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Wear Analysis of Iron Slag Reinforced Polyester Composites with Taguchi Optimization

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ABSTRACT

In this paper, the dry sliding wear behaviour of the polyester composite reinforced with iron slag as filler was studied experimentally. The Taguchi method-based experiments were carried on pin-on-disk wear test set-up. The control factors considered for studying wear rate were sliding velocity, slag percentage and normal load applied on the member with constant sliding distance. The output performance parameters considered were coefficient of friction and weight loss. From the analysis of variance (ANOVA), it was observed that coefficient of friction is significantly affected by normal load then followed by slag content and sliding velocity. Sliding velocity plays a vital role on the weight loss, then followed by slag content and normal load. The optimal factor combination obtained was sliding velocity = 50 cm/s, slag percentage = 30 % and normal load = 4 kg. The model was validated using the set of optimal factor combinations to conduct a confirmation experiment.

Keywords: sliding velocity, pin-on-disk wear test, coefficient of friction, confirmation experiment, signal-to-noise ratio.

INTRODUCTION

Due to paucity of metals, polymer reinforced composites have created enormous engineering applications including tribology. Composites are beneficial by virtue of their better mechanical properties, high weight to strength ratio, fast manufacturing and low density. However, the high cost of lightweight composites for weight-sensitive applications makes commercial use difficult. Hence, to reduce the cost of components, low cost and easily available fillers and polymers are very useful. Unsaturated polyester is the better choice in view of dimensional stability, lightweight and low price. At the same time, one should ensure that addition of filler should not affect the mechanical properties adversely. It is suggested that a wide range of materials could be used in polymers as fillers (Katz and Mileski, 1987).

Due to industrial revolution and technical advancements in recent years, a large amount of wastage is produced in the industries. Alternatives must be discovered to reuse the waste materials instead of leaving it in landfills or pile up, which in turn damages the ecosystem. Government policies and environmental awareness forces the researchers to try industrial wastes as alternative fillers in polymer composites. There is evidence from past literature that cheap materials like industrial wastes are used as particulate fillers in developing particulate-reinforced polymer composites. Improvisations in tensile and flexural properties of composites were observed when fly ash and granite powder were used as fillers (Ramakrishna et. al., 2015). Chand, (1988) investigated the influence of fractional fly ash on the mechanical properties of polyester composites. Satapathy and Patnaik, (2008) explored the effects of reinforcement of red mud in polymer matrix with respect to dry sliding behaviour. The erosive wear action of red mud filled metal matrix composites was studied by Acharya et al. (2008). Biswas et al. (2012) performed extensive studies to examine the effects of red mud and copper slag particles as fillers on various bamboo – fiber – enhanced epoxy composites properties.

There is dearth of studies on wear behaviour of polymer composites especially in sliding conditions. Mao et al. (2015) stated that the sudden increase in wear rate occurs in polymer composites owing to frictional temperatures approaching the melting point of the material under loaded conditions. The friction between elements brings the high working temperatures, which will increase the wear. This reduces the life of the component and leads to faster replacement of parts. Therefore, the wear property should be considered in improving the life of the component (Rout and Satapathy, 2012). As a result of their limitations with respect to load carrying at high temperatures, they are appropriate in low energy transfer applications. Under dry sliding conditions, the tribological behaviour of metal matrix polymers, hybrid metal matrix composite materials and fibre-reinforced polyester composite materials were investigated (Prasat et al., 2011; Basavarajappa et al., 2006). Deuis et al. (1997) concluded that the dry sliding wear behaviour of composites is influenced by volume percentage of filler, normal load applied and sliding conditions such as time, distance, speed etc. Blast furnace slag or iron slag is the waste generated during the production of iron and steel. Vijaya Kumar et al. (2014), Vijaya Kumar et al. (2014), examined the dielectric properties of iron-slag reinforced polymers and their dry sliding wearing properties. Padhi and Satapathy, 2012, Padhi and Satapathy, 2013 analysed the tensile and flexural properties of blast furnace slag mixed epoxy-hybrid composite materials and their response to erosion. The dry sliding wear behaviour of aluminium matrix composites fabricated by powder metallurgy were studied and observed improvement in physical properties such as density and porosity of composites (Salman and Hasan, 2021).

