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Multi-Response Optimisation of Wear Behaviour of Epoxy Composites Reinforced with Metallic and Ceramic Particles Using Taguchi-Grey Method

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Abstract

In this work, a multi-response optimization technique has been used to optimize the process parameters considered while conducting the wear tests of fabricated particle-reinforced epoxy composites. The paper signifies the effect of $CaSiO_3$ and WS_2 particles reinforced epoxy composite's performance at different filler wt.% (2 wt.% $CaSiO_3$ and 1, 2.5, 4, 5.5 and 7 wt.% WS_2), load (30-70 N), and sliding distance (400-2000 m) parameters that are considered while conducting friction and wear tests. Experiments were conducted on a pin-on-disc configuration using an L25 OA through Taguchi's design of experiment for a constant time of 15 min. The results showed that the inclusion of particles improved the material's friction and wear resistance. The optimal combination of parameters was obtained with Taguchi-GRA followed by determining the most influencing factor using the ANOVA tool. The ANOVA tool calculates the percentage contribution of the process parameters. The wear behaviour was optimized to achieve the lowest coefficient of friction and specific wear rate. At a sliding distance of 2000 m and 15 min testing duration, the combination of parameters that yields the best result is a filler content of 2 wt. % $CaSiO_3$ and 5.5 wt. % WS2, along with a load of 70 N. The ANOVA results reveal that the load with a percentage contribution of 50.87% is the most significant parameter followed by filler content (15.63%) and sliding distance (13.55%). A confirmation test is carried out using the optimal control parameters to validate the experimental results. Additionally, the SEM was used to analyse the worn surfaces of epoxy composites. The SEM images reveal the adhesive and abrasive wear mechanism is most prevalent in the observed material.

Keywords: *$CaSiO_3$, Coefficient of Friction, Epoxy, Grey Relational Analysis, Specific Wear Rate, WS_2*

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1.0 Introduction

In recent times, polymer materials have been replacing metallic materials in various industries such as aerospace, automobile, civil, defence, etc. due to their lower weight, low cost, ease of processing, and ability to incorporate fillers[1–3]. To utilize polymers more effectively, attempts have been made to include particulate fillers in them. Polymers can have their properties such as strength, wear, thermal resistance, and modulus altered by the incorporation of fillers in them[4,5]. Various kinds of fillers like $CaCO_3$, talc, ZnO, CuO, TiO_2, WS_2, mica, etc. are incorporated into polymers to improve modulus, hardness, strength and wear resistance[6–8].

One of the engineering polymers that has been utilized extensively over the past several decades and found usage in several kinds of industries is epoxy resin. The variation in the behaviour of epoxy composite depends on the amount, type, properties, and compatibility of the reinforcement with the matrix. In recent years, several epoxy composites have been developed, and they are reported for their promising mechanical, thermal, and wear properties[9]. Researchers have focused on studying the wear behaviour of epoxy composites due to their potential use in mechanical and structural applications like cams, seals, brakes, and bearings. Wear resistance is now a key criterion for selecting materials, highlighting the importance of understanding the tribological properties of polymer composites. To design structural components and choose materials that minimize wear, it is essential to understand how various tribological factors influence the wear rate[10].

The selection of material with preferred properties from a vast range of existing materials available is a tedious and tough task as no single material meets all the required demands. Thus, it turns out to be a real challenge for the engineers to select the best alternative materials that meet the requirements of complex design problems.

Lately, the Multi-Criteria Decision-Making (MCDM) technique has been used as an efficient tool to select material for complex design problems. The outcome of these steps is the ranking order of all alternative solutions. Various MCDM tools namely, the Analytic Hierarchy Process (AHP), Elimination And Choice Translating Reality (ELECTRE), Weighted Product Model (WPM), a Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Grey-relational analysis are employed, depending upon the complexity of the situation in engineering decision-making problems[11]an effort is made to manufacture a tractor pedal shaft using two different materials En8D and SAE1018. The shaft was made by using a Gas Metal Arc Welding technique. The welded shaft was then tested for ultimate tensile strength along with radiographic NDT testing to detect the welding defects in the shaft. Furthermore, the study uses Taguchi technique to optimize welding parameters like welding current, welding voltage, gas pressure, wire feeding rate, and nozzle to work piece distance in order to achieve high strength, defect-free welding for a tractor pedal shaft. A standard Taguchi experimental plan with notation L9 was chosen. Finally, the most significant design factor affecting the tensile strength of the shaft was investigated using Analysis of Variance (ANOVA).

GRA is used to solve multi-criteria decision-making problems by combining all the performance attribute values for every alternative into one single value. This reduces the original problem into a single decision-making problem[12].

Subbaya *et al.*[13] Fabricated SiC/carbon fabric epoxy materials and evaluated the mechanical and tribological behaviour. Taguchi's DOE is used to conduct wear tests on a pin-on-disc machine considering the design parameters like filler per cent, grit size, load, and abrading distance. Furthermore, GRA is employed to optimize the wear parameters followed by ANOVA which determined that filler content is the parameter with the highest significance. Also, it is observed that the addition of SiC particles into Carbon fabric reinforced epoxy composite showed increased wear resistance. J. Sudeepan *et al.*[14] Focused on the study of optimization of parameters (filler content, load, speed) involved in the wear of kaolin/ Acrylonitrile-Butadiene-Styrene (ABS) composites. The wear tests on multi-tribe testers are conducted using L_{27} OA. Moreover, GRA is used to find the best combination of parameters for the lowest friction coefficient and specific wear rate. After which ANOVA was performed, which determined filler content is the highest influencing parameter. Lastly, worn surfaces are examined to reveal the wear mechanisms.

Yıldız Cabuk *et al.*[15] Developed polyhydroxybutyrate/ polylactic acid/cellulose nanofibrils and polyhydroxybutyrate /polylactic acid/nano-TiO_2 (0.5, 1,

and 2%) hybrid composites. Taguchi-GRA was chosen to optimize the parameters of the blends. The GRA results revealed that blends with 0.5% CNF possess good mechanical properties. However, Taguchi analysis found that a blend with 2% nano TiO_2 possesses the best mechanical properties. Ganesh *et al.*[16] Conducted wear tests of Mg-TiO_2 nanocomposite on a Pin-On-Disc machine. Later the parametric optimization is done through the Taguchi-Grey method to evaluate the wear behaviour of composites. The study concluded an optimal combination of 5wt% TiO_2, 1 kg load and 1.5 m/s sliding speed to obtain minimum wear and coefficient of friction. Also, ANOVA was carried out to reveal load is the most significant factor.

Musa Alhaji Ibrahim *et al.*[17] Experimentally studied the wear properties of polytetrafluoroethylene (PTFE) composites. They performed an optimization for the load (L), grit size (G) and sliding distance (D) using the Taguchi-GRA method. The responses COF and SWR were recorded for each experiment. Using ANOVA, they calculated the percentage contribution of each parameter and reported that grit size had the most significant effect on abrasive wear properties. Balamurugan Ponnambalam *et al.*[18] Applied Taguchi-based GRA to analyse the effect of reinforcement, load and sliding velocity parameters included in the wear test on multiple responses (SWR, wear rate, and COF) of SiC/flyash/copper composites. Furthermore, ANOVA is used to reveal sliding velocity is the utmost significant factor that impacts wear performance.

A variety of ceramic powders such as Aluminium nitride (AlN), beryllium oxide (BeO), Zinc oxide (ZnO) etc. and solid lubricants such as molybdenum disulphide (MoS_2), graphite, etc., are commonly used as conventional fillers, but the combination of ceramic and solid lubricants reinforced in matrices is hardly found. In consideration of this, two fillers in the powder form viz. $CaSiO_3$ and WS_2 are chosen to be used in the present study.

This paper aims to examine the tribological behaviour of $CaSiO_3$/WS_2/epoxy composites conducted according to OA for Taguchi design. The design factors selected for the present work are filler content (A), load (B), and sliding distance (C), each with five levels. The responses analysed in this study are COF and SWR. To determine the optimal combination of design factors, the study employs a combination of GRA and the Taguchi method. To validate the findings of the study, a confirmation test is carried out. Additionally, ANOVA is employed to identify the most influential factor that impacts the responses.

2.0 Materials and Methods

2.1 Production of Epoxy Composites

For the current study, epoxy resin (AW106) supplied by Huntsman International (India) Pvt. Ltd. and its corresponding hardener (HV953U), a thermoset polymer is chosen as a matrix material. The materials used are mixed in a weight ratio of 10:9 as recommended[19]. The study uses two types of fillers: Wollastonite ($CaSiO_3$) procured from Galaxy Corporation in Mumbai, and Tungsten disulphide (WS_2) from Sajan Overseas in Vatva, GIDC, Ahmedabad, Gujarat. The particles used are shown in Figure 1. Wollastonite ceramic particles



Figure 1. **(a)** $CaSiO_3$ **(b)** WS_2 particles.

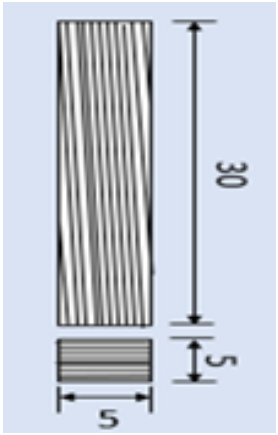


Figure 2. Schematic of specimens prepared.



Figure 3. Sample specimens for tribometer.

with a density of 2.4 g/cc and a size of 2 µm were used for reinforcement. Another material used for reinforcement was solid lubricant, Tungsten disulphide with a density of 4.2 g/cc and a size of 3 µm. The purpose for selecting the epoxy matrix is that the epoxy receives much importance in automotive, marine and aerospace sectors for manufacturing parts like chassis and external framework, window frames, brackets, fittings, boat's cabin, roof and bulwark[20]. The reason for selecting the reinforcement, wollastonite is its high strength and wear resistance in friction devices whereas the addition of tungsten disulphide reinforcement acquires a certain self-lubricating property in the cast composite[21,22].

A simple hand mixing and magnetic stirring technique were used to prepare five combinations of $CaSiO_3$/WS_2/Epoxy specimens. The weighed amounts of powders in terms of grams are mixed in epoxy resin. The mixture is stirred manually for 30 min followed by magnetic stirring for 2 hrs. The hardener is added to the blend by mixing it with hand for 5 min. The resulting mixture is poured into a metallic mould with two slots of 150 mm × 25 mm × 5 mm each. The specimens are then allowed to cure at room temperature for 24 hrs. After the curing process, specimens measuring 150 × 25 × 5 mm in dimensions are released. Table 1 presents the composition of the matrix and filler, as well as the designation of the fabricated composites. The pins required for wear testing were cut into rectangular dimensions of 30 mm × 5 mm × 5 mm as shown in Figure 3. The schematic diagram of the specimen is shown in Figure 2.

2.2 Design of Experiments

A standard Taguchi experimental plan with OA L_{25} was chosen for the study[23].

The three design factors taken into consideration while analysing the friction and wear tests of $CaSiO_3$/WS_2 filled epoxy composites are:

- Filler content
- Load
- Sliding distance

Table 2 displays the three design factors, each with five levels, used to create the Taguchi design of experiments. Performing a full factorial experiment with three factors, all at five levels, 125 runs would be needed, calculated as 5^3. The choice of OA is determined by the DOF required for the experiments. The DOF for main factors can be calculated as: (no. of levels – 1) × (no. of factors). Therefore, degrees of freedom will be (5 – 1) × (3) = 12. The total DOF in the OA must exceed the DOF of the factors being tested in the experiment according to the Taguchi method. So, from the available Taguchi designs, OA L_{25} (12 DOF), is selected for this study.

Table 1. List of particulate-filled composites

Material Designation	Material Compositions (wt. %)	
	Epoxy + Hardener	$CaSiO_3$ + WS_2
S1	97	2 $CaSiO_3$ + 1 WS_2
S2	95.5	2 $CaSiO_3$ + 2.5 WS_2
S3	94	2 $CaSiO_3$ + 4 WS_2
S4	92.5	2 $CaSiO_3$ + 5.5 W_S2
S5	91	2 $CaSiO_3$ + 7 WS_2

Table 2. Design factors at varying levels

Denotation	Design Factors	Factor Levels				
		1	*2*	*3*	*4*	*5*
A	Filler Content (%)	S1	S2	S3	S4	S5
B	Load (N)	30	40	50	60	70
C	Sliding Distance (m)	400	800	1200	1600	2000

2.3 Experimental Set-up

The pin-on-disc setup (Figure 4) made by DUCOM™ in Bangalore, is utilized to conduct the friction and wear tests on composite samples according to the ASTM G99 standard[24]. The experiments are carried out as per L_{25} OA, under dry sliding conditions, with a relative humidity of 42 % and a temperature of 24°C. A steel pin holder with a cross-section of 6 mm is used to hold the specimens of 30 mm × 5 mm × 5 mm (Figure 3).

Before testing, specimens are polished with 400-800 grade emery sheets to ensure proper contact with the counter face. The specimens are then pressed against a rotating steel disc for 15 min. The disc having a track diameter of 80 mm is made of EN 31 steel, with a hardness range between 58 HRC and 62 HRC, and a thickness of 8 mm. The weight of samples before (W_1) and after (W_2) the testing is noted using a precision electronic weighing instrument having the least count of 0.001 g[25].

The Specific Wear Rates (SWR) in mm^3/N-m, were then calculated using Equation (1),

$$SWR = \frac{\Delta W}{L \times \rho \times Sd} \quad (1)$$

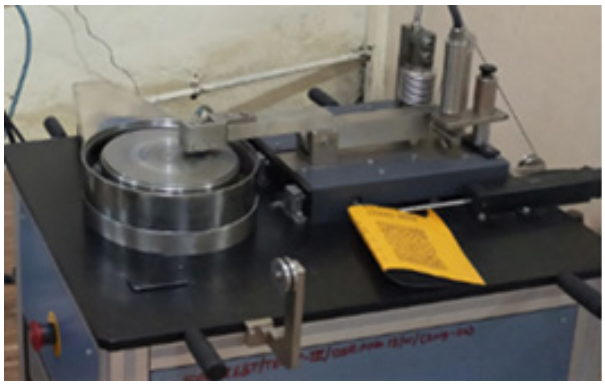


Figure 4. Pin-on-Disc tester.

Where, $\Delta W = (W_1 - W_2)$ i.e., weight loss in grams, L is applied normal load in N, ρ is density in g/cm^3 of specimens, and Sd is sliding distance in m. The experimental values for COF (μ) are recorded in the database of a computer connected to the testing apparatus. The results of the tests are presented in Table 3.

3.0 Results and Discussion

3.1 Multi-Response Optimisation using Grey-Relational Analysis

GRA, one of the broadly used models of grey system theory, was created by Julong Deng in 1982. GRA is a powerful technique that can effectively handle the interrelationships between multiple performance criteria. By integrating all performance criteria values into a single value for each alternative, GRA facilitates the resolution of Multi-Criteria Decision-Making (MCDM) problems. This approach effectively simplifies the initial problem, transforming it into a problem of single-attribute decision-making[13]. In the present work, the Grey-based Taguchi method was used to determine the optimum combination of control parameters namely filler content, load and sliding distance on multi-response characteristics to minimise COF and specific wear rate.

The procedure of GRA coupled with the Taguchi method is shown in Figure 5.

The steps followed in GRA are as follows[14]:

Step 1: Normalizing the Results

The initial step in GRA is to normalize the experimental results using Equation (2), which employs a lower-the-better criterion. During this process, the results are transformed to a scale ranging from 0 to 1.



Figure 5. Procedure of GRA.

$$a_i(m) = \frac{\max b_i(m) - b_i(m)}{\max b_i(m) - min\ b_i(m)} \quad (2)$$

Where, a_i (m) denotes normalized grey relational value, b_i (m) are experimental values for m^{th} response, maxb_i (m) denotes the largest value of b_i (m), min b_i (m) denotes the smallest value of b_i (m)And i = 1 to 25, which is the experiment number, and m is the quality characteristic.

The data is normalized in a range between 0 and 1 to overcome challenges caused by differences in units, scales, and targets of the responses. The normalization process employs the lower-the-better criterion, as stated in Equation (2), where the minimum response values are considered targets. Table 3 illustrates the normalized values for both the responses. The best-normalized values are the highest i.e., unity '1' for both responses.

Step 2: Computation of Grey Relational Coefficient (GRC)

The second step entails computing the GRC for the responses derived from the normalized outcomes. This coefficient reflects the relationship between the ideal-case scenario and actual experimental data and is determined using Equation (3).

$$\xi_i = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{oi}(m) + \zeta\Delta_{max}} \quad (3)$$

Where, ξ_i is the GRC, Δ_{min} and Δ_{max} is the minimum and maximum deviations. The quantity Δ_{oi} = b_0 (m)-b_i (mrepresents the absolute difference between b_0 (m) and b_i (m), b_0 (m) is the reference and b_i (m) is comparability sequence and ζ is the distinguishing coefficient. This investigation gives equal importance to both responses, resulting in a distinguishing coefficient of 0.5. Table 4 shows the GRCs of SWR and COF.

Step 3: Grey Relational Grade (GRG)

Once the GRC is calculated, the next step involves determining the GRG (which is obtained by applying Equation (4). The calculation of GRG converts the multiple-response problem into a single response. Higher values of GRG indicate a stronger correlation between the experimental and normalizing values. The GRG is calculated by taking the average of the GRCs that correspond to each performance characteristic.

$$\gamma_i = \frac{1}{n}\sum_{m=1}^{n} \xi_i(m) \quad (4)$$

Where n is the number of responses. Table 4 displays the GRG, with an overall mean value of 0.5670.

Step 4: Calculation of the S/N ratio

Further, the Taguchi method is used to optimize single GRG performance characteristics[23]. Taguchi uses a loss function to assess how much a performance characteristic deviates from the target value. Subsequently, the loss function value is converted into a signal-to-noise ratio, which serves the use of determining the quality characteristics and assessing the parameters. In this case, the S/N ratio is calculated as the logarithmic transformation of the loss function, using a larger-the-better criterion. The criteria are outlined in Equation (5), and it is selected as higher values of GRG are desirable[26].

$$\frac{S}{N}\ ratio = -10 * log_{10}\left(\frac{1}{n} * \frac{1}{y^2}\right) \quad (5)$$

In the above equation, y denotes the experimental data for the GRG, while n represents the total number of experiments conducted. The experimental data for

Table 3. OA for L_{25} Taguchi design, responses and normalized responses

Exp. No.	Filler Content (A)	Load (B)	Sliding Distance (C)	Response I		Response II	
				SWR	Normalized (SWR)	COF	Normalized (COF)
1	1	1	1	0.0007230	0.2128	0.48	0.625
2	1	2	2	0.0005125	0.4611	0.507	0.2875
3	1	3	3	0.0003510	0.6516	0.51	0.25
4	1	4	4	0.0002720	0.7448	0.50	0.375
5	1	5	5	0.0001168	0.9279	0.48	0.625
6	2	1	2	0.0007853	0.1393	0.49	0.5
7	2	2	3	0.0005017	0.4738	0.52	0.125
8	2	3	4	0.0002377	0.7853	0.50	0.375
9	2	4	5	0.0002051	0.8237	0.49	0.5
10	2	5	1	0.0004806	0.4987	0.45	1
11	3	1	3	0.0004545	0.5295	0.53	0
12	3	2	4	0.0001422	0.8979	0.52	0.125
13	3	3	5	0.0000557	1	0.51	0.25
14	3	4	1	0.0005331	0.4368	0.46	0.875
15	3	5	2	0.0003015	0.7100	0.48	0.625
16	4	1	4	0.0001449	0.8947	0.51	0.25
17	4	2	5	0.0002093	0.8188	0.51	0.25
18	4	3	1	0.0005343	0.4354	0.48	0.625
19	4	4	2	0.0001255	0.9176	0.48	0.625
20	4	5	3	0.0000732	0.9793	0.493	0.4625
21	5	1	5	0.0004561	0.5276	0.501	0.3625
22	5	2	1	0.0009034	0	0.47	0.75
23	5	3	2	0.0004580	0.5254	0.498	0.4
24	5	4	3	0.0002687	0.7487	0.52	0.125
25	5	5	4	0.0002935	0.7194	0.48	0.625

GRG is converted into an S/N ratio based on the larger-the-better criterion using Minitab 14 software. The converted S/N ratio values for GRG are presented in Table 4.

Table 4. GRC, GRG, and rank

Exp. No.	GRC				
	Response I (SWR)	Response II (COF)	**GRG**	**S/N ratio**	**Rank**
1	0.3884	0.5714	0.4799	-6.3763	20
2	0.4812	0.4123	0.4468	-6.9971	22
3	0.5893	0.4000	0.4946	-6.1133	18
4	0.6621	0.4444	0.5532	-5.1411	14
5	0.8740	0.5714	0.7227	-2.8206	2
6	0.3674	0.5000	0.4337	-7.2555	23
7	0.4872	0.3636	0.4254	-7.4229	24
8	0.6995	0.4444	0.5720	-4.8517	12
9	0.7393	0.5000	0.6196	-4.1565	7
10	**0.4993**	**1**	**0.7496**	**-2.5023**	**1**
11	0.5152	0.3333	0.4242	-7.4469	25
12	0.8305	0.3636	0.5970	-4.4794	11
13	1	0.4000	0.7000	-3.0980	5
14	0.4702	0.8000	0.6351	-3.9425	6
15	0.6329	0.5714	0.6021	-4.4053	10
16	0.8261	0.4000	0.6130	-4.2498	8
17	0.7340	0.4000	0.5670	-4.9283	13
18	0.4696	0.5714	0.5205	-5.6707	15
19	0.8586	0.5714	0.7150	-2.9136	4
20	0.9603	0.4819	0.7211	-2.8396	3
21	0.5142	0.4395	0.4768	-6.4315	21
22	0.3333	0.6666	0.5000	-6.0205	17
23	0.5130	0.4545	0.4837	-6.3067	19
24	0.6655	0.3636	0.5145	-5.7707	16
25	0.6405	0.5714	0.6060	-4.3503	9

Step 5: Rank all the alternatives in descending order of S/N ratio

The last step includes ranking of alternatives using calculated S/N ratios. The highest S/N ratio is ranked 1, indicating the ideal parameter conditions for multi-response characteristics. Table 4 shows the grey grades in order of rank.

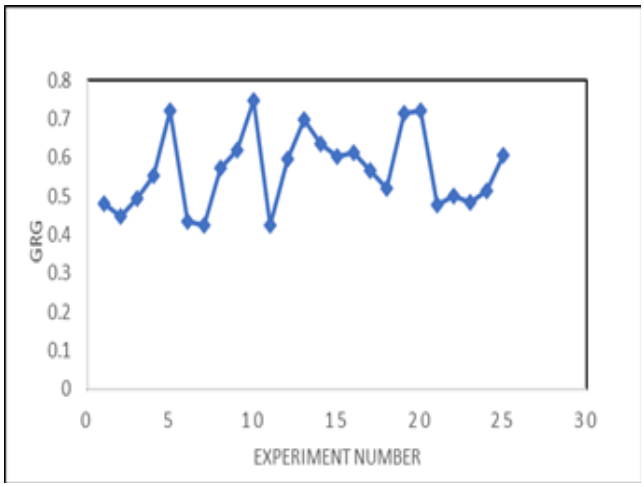


Figure 6. Rank plot for GRG.

From Table 4, it is observed that the ideal conditions of factors correspond to the highest GRG and S/N ratio. A higher S/N ratio is beneficial, if the tests are near the normalized magnitudes of GRG. It was seen that experