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RESPONSE SURFACE METHOD ACHIEVES ENHANCES TRIBOLOGICAL BEHAVIOUR OF AL-NANOTIO2 COMPOSITES USING IMPROVED OPTIMIZATION

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Abstract

Al- nano TiO_2 composite powder metallurgy and wear behaviour was experimentally examined on aluminium with combined nano TiO_2 weight percent reinforcements of 4%,7% and 10% at varied sliding velocities of 1.5 m/s,2.0 m/s,2.5 m/s and varying normal loads of 10N,30N,50N. The influence of particular wear rate and friction coefficient, optimised using the response surface method. The created model predicts outcomes that are consistent with the observed values. In accordance with the degree of precision of the mathematical model, the correlation coefficients for the particular wear rate and friction coefficient were around 0.98 and 0.96, respectively. The best conditions achieve the smallest specified wear rate and friction coefficient at a sliding velocity of 2.06 m/s and a normal load of 13.5 N with a weight of 10% Al-TiO_2. The expected value of specific wear rate is 1.08e-7, and the friction coefficient is 0.33.

1 Introduction

Powder Metallurgy (PM) processes are utilised in the aerospace and car industries to produce novel composite material components because to their better properties. Aluminium metal matrix composites (AMCs) are extremely desirable, and several investigations on the wear behaviour of Aluminium composites reinforced with diverse materials [1-3] have been published. The use of a Powder Metallurgy routing approach in the production of a metal matrix nano composite will result in a homogeneous dispersion of the reinforced material [4,5].

The mechanical and wear resistance of aluminium-based hybrid AMCs supplemented with TiO_2 and different particles of SiC, SiO_2 and Gr would be enhanced [6,7]. The addition of metal oxide TiO_2 to aluminium alloy improves its resistance to wear [8-11]. The porosity and tensile strength of Al with nano-sized TiO_2 (50nm) will result in enhanced wear resistance[12].

1.1 Response Surface Methodology

As previously indicated, RSM may be an effective method for analysing a process's reaction and determining the optimum connection between a process's characteristics. Statistical approaches are used to build models that study the relationship between the inputs and outcomes of any activity.

On the basis of the experimental data, a mathematical model was built with the purpose of determining the specific wear rate and coefficient of friction, as well as studying the interrelationships between the test variables of Al – nano TiO_2 composite.

The fundamental idea behind response technique [13] is to approximate this implicit limit state using a simple and explicit polynomial function. Typically, a response surface equation is written as

$$Y = \beta_0 + \sum_{i=1}^{m} \beta_i x_i + \sum_{i=1}^{m} \beta_{ii} x_i^2 + \sum_{i=1}^{m} \sum_{i<j}^{m} \beta_{ij} x_i x_j + \varepsilon \quad (1)$$

Where β0, βi, βii, and βij, represent regression coefficients; xi (i = 1,2,…,m) are design variables, ε is the random error, Y is the response and m is the total number of design variables.

Design Expert V8.0.6.0 software was used for the regression graphical analysis of the findings and to produce the regression equations for the coefficients. To quantitatively analyse the model, Analysis of Variance (ANOVA) was utilised. In addition, the data were utilised to anticipate the outputs under fresh situations. ANOVA [9] was also used to examine the Fisher's F-test (global model significance), its probability p(F), and determination coefficient R2 (used to determine the fitness of regression model).

1.2 Multiple response optimizations

In the majority of contemporary technical circumstances, many response variables are relevant to the success of an industrial process or system. In this work, the effects of sliding velocity, sliding velocity, and weight percent reinforcement of nano TiO2 on the specific wear rate and Co-efficient of friction are explored, as well as the ideal input parameter for reducing the specific wear rate and co-efficient of friction. In this study, a simultaneous optimization strategy based on a desirability function is applied [14].

2 Materials and Experimental Details

2.1 Materials

The materials utilised in current study are Aluminium fine powder with size range 130 – 180 micrometre, the purity 98% as base material acquired from Loba Chemi, India. The reinforced material TiO2 powder of size 5 nm, the purity 99.89 % acquired from US Research Nano Materials Inc, USA.

2.2 Pin Specimen preparation

Al powder with 4 wt%, 7 wt%, and 10 wt% of TiO2 nano powder is blended utilising a high-energy planetary ball milling machine. Using a Compacting machine, the blended powder is compressed to a height of 30mm at an applied pressure of 8.5MPa. The compacted specimens are sintered for 90 minutes at 580 degrees Celsius in a sintering furnace.

2.3 Wear test methodology

Wear tests were done on Al-TiO2 P/M pin specimens using a Pin-on-Disc tribometer in accordance with ASTM G99 and the output values of wear rates, frictional force, and coefficient of friction were recorded based on the design variables listed in Table 1.

Table 1. Experimental factor and their levels

Symbol	Parameter	Unit	Coded values and the corresponding values of parameters		
			-1	0	+1
A	Load	N	10	30	50
B	Sliding Velocity	m/s	1.5	2.0	2.5
C	TiO_2 Weight Fraction	%	4	7	10

Sliding distance 1000 m

Specific wear rate (SWR) are calculated by wear volume per unit distance and load and Co efficient of friction (COF).

3 Results and Discussion

3.1 RSM Modeling

Table 2 presents the experimental design and accompanying outcomes. The following models, Eq. (2) and (3), were created for the specific wear rate and friction coefficient using the regression coefficients listed in Table 2. After calculating the regression coefficient, the following model for predicting Specific Wear Rate and Coefficient of Friction was established:

$$\mathrm{SWR} = 2.11e^{-6} + 4.64e^{-7}A + 2.31e^{-6}B - 1.04e^{-6}C + 2.37e^{-7}A^2 + 9.68e^{-7}B^2 - 4.94e^{-8}C^2 + 4.3e^{-7}AB - 3.39e^{-7}AC + -9.06e^{-7}BC \quad (2)$$

$$COF = 0.4989 + 0.0390A + 0.1192B - 0.0683C + 0.0119A^2 + 0.0257B^2 - 0.0199C^2 + 0.0137AB - 0.0055AC - 0.0159BC \quad (3)$$

Where A, B, and C are corresponding coded values for temperature, strain rate, and solid lubricant.

The significance of each regression coefficient in Equations (2) and (3) is determined by the t-values and p-values in Table 2. A coefficient is more significant if its t-value is greater and its p-value is lower. In general, if p 0.05, a word is considered significant.

Table 2 Analysis of the design results for Specific wear rate and Co efficient of friction

	Specific wear rate (SWR)			Co efficient of friction(COF)		
	Regression Coefficient	t-value	p-value	Regression Coefficient	t-value	p-value
Constant	2.11E-06	8.091	< 0.0001	0.49898	24.775	< 0.0001
A	4.64E-07	3.822	0.0014	0.03903	4.165	0.0006
B	2.31E-06	19.923	**< 0.0001**	0.11924	13.344	**< 0.0001**
C	-1.04E-06	-8.589	**< 0.0001**	-0.06837	-7.295	**< 0.0001**
A^2	4.13E-07	2.998	0.0081	0.01372	1.290	0.2144
B^2	-3.39E-07	-2.285	0.0354	-0.00550	-0.481	0.6367
C^2	-9.06E-07	-6.572	< 0.0001	-0.01597	-1.501	0.1517
AB	2.37E-07	1.132	0.2734	0.01189	0.735	0.4723
AC	9.68E-07	5.339	**< 0.0001**	0.02571	1.838	0.0837
BC	-4.94E-08	-0.236	0.8165	-0.01994	-1.233	0.2343

Referring to the value of specific wear rate presented in Table 3, the sliding velocity and the weight percentage of reinforcement whose p-values are less than 0.05 indicate significance with regard to specific wear rate, and the interaction between the load and weight percentage of reinforcement parameters was significant. Coefficient of friction values are significantly affected by sliding velocity and the fraction of reinforcement's weight. Regarding the interaction of factors, there was no significant interaction among friction coefficient parameters.