The primary objective of present research work was to examine dry sliding wear behaviour of the polyester composite, reinforced with blast furnace slag. For this reason, the impact of control parameters on the wear amount i.e., successful wear resistance of composite designs were investigated. Therefore, individual impact of control factors has been studied at fixed levels. However, it is difficult to visualize the effect of any single operating feature or control parameter on interest output in an interacting system of operating parameters. To solve this issue, a cost-effective and easy-to-implement scheme built on Taguchi's factor design was followed to test the effects of different parameters on the dry sliding wear behaviour of blast furnace slag-reinforced composites. This methodology has been successfully employed for parametric assessment of tribological behaviour of various polymer–matrix composites (Basavarajappa et al., 2009; Pattanaik et al., 2016). In this analysis, under dry sliding conditions, the tribological activity of blast furnace slag reinforced polyester composite was performed. The coefficient of friction (COF) and weight loss of the sample were noted from the experiments conducted using Taguchi technique. The optimal parameter setting was found to obtain the minimum wear rate. The significance of each parameter was evaluated in terms of percentage.

METHODS AND MATERIALS

Blast furnace slag collected from LANCO pig iron industry at Sri Kalahasthi, Andhra Pradesh, India was ground to obtain a fine powder. The composition of slag collected consists of SiO_2 – 34.4%, Al_2O_3 – 19.95%, Fe_2O_3 – 0.57%, CaO – 32.4%, MgO – 9.8%, FeO – 0.32%, MnO – 0.45% and $P_2O_5 < 0.1$. Matrix material was purchased from ECMAS Resins Private Limited, Hyderabad, India. It consists of ECMALON 4413 grade (density 1.13 gm/cc at 25 °C), an unsaturated orthophthalic-grade polyester resin with a transparent colourless or pale-yellow colour. Methyl ethyl ketone peroxide (MEKP) hardener of about 2% and 2% cobalt accelerator (Catalyst) are added for curing the dough.

Table 1. Proportions of constituents in specimens

Sample (Iron slag)	Resin	Catalyst	Accelerator
10%	86%	2%	2%
20%	76%	2%	2%
30%	66%	2%	2%

Blast furnace slag powder was thoroughly mixed with the resin and others to prepare the samples in the correct proportion by weight. The percentages of materials added are presented in Table 1.

The method of hand layup was used to prepare samples. The glass test tubes (diameter of 9 mm and length of 12 mm) encased with standard thinly film of silicone discharging agent were then filled gradually with the dough to ensure that no air gaps were present. After leaving the castings for 24 hours, the specimens were extracted by breaking the tubes. The specimens were then cut into correct lengths, rubbed over sand paper to ensure adequate friction with counter surface. Composites with three different compositions were prepared as samples (10, 20 and 30 wt percent iron slag).

Testing

The pin-on-disk wear and friction monitor (DUCOM; TR-201C) provided by M/s DUCOM, Bengaluru, India with data acquisition system was used in the experimentation. The counter body was an En-31 hard ground steel disk with 60–65 HRC hardness and 0.5μm surface roughness (Ra). It is a versatile device designed solely for studying wear under dry sliding conditions. Normally, sliding occurs between a stationary pin (particulate composite specimen) and a 100 mm track diameter spinning disk. The D.C motor facilitates the disk to rotate with a speed range of 0–800 rev/min, which would trigger sliding speeds from 0 to 10 m/sec. The load was applied by dead weight on pin through the arrangement of the pulley string. The system has an upper limit load capacity of 10 kg and a wear range of between 0 and 2 mm. Under dry sliding conditions, as per ASTM G99 requirements, the wear tests on the samples were carried out. The testing was done by selecting the test time, velocity and load. First, the test samples were washed with acetone soaked in soft tissue. The test setup employed for experimentation is depicted in Figure 1.

