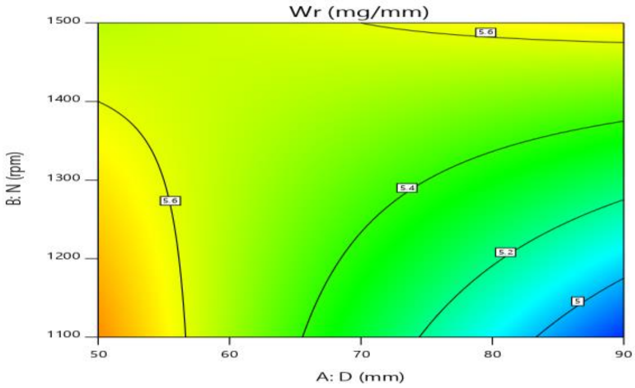

Figure 3: Contour plot for speed and track diameter parameters

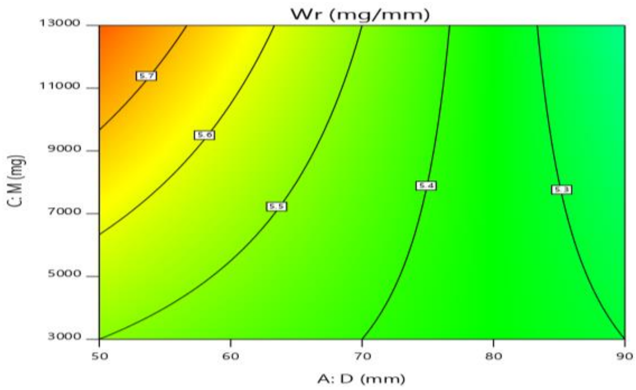

Figure 4: Contour plot for mass difference and track diameter

The contour plot shown in Figure 3, depicts that rate of wear is minimum at track diameter of 90mm and maximum at 50mm while an increase in speed of disc displays moderate wear rate. The surface plot shown in Figure 4 indicates that a high mass difference gives a high wear rate. An increase in specimen mass difference and speed of disc yields moderate increase of wear rate as shown in Figure 5.

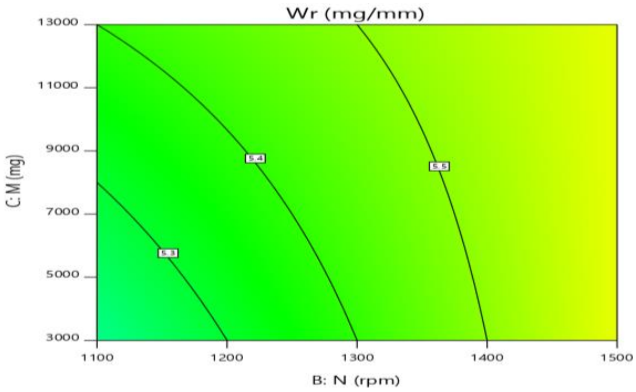

Figure 5: Contour plot for speed and mass difference

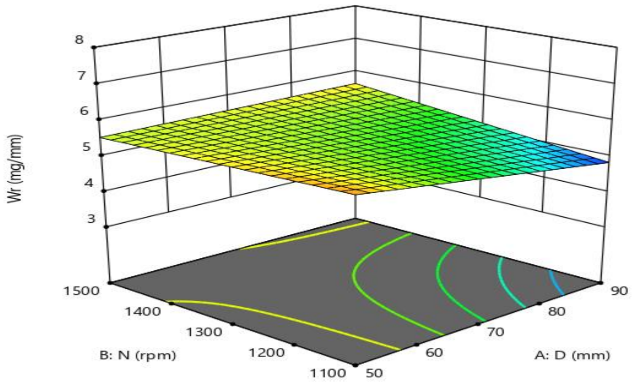

Figure 6: Surface plot for Wear rate from the interaction between speed and track diameter

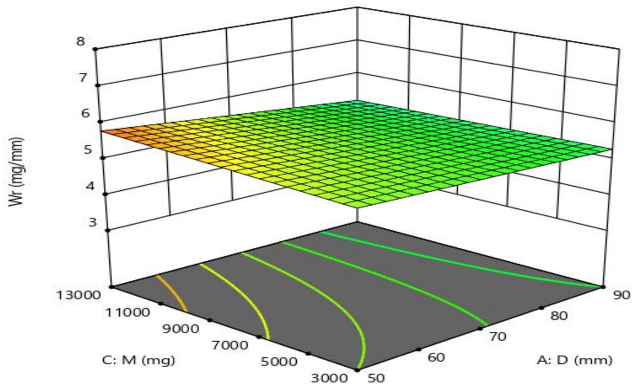

Figure 7: Surface plot for Wear rate from the interaction between mass difference and track diameter