Table 3. Response for Specific wear rate and Co efficient of friction observed experimental and predicted

Exp. No	Process parameters levels: Load N	Sliding Velocity m/s	TiO2 Weight Fraction %	Experimental result: specific wear rate m3/Nm	coefficient of friction	Predicted value: specific wear rate m3/Nm	coefficient of friction
1	10	2.0	4	2.30E-06	0.495	2.33E-06	0.534
2	30	2.5	10	3.47E-06	0.519	3.39E-06	0.561
3	30	2.5	7	4.97E-06	0.613	5.39E-06	0.629
4	30	1.5	4	1.01E-06	0.440	6.90E-07	0.448
5	50	1.5	10	7.25E-07	0.361	5.75E-07	0.351
6	50	2.5	7	6.91E-06	0.722	6.50E-06	0.667
7	30	2.5	4	6.90E-06	0.721	7.29E-06	0.696
8	50	2.0	10	1.46E-06	0.474	1.25E-06	0.475
9	30	2.0	7	2.10E-06	0.491	1.94E-06	0.505
10	30	2.0	10	1.55E-06	0.450	9.19E-07	0.437
11	10	1.5	7	8.74E-07	0.391	9.87E-07	0.343
12	50	1.5	4	1.16E-06	0.473	1.25E-06	0.486
13	50	2.5	4	9.77E-06	0.848	8.74E-06	0.734
14	50	2.0	4	3.12E-06	0.529	3.88E-06	0.610
15	50	2.5	10	3.39E-06	0.569	4.16E-06	0.599
16	10	2.5	4	6.37E-06	0.651	6.31E-06	0.658
17	10	2.0	7	1.94E-06	0.486	1.75E-06	0.467
18	50	1.5	7	1.01E-06	0.440	9.65E-07	0.419
19	30	2.0	4	2.40E-06	0.503	2.87E-06	0.572
20	10	1.5	4	9.32E-07	0.426	6.00E-07	0.410
21	10	2.0	10	1.35E-06	0.432	1.06E-06	0.399
22	10	1.5	10	5.52E-07	0.250	1.28E-06	0.275
23	10	2.5	10	3.29E-06	0.510	3.09E-06	0.523
24	30	1.5	10	6.24E-07	0.312	6.88E-07	0.313
25	30	1.5	7	8.87E-07	0.421	7.39E-07	0.381
26	50	2.0	7	2.40E-06	0.503	2.61E-06	0.543
27	10	2.5	7	4.54E-06	0.594	4.75E-06	0.591

In Fig.1 for SWR and COF, a comparison between the values predicted by the model and those obtained experimentally is provided. As observed in the picture, the majority of points are near to the centre line, indicating that this empirical model with great agreement between projected and measured values is highly accurate.