The initial weight of the specimen was determined using a precision 0.0001 gm electronic balance. The load pin was compressed opposed to the counterpart during the wear test to rotate against the steel disc. After passing a sliding distance of 1500 m specimen was detached. Then, it was washed with acetone and weighed to measure the weight loss due to wear. The sliding wear weight loss of the composite specimens was evaluated by finding the weight difference before and after testing.

Experimental design

Design of experiments (DOE) is a tool to model and analyze the effect of control factors on the production of quality. There are several types

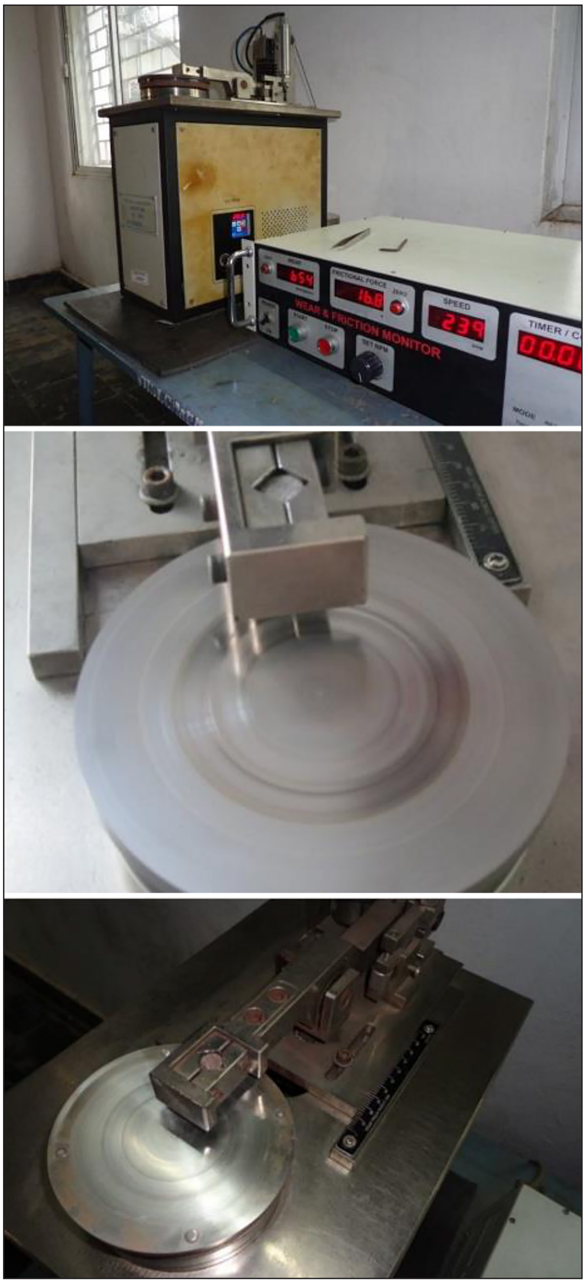

Figure 1. Wear test experimental setup

Table 2. Process parameter values at three different levels

Control factor	Levels			
	1	2	3	Units
Sliding velocity (A)	50	75	100	cm/s
Slag content (B)	10	20	30	wt%
Normal load (C)	4	6	8	N