It is evident in Figure 6 that an increase in the speed and track diameter of the disc leads to a moderate increase of the rate of wear. Also, it is clear that a slight decrease of wear rate from 5.5 to 4.8mg/mm was observed as a result of an increase of the track diameter from 50mm to 90mm. This shows that a large track diameter of disc favours reduction of wear as supported by [14].

Also, Figure 7 clearly shows the reduction of wear being occasioned by the increase of track diameter of the disc. While an increase in mass difference clearly depicts an increase in wear rate of the aluminium alloy specimen. The surface plot shown in Figure 8 depicts that an increase in specimen mass difference and speed of disc yields slight increase in wear.

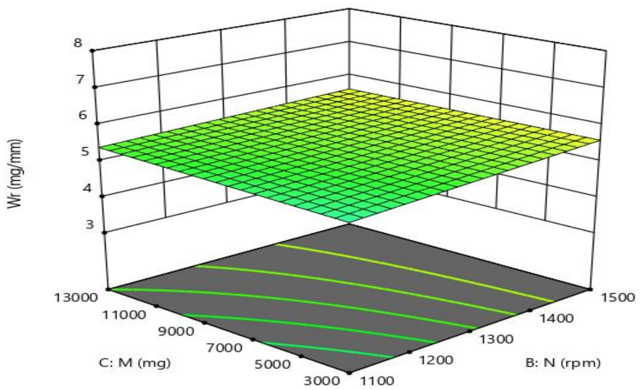

Figure 8: Surface plot for Wear rate from the interaction between speed and mass difference

Table 3: Design of Experiment for Box-Behnken design

STD	Run	Track diameter, A:D(mm)	Speed, B:N(rpm)	Mass difference,C:M(mg)	Wear rate, Wr (mg/mm)
2	1	90	1100	8000	5.85
11	2	70	1100	13000	5.75
10	3	70	1500	3000	5.80
3	4	50	1500	8000	5.60
6	5	90	1300	3000	5.40
14	6	70	1300	8000	5.60
12	7	70	1500	13000	5.00
1	8	50	1100	8000	4.90
15	9	70	1300	8000	5.15
13	10	70	1300	8000	5.20
8	11	90	1300	13000	4.95
17	12	70	1300	8000	5.40
9	13	70	1100	3000	4.90
4	14	90	1500	8000	4.95
5	15	50	1300	3000	5.50
16	16	70	1300	8000	5.60
7	17	50	1300	13000	5.7

Table 4: ANOVA result for the Box-Behnken experiment

Source	Sum of Squares	df	Mean square	F-value	p-value
Model	1.48	9	0.1643	3.24	0.046
A-D	0.0378	1	0.0378	0.7459	0.041
B-N	0.0003	1	0.0003	0.0062	0.934
C-M	0.0050	1	0.0050	0.0986	0.007
DN	0.6400	1	0.6400	12.620	0.009
DM	0.1056	1	0.1056	2.0800	0.921
NM	0.6806	1	0.6806	13.430	0.008
D^2	0.0009	1	0.0009	0.0187	0.895
N^2	0.0067	1	0.0067	0.0133	0.726
C^2	0.0021		0.0021	0.0420	0.843
Residual	0.3549	7	0.0407		
Cor Total	1.83	16			

3.2 Box-Behnken Design Analysis

The Design of Experiment platform applied in the Box-Behnken response surface methodology is shown in Table 3. The R^2 and Adj R^2 value were determined to be 0.8065 and 0.6077 respectively.

The developed mathematical model from the Box-Behnken experiment is as given in equation (3)

$$W_r = -10.410D + 0.141N + 0.123M - 0.001DN + 0.001DM - 0.003NM - 0.001D^2 - 0.0004N^2 + 0.00009M^2 \quad (3)$$

Where D: Track diameter in mm; N: Speed in rpm; M: Mass difference in mg; W_r: Wear rate.