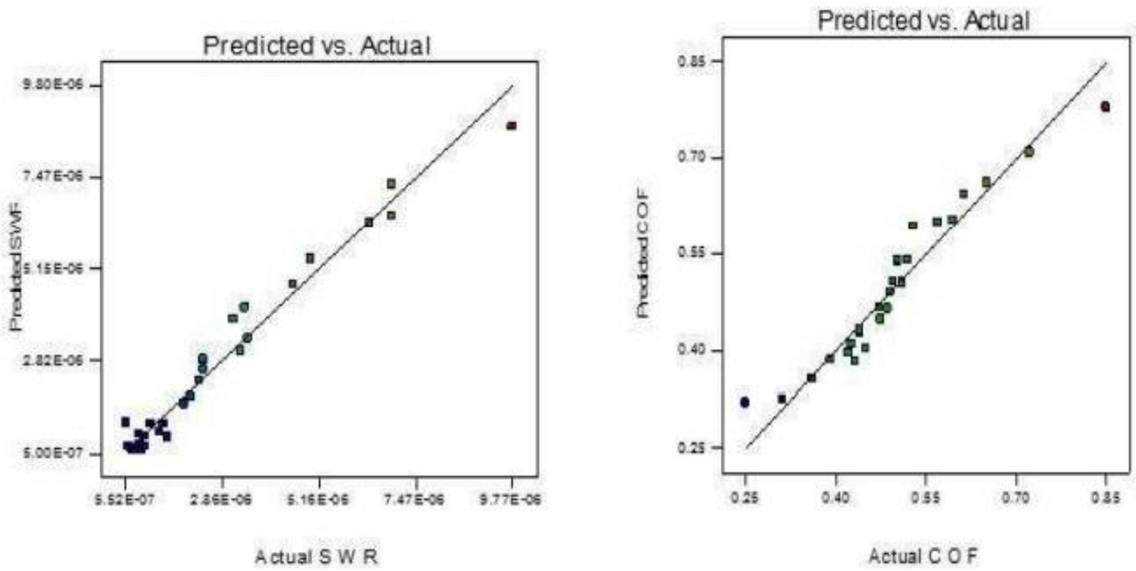

Figure 1. Experimental and predicted value of SWR and COF

Table 4. ANOVA based on RSM for models

Source	Specific wear rate (SWR)				
	SS	DF	MS	F-value	p >F
Model	$1.41e^{-10}$	9	$1.56e^{-11}$	59.31	<0.0001
Residual	$4.48e^{-12}$	17	$2.64e^{-13}$		
Total	$1.45e^{-10}$	26			
R^2			**0.9617**		
	Co efficient of friction (COF)				
Model	0.39925	9	0.04436	162.72	<0.0001
Residual	0.02668	17	0.00157		
Total	0.4259	26			
Total			**0.9374**		

The results of the analysis of variance (ANOVA) have been shown in Table 4. ANOVA is applied to analyze statistically the performance of the models developed by RSM. The ANOVA, performed on the RSM regression, indicates that p is greater than F (p>F) demonstrating that the models are significant and there is only a 0.01% chance that a model F-value this large could occur due to noise. Another way to check the accuracy of a model is normally by calculating the R2 coefficient. The R2 values were 0.9617 and 0.9374 for SWR and COF, respectively.

3.2 Contour plats

After the model is validated, contour plots may be used to examine the influence of interaction between factors on the SWR and COF of analysed AMCs. Figures 2 and 3 illustrate visually the 2D contour plots for the response surface of SWR and COF for the varied interaction among load (A), sliding velocity (B), and TiO2 wt% reinforcement (C).

It is evident from Figure 2 that the specific wear rate increases as sliding velocity and reinforcement % increase. It is evident that when the combination of load and reinforcement % rises, the specific wear rate falls.