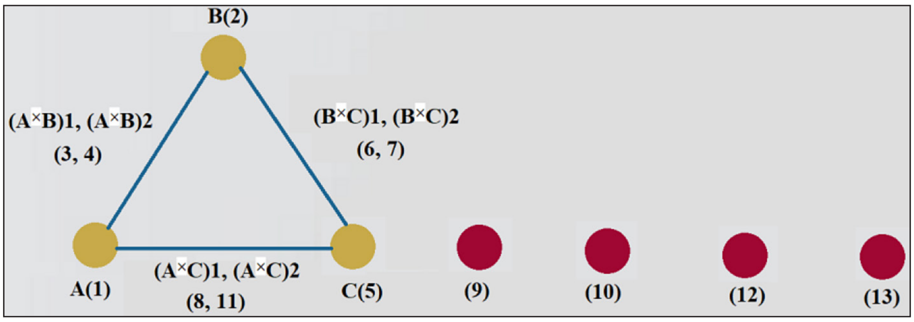

Figure 2. Modified linear graph of L_{27} (3^{13}) orthogonal array

of DOE approaches, among which the Taguchi technique is preferred for configuring high-quality systems, because it gives a good time and cost advantage (Roy, 2001). The Taguchi methodology offers a systematic approach for data collection, analysis of the effect of process variables and interpretation of data to fulfil study objectives. The largest amount of data can be obtained in DOE with the amount of analysis used by the use of these techniques. Taguchi Parameter Design can improve efficiency by setting design parameters and reducing sensitivity to device output to source of variation (Ross, 1996). The purpose of this study was to perform experiments using Taguchi's DOE methodology to determine the optimal levels of control factors that will give the minimum wear rate. From the experimental work, the dry sliding wear of the composites was observed as a function of the weight percentage of the applied reinforcement, sliding velocity, and load. The process parameters were changed at various levels, as presented in Table 2.

To accommodate the effect of two or more control factors, a Taguchi technique uses a standard orthogonal array and defines the experimental plan. L_{27} (3^{13}) orthogonal array was found suitable to assess the control factors and their interactions. It contains the outcomes of 27 different combinations. The experiment plan is followed as described in Figure 2 as modified linear graph by Taguchi orthogonal array design. For conducting the experiments, the interaction columns (3, 4, 6, 7, 8, 11) and dummy columns (9, 10, 12, 13) shall not be considered.

The effects of the experiment are then transformed to the signal-to-noise ratio (S/N). Depending on the type of performance characteristics, many S/N ratios are available. The S/N ratio for minimum wear rate can be demonstrated as the characteristic of "lower is better". This is evaluated as the conversion of the logarithmic loss function (Equation 1).

The "Lower is better" characteristic is as follows:

$$\frac{S}{N} = -10\log\left(\frac{\sum y^2}{n}\right) \qquad (1)$$

where: n – no. of observations;
y – noted data.

The experimental results were analyzed using variance analysis and S/N ratios to examine the effect of control factors and to find the noise factors. The optimum level of factor input is the combination of control factors with the highest-level signal-to-noise ratio.

RESULTS AND DISCUSSION

In this study, 27 experiments were conducted. The experimental output parameters noted were weight loss of the specimen and friction coefficient to analyze the wear rate effect. These tests were performed in accordance with the table of the L_{27} orthogonal array and results were noted in Table 2. Using Equation 1, the S/N