The model is adjudged significant for a p-value of 0.046 which is below 0.05 used as confidence level. Also, parameters such as track diameter and mass difference are observed to be significant as a result of their p-values which are 0.009 and 0.007 respectively as shown in Table 4. The normality plot shown in Figure 9 portrays the proximity of the residual points to the ideal diagonal distribution line. It further gives credence to the model adequacy. In a similar manner to what was obtained in the linear model shown in Figure 2, there are no visible outliers in the distribution.

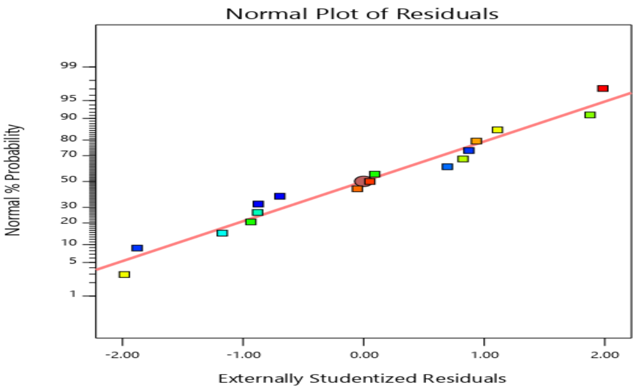

Figure 9: Normality plot for the Box-Behnken experiment

3.3 Graphical Analysis of the Box-Behnken Design Non-linear Model

The contour and the response surface plots shown in Figures 10 and 11 respectively, clearly indicates the magnitude and regions where wear rate occurs when track diameter and speed parameters were applied while having mass difference constant. It was observed that there exists a sharp reduction of wear with the increase of speed and the track diameter, as seen in Figure 11 where a very high value of track diameter of 90mm and speed of 1500m/s yielded the lowest value of wear rate of 4.5mg/mm.

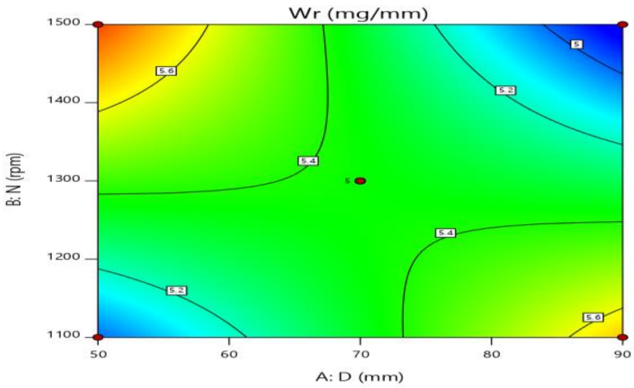

Figure 10: Contour plot for BBD wear rate involving track diameter and speed

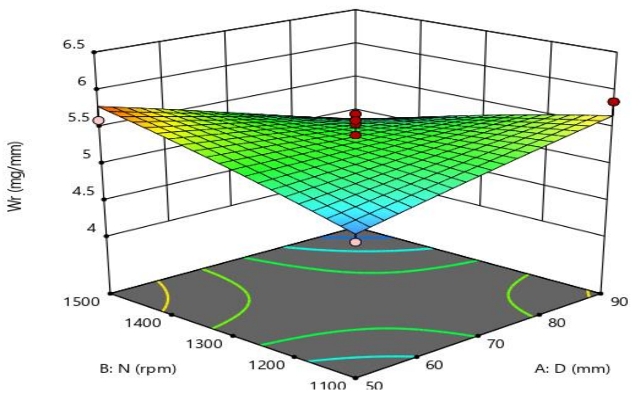

Figure 11: Response Surface plot for BBD wear rate involving track diameter and speed

A very moderate increase in wear rate occurred in the contour and the response surface plots shown in Figures 12 and 13 respectively. It is a clear indication that the combination of the mass difference and track diameter parameters will yield slight wear of the aluminium specimen.