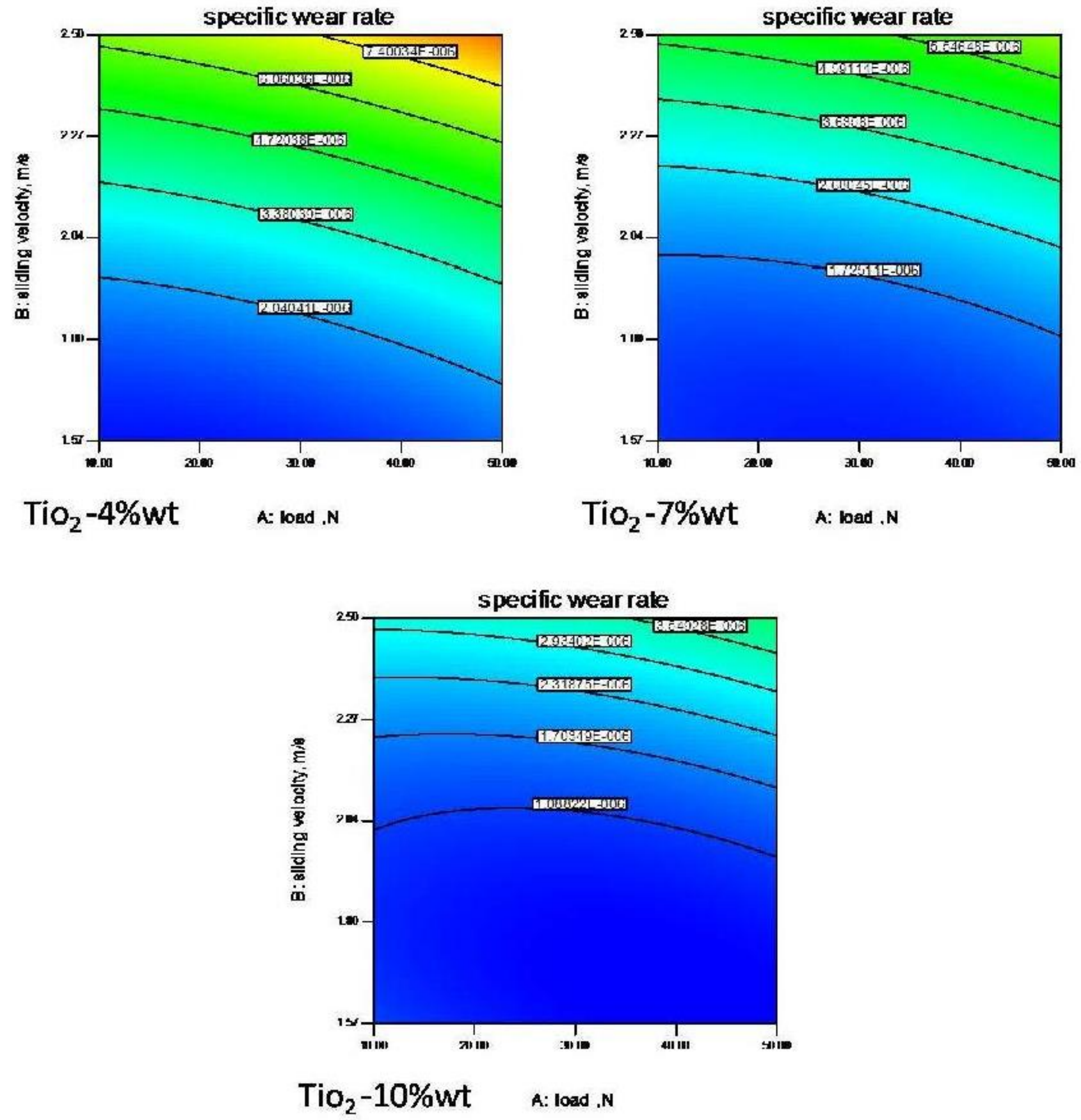

Figure 2. Contour plots of the SWR with different interaction among load (A), sliding velocity (B) at different TiO2 wt % reinforcement (C)

From the Figure 3, it is clear that as coefficient of friction increases with increase in sliding velocity and load. It is more significant that as the percentage of reinforcement increases, coefficient of friction decreases.

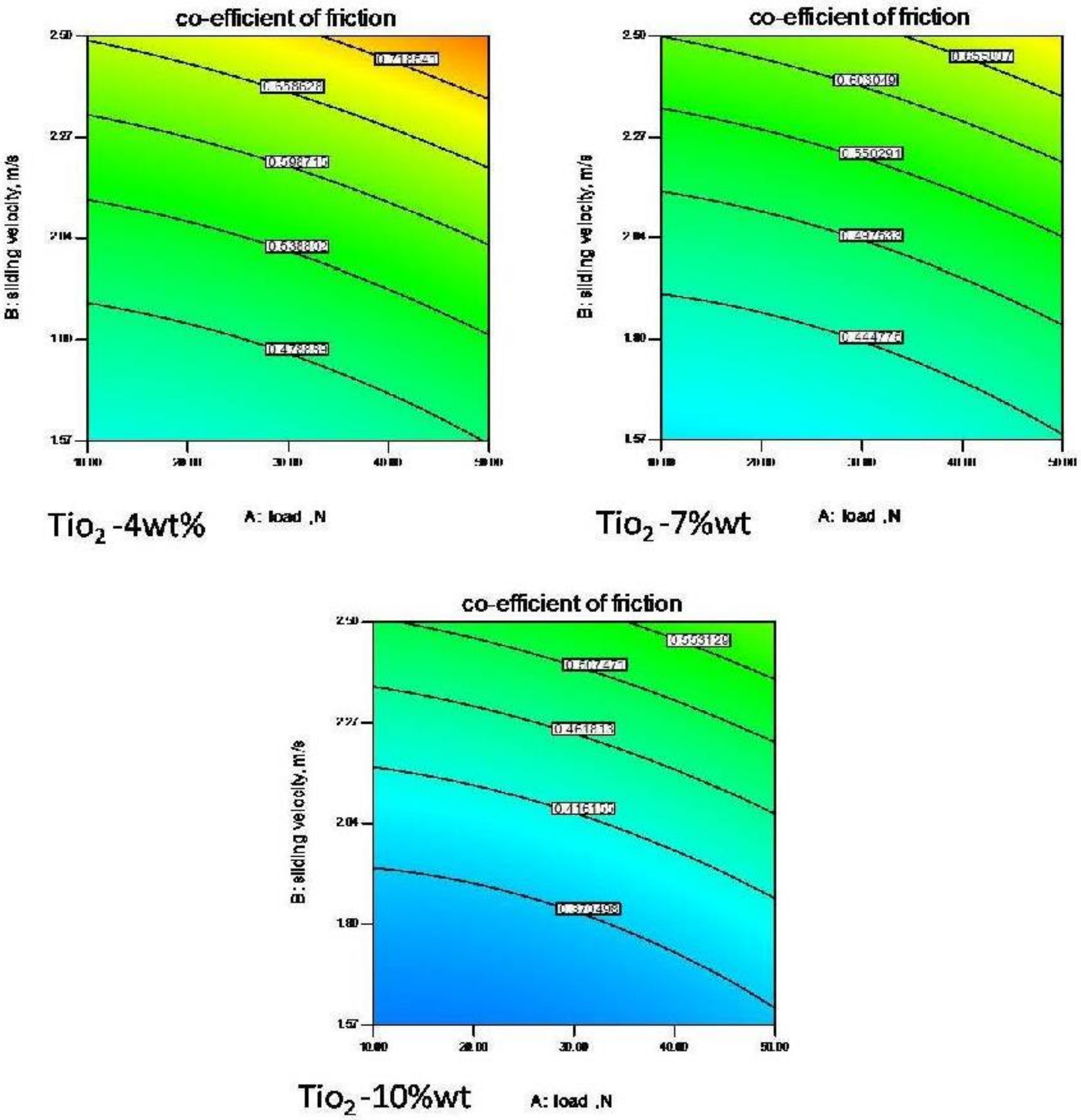

Figure 3. Contour plots of COF with different interaction among load (A), sliding velocity (B) at different TiO2 wt % reinforcement (C)

3.3 Multiple response optimizations

The optimization analysis was carried out using Design-Expert software. The goal set, lower limits used, upper limits used, weights used, and importance of the factors given are presented in Table 5. In desirability-based approach, different best solutions were obtained.

Table 5. Goals set and limits used for optimization

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Load (N)	is in range	10	50	1	1	3
Sliding Velocity(m/s)	is in range	1.5	2.51.0	1	1	3
TiO_2 Weight Fraction (wt %)	is in range	4	10	1	1	3
Specific wear rate (mm^3/Nm)	minimize	$5.52e^{-7}$	$9.77e^{-6}$	1	1	3
Co efficient of friction	minimize	0.250	0.848	1	1	3

Solutions with a high degree of attractiveness are favoured. Table 6 presents the three optimal solutions developed for multi-response optimization.

Table 6. Best solution for optimization

Number	Load N	sliding velocity m/s	TiO2 weight percentage	Specific wear rate mm3/Nm	Co efficient of friction	Desirability
1	13.49	2.04	10	1.08E-06	0.391	0.849
2	13.75	2.04	10	1.07E-06	0.391	0.849
3	13.20	2.04	10	1.08E-06	0.391	0.849

From Table 6, the obtained models were employed for multiple response optimizations using a desire function technique to produce the greatest strength coefficient and the smallest strain hardening exponent. According to Harrington's assessment system[14], the desirability is 0.849, which is acceptable and excellently significant. The optimal Specific wear rate 1,08e-6 mm3/Nm and Co efficiency of friction 0.3910 for load 13,49 N and sliding velocity 2,050 m/s, when the TiO2 weight percentage 10(wt%) is chosen from Table 6.

4 Conclusion

Response surface model and experimental design were used to model the tribological behaviour of Al- nano TiO2 powder metallurgy composite response of AMCs and predict the optimal Wear behaviour, which is distinguished by a significant effect of load, sliding velocity, and reinforcement weight percentage condition. In accordance with the analysis of variance (ANOVA), R2 and p-value represent the correctness of the constructed model. The relationship between the anticipated and measured values is good. Moreover, statistically generated models can forecast the optimal combination of process parameters to achieve the minimum specific wear rate and friction coefficient.

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