Table 3. L_{27} (3^{13}) orthogonal array and corresponding experimental results

L27	Sliding velocity (A)	Slag content (B)	Normal load (C)	Coefficient of Friction (COF)	S/N Ratio of COF (dB)	Weight loss	S/N Ratio of weight loss (dB)
1	50	10	4	0.3685	8.6713	7.450	-17.4431
2	50	10	6	0.4384	7.1626	8.100	-18.1697
3	50	10	8	0.4731	6.5009	10.550	-20.4650
4	50	20	4	0.3251	9.7597	7.030	-16.9391
5	50	20	6	0.3795	8.4158	7.675	-17.7016
6	50	20	8	0.4239	7.4547	9.950	-19.9565
7	50	30	4	0.2928	10.6686	6.755	-16.5925
8	50	30	6	0.3173	9.9706	7.355	-17.3317
9	50	30	8	0.3938	8.0945	8.825	-18.9143
10	75	10	4	0.3898	8.1832	7.860	-17.9085
11	75	10	6	0.4766	6.4369	10.240	-20.2060
12	75	10	8	0.5297	5.5194	12.500	-21.9382
13	75	20	4	0.3481	9.1659	7.650	-17.6732
14	75	20	6	0.4260	7.4118	9.250	-19.3228
15	75	20	8	0.4727	6.5083	10.820	-20.6845
16	75	30	4	0.3307	9.6113	7.355	-17.3317
17	75	30	6	0.3792	8.4226	8.825	-18.9143
18	75	30	8	0.4209	7.5164	9.855	-19.8731
19	100	10	4	0.4347	7.2362	12.900	-22.2118
20	100	10	6	0.5131	5.7960	16.545	-24.3733
21	100	10	8	0.6030	4.3937	21.070	-26.4733
22	100	20	4	0.3738	8.5472	10.250	-20.2145
23	100	20	6	0.4617	6.7128	14.120	-22.9967
24	100	20	8	0.5448	5.2753	18.350	-25.2727
25	100	30	4	0.3195	9.9106	8.570	-18.6596
26	100	30	6	0.4209	7.5164	11.150	-20.9455
27	100	30	8	0.4985	6.0467	16.650	-24.4283

ratio of friction coefficient and weight loss was evaluated for each combination and presented in Table 3.

To carry out analysis, statistical software MINITAB 17 is used. The graphical depiction of the impact of the three control parameters on COF and weight loss is presented in Figure 3 and Figure 4, respectively. The means of signal-to-noise response for COF and weight loss are given in Tables 4 and 5, respectively,

From Table 4 and Figure 3a, it is evident that all the three control factors have significant impact on the COF. The average sliding velocity S/N ratio of COF at level 1 is higher than the remaining stages. At level 3-slag content, the average S/N ratio of COF is greater than level 2 and level 1. Among the three levels, the average S/N ratio of COF at normal load level 1 is best. On comparable lines, level 1 (50) for sliding velocity, level 3 (30) for slag content and level 1 (4) for normal load yields the best

Table 4. Response table of COF

Level	A	B	C
1	8.522	6.656	9.084
2	7.642	7.695	7.538
3	6.826	8.640	6.368
Delta	1.696	1.984	2.716
Rank	3	2	1

Note: Delta = maximum value - minimum value.

Table 5. Response table of weight loss

Level	A	B	C
1	-18.17	-21.02	-18.33
2	-19.32	-20.08	-20.00
3	-22.84	-19.22	-22.00
Delta	4.67	1.80	3.67
Rank	1	3	2

Note: Delta = maximum value - minimum value.