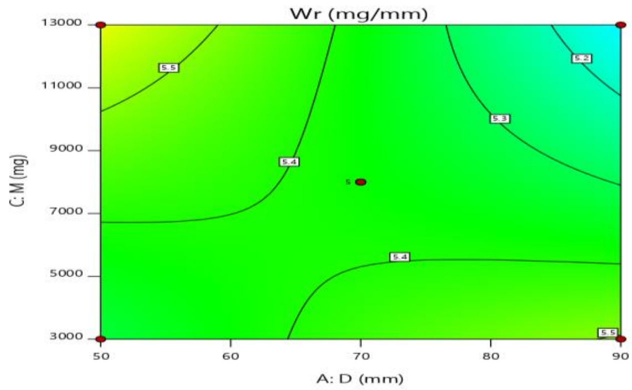

Figure 12: Contour plot for BBD wear rate involving track diameter and mass difference

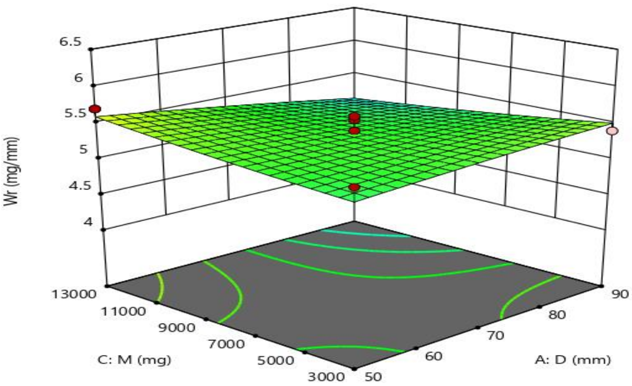

Figure 13: Response Surface plot for BBD wear rate involving track diameter and mass difference

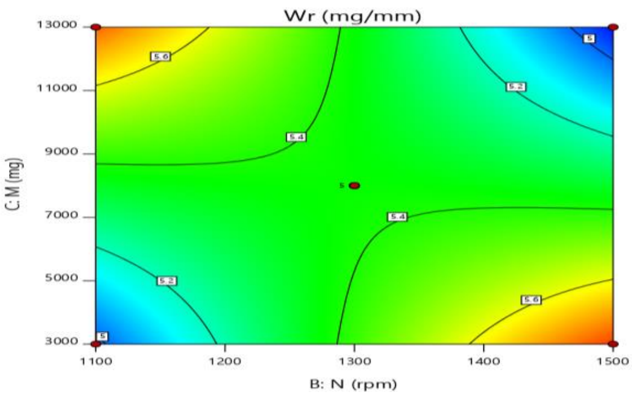

Figure 14: Contour plot for BBD wear rate involving mass difference and speed

Also, an increase in mass difference and speed resulted in a sharp increase in the wear response as described in the contour and response surface plots shown in Figures 14 and 15 respectively. The reddish brown patches in the contour and response surface plots represent high wear values and regions. While the blue patches represent low wear values and regions. To this end, it is noticed that low speed and low mass difference favours low wear rate. Also, evident from the plot is the attainment of low wear in the presence of high speed and high mass difference. The plot gives a strong indication that a better low wear rate is favoured more by low speed and low mass difference.

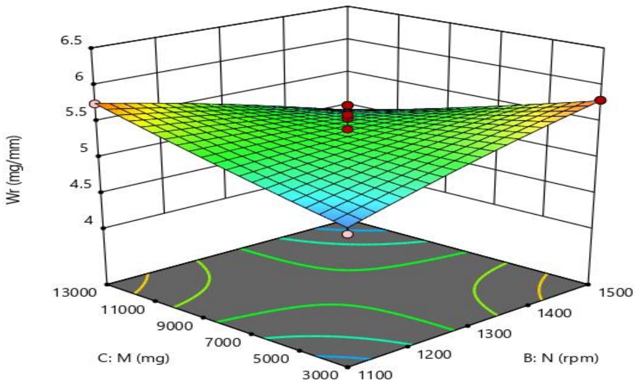

Figure 15: Response Surface plot for BBD wear rate involving mass difference and speed

4.0 CONCLUSION

Full Factorial and the Box-Behnken Design methods were successfully applied on the wear rate response of an aluminium alloy specimen using pin-on-disc parameters such as track diameter, mass difference and speed of disc. The factorial and Box-Behnken Design methods were used to analyse linear and non linear model respectively as applied in [15]. The data fitting analysis carried out on the first order and quadratic models showed that latter had the best fit and better adjusted R^2 values which qualified it to be used to navigate through the design space in order to obtain optimal values. The developed mathematical model for the factorial and Box-Behnken Design methods were found to be adequate with a p-value of 0.025 and 0.046 respectively. While the adjusted R^2 values of Factorial and Box-Behnken Design were 0.89 and 0.69 respectively. This served as pointers that the developed mathematical models are significant. The factorial method and the Box-Behnken Design showed some similarities in the contour plots and response surface plots. Some of the similarities were found in the reduction of wear rate which was occasioned by the increase in track diameter and speed of the disc. Also, an increase in speed and mass difference resulted in reduction of wear rate response while increase in mass difference and track diameter resulted in moderate increase in wear rate.