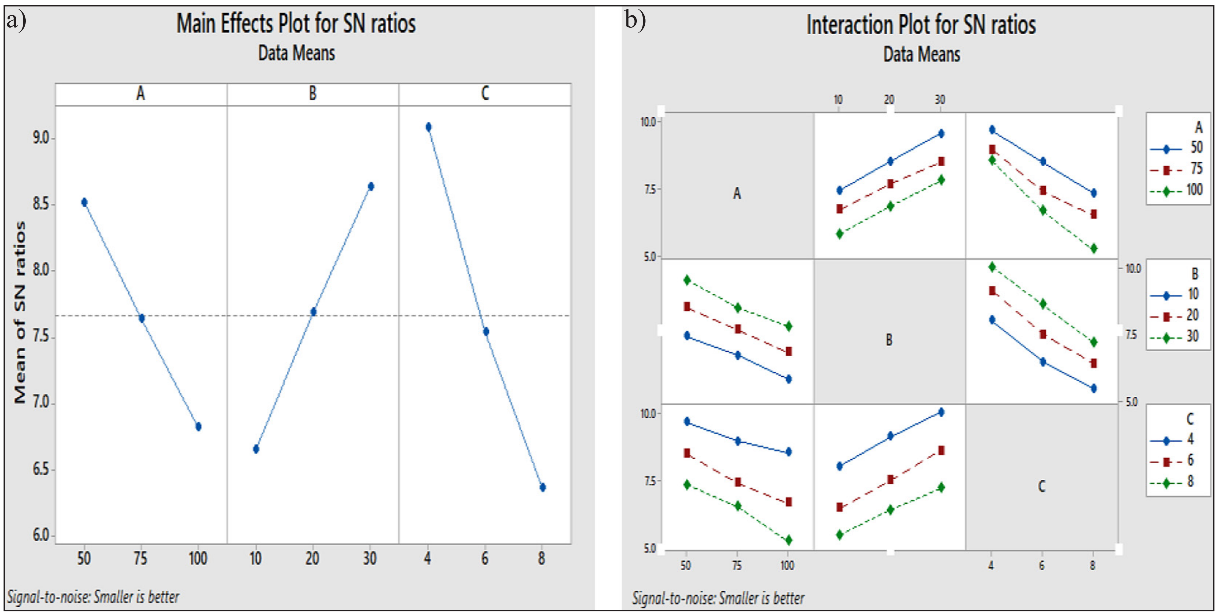

Figure 3. Effect of control parameters and their interactions on COF; (a) control factors; (b) interactions

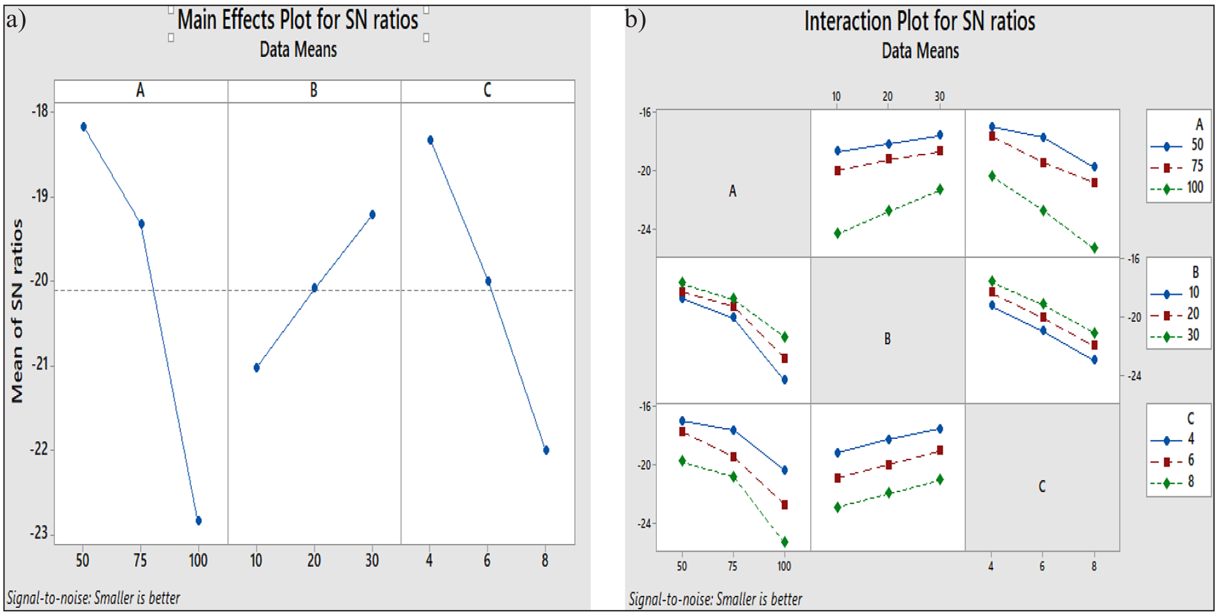

Figure 4. Effect of control parameters and their interactions on weight loss; (a) control factors; (b) interactions

combination for COF. Therefore, the optimum combination for minimum COF is $A_1B_3C_1$. From Figure 3b, the interaction of A*C shows significant effect. Normal load affects more on COF, followed by slag content and sliding velocity has least impact on COF.

Similarly, Table 5 and Figure 4a, indicates that all the three control factors affect the weight loss. The optimum combination for minimum weight loss is $A_1B_3C_1$. From Figure 4b it is found that the interactions of A*B and A*C have a substantial effect. Sliding velocity affects more on weight loss followed by slag content and normal load has the least impact on weight loss.

Analysis of both the S / N ratio response to COF and weight loss points to the fact that the combination of A_1, B_3 and C_1 factors provides a minimum COF and weight loss.

ANOVA results

A variance of analysis (ANOVA) table should be designed to analyze the important factors and their interactions in order to quantitatively illustrate a detailed overview of the effect of various factors and their interactions. The ANOVA results with respect to COF and weight loss are showed

Table 6. ANOVA results for COF

Source	DF	Adj SS	Adj MS	F	*p* value
A	2	0.031909	0.015955	107.92	0.000
B	2	0.040599	0.020299	137.92	0.000
C	2	0.077140	0.038570	260.89	0.000
A*B	4	0.0001990	0.000050	0.34	0.846
A*C	4	0.004349	0.001087	7.35	0.008
B*C	4	0.000354	0.000088	0.60	0.675
Residual error	8	0.001183	0.000148		
Total	26	0.15573			

Table 7. ANOVA results for weight loss

Source	DF	Adj SS	Adj MS	F	*p* value
A	2	195.844	97.9221	616.79	0.000
B	2	26.688	13.3439	84.05	0.000
C	2	102.678	51.3391	323.37	0.000
A*B	4	12.001	3.0003	18.90	0.000
A*C	4	26.774	6.6936	42.16	0.000
B*C	4	0.941	0.2351	1.48	0.294
Residual error	8	1.270	0.1588		
Total	26	366.196			

in Table 6 and Table 7, respectively. This analysis was carried at a confidence level of significance of 5%. The *p* value designates the rank of significant factors and their interactions.

It can be observed from Table 5 that the sliding velocity ($p = 0.000$), slag content ($p = 0.000$) & normal load ($p = 0.000$) have a major effect on the friction coefficient. The interaction of sliding velocity X normal load ($p = 0.009$) showed significant contribution on the COF. The interactions, sliding velocity X slag content ($p = 0.846$) and slag content X normal load ($p = 0.675$), represent no significant contribution towards COF. Moreover, from Table 6, it was found that the sliding velocity ($p = 0.000$), slag content ($p = 0.000$) & normal load ($p = 0.000$) have significant influence on weight loss. The interactions such as sliding velocity X slag content ($p = 0.000$), sliding velocity X normal load ($p = 0.000$) show significant contribution to the weight loss. The interaction, slag content X normal load ($p = 0.294$) represent no significant contribution towards weight loss.

Validation test

The final verification step in the design process of the experiment is the validation experiment. The purpose of the confirmation experiment was to validate the findings obtained from the research carried out. It concludes the similarity of the predictive values of the optimal setting parameters to the real ones. The expected S/N ratio can be determined with the optimum level of design parameters as follows (Equation 2):

$$\hat{\mu} = \mu_m + \sum_{i=1}^{o} (\overline{\mu}_i - \mu_m) \tag{2}$$

where: μ_m – total average S/N ratio;
$\overline{\mu}_i$ – average S/N ratio at the optimal level;
o – number of the main design parameters which affect the quality characteristics.

The final step will be to estimate and verify the performance characteristic improvement once the optimum level of the design parameters has been selected. Table 7 reflects a comparison of the expected average combination of the input control factor with the real one, using the optimum settings.

Confirmation experiment for COF

In order to predict the COF, it is done by running a fresh set of $A_1B_3C_1$factor settings. Using the optimum level of the design parameters, the approximate S / N ratio can be defined as (Equation 3):

Table 8. Results of the confirmation experiments for coefficient of friction

Parameters	Set of optimal parameters	
	Predicted value	Experimental value
Factor levels	$A_1B_3C_1$	$A_1B_3C_1$
S/N ratio of COF (dB)	10.68	10.6686
S/N ratio of weight loss (dB)	-16.44	-16.5925

$$\widehat{\mu_1} = \bar{T} + (\overline{A_1} - \bar{T}) + (\overline{B_3} - \bar{T}) + \\ +(\overline{C_1} - \bar{T}) + \begin{bmatrix} (\overline{A_1C_1} - \bar{T}) - \\ -(\overline{A_1} - \bar{T}) - (\overline{C_1} - \bar{T}) \end{bmatrix} \tag{3}$$

where: $\hat{\mu}_1$ – the expected average;
$\bar{T}$ – the overall average of the experiment;
$\bar{A}_1$, $\bar{B}_3$, $\bar{C}_1$ – the average responses at designated levels for factors and their interactions.

By aggregating like terms, the equation transforms to Equation 4.

$$\widehat{\mu_1} = \overline{A_1C_1} + \overline{B_3} - \bar{T} \tag{4}$$

As shown in Table 8, the expected coefficient of friction through the use of the predictive equation for the optimal parameter setting $A_1B_3C_1$ is μ = 10.67 dB. An error of 0.1% is observed for the friction coefficient S/N ratio.

Confirmation experiment for weight loss

The optimal parameter settings for minimum weight loss are $A_1B_3C_1$. The estimated S/N ratio of the design parameters at the optimal level can be calculated as (Equation 5):

$$\widehat{\mu_1} = \bar{T} + (\overline{A_1} - \bar{T}) + (\overline{B_3} - \bar{T}) + \\ +(\overline{C_1} - \bar{T}) + \begin{bmatrix} (\overline{A_1B_3} - \bar{T}) - (\overline{A_1} - \bar{T}) \\ -(\overline{B_3} - \bar{T}) \end{bmatrix} + \\ +[(\overline{A_1C_1} - \bar{T}) - (\overline{A_1} - \bar{T}) - (\overline{C_1} - \bar{T})] \tag{5}$$

where: $\hat{\mu}_1$ – the expected average;
$\bar{T}$ – the overall average of the experiment;
$\bar{A}_1$, $\bar{B}_3$, $\bar{C}_1$ – the average responses at the designated levels for factors and their interactions.

By aggregating like terms, the equation transforms to Equation 6.

$$\widehat{\mu_1} = \overline{A_1C_1} + \overline{A_1B_3} - \overline{A_1} \tag{6}$$

From Table 8, for the optimal parameter setting $A_1B_3C_1$, predicted weight loss through predictive equation is = -16.44dB. The ensuing model seems to be adequate to predict weight loss to an acceptable accuracy. For the S/N ratio of weight loss, a 1% error is observed.

CONCLUSIONS

In this investigation, the experimental plan and statistical analysis of blast furnace slag reinforced composite allow drawing the following conclusions. Blast furnace slag, an industrial waste, can be used with polyester resin as a possible filler material. Increasing the content of slag results in weight loss and friction coefficient increases for slag composites. As normal loads and sliding velocity increase, weight loss and coefficient of friction of slag composites decrease. The coefficient of friction is more influenced by normal load, then followed by slag content and sliding velocity. Sliding velocity plays a vital role on the weight loss then followed by slag content and normal load. From ANOVA test, the control factors like sliding velocity, slag percentage and normal load show significant influence on the wear properties along with interactions of sliding velocity * slag percentage and sliding velocity * normal load. As a percentage error is minimum, the results of the confirmation experiment agree well with the expected optimal factor settings. Therefore, it can be concluded that the Taguchi orthogonal array L_{27} has given the accurate results with least possible no. of experiments. The optimal factor combination is $A_1B_3C_1$ i.e, Sliding velocity = 50 cm/s, Slag percentage = 30% and Normal load = 4kg.

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