REFERENCES

[1] Ravindranath, B. S., Murthy, B. R. N., Ramu H. C., and Sandeep, N. S. "Process parameters Optimization of Pin on disc wear test to reduce wear loss of Aluminium alloys using Taguchi Design", *Engineered Science, Vol. 16, No.1*, 2021, Pp.366-373.

[2] Abdulwahab, U., Ndaliman, M. B., Olugboji, O. A., and Bala, K. C. "Development of a Dual Condition Pin on Disc Automated Wear Test machine", *Proceedings of the 7th North American international Conference on Industrial Engineering and Operations Management*, 2022, Orlando, Florida, USA,

[3] Anuar, N., Adnan, A. F., Saat, N., Aziz, N., and Taha, R. "Optimization of Extraction Parameters by Using Response Surface Methodology, Purification and Identification of Anthocyanin Pigments in Fruit", *The Scientific World Journal, Vol.2*, 2013, Pp.10-21

[4] Avalle, M., Belingardi, G., and Cavatorta, M. "Static and fatigue Strength of a Die Cast Aluminium Alloy Under Different Feeding Conditions", *Journal for Metallurgical Science and Technology, Vol. 2, No. 2*, 2011, pp. 9-13.

[5] Dwivedi, D. K. "Sliding Temperature and Wear Behaviour of Cast Al-Si-Mg Alloys", *Materials Science and Engineering, Vol. 3, No. 8*, 2006, Pp. 328-334

[6] Giwa, A., Adeyi, A. A., and Giwa, S. O. "Empirical Modelling and Optimization of PAME Reactive Distillation Process Using Minitab", *International Journal of Scientific and Engineering Research, Vol.6, No.6*, 2015, pp.538-549.

[7] Kharthik, M. N., Rohit, B., Bahett, N. N., Rohan, M., and Bhaskar, A. "Fabrication of Wear Test machine", *International Journal of Science and Research, Vol. 8, No. 4*, 2019, pp.1863-1866.

[8] Hassan, Z., Pandey, R. K., and Sehgal, D. K. "Wear characteristics in Al-SiC Particulate Composites and the Al-Si Piston Alloy", *Journal of Minerals and Materials Characterization and Engineering, Vol.10, No.14*, 2011, pp.1329-1335

[9] Agarwal, A., Kharb, V., and Saharan, V. A. "Process Optimization, characterization and Evaluation of Resveratrol-Phospholid Complexes Using Box-Behnken Statistical Design", *International Current Pharmaceutical Journal, Vol.3, No.7*, 2014, pp. 301-308

[10] Manohar, M., Joseph, J., Selvaraj, T., and Sivakumar, D. "Application of Box-Behnken Design to Optimize the parameters for Turning Inconel 718 Using Coated Carbide Tools",

International Journal of Scientific and Engineering Research, Vol.4, No.4, 2013, pp.620-643.

[11] Montgomery, D. C. "Design and Analysis of Experiments". *John Wiley and sons*, PTE limited, fifth edition, Asia, 2007.

[12] Thakker, J., and Patel, M. I. "Optimization of Process parameters for Surface Roughness and Material Removal Rate for SS 410 Material During Turning Operation", *Journal of Engineering Research and Application,Vol.4, No.2,* 2014, pp.235-242.

[13] Patel, G. C. M., Krishna, P., and Parappagouder, M. "Modelling of Squeeze Casting Process Using Design of Experiment and Response Surface Methodology", *International Journal of Cast Metals Research, Vol. 28, No.3*, 2015, Pp.167-180

[14] Ramesh, B. T., Arun, K., and Swamy, R. P. "Dry Sliding Wear Test Performed on Pin on Disc Test Set up for Aluminium Alloy and Metal Matrix Composite", *International Journal of Innovative Science, Engineering and Technology,* Vol. 2, No. 6,2015, pp. 264-270.

[15] Tekindal, M. A., Bayrak, H., Ozkaya, B., and Genc, Y. "Box-Behnken Experimental Design in Factorial Experiment", *Turkish Journal of Field Crops,* Vol. 2, No.17, 2012, pp.115-123

https://doi.org/10.4314/njt.v42i4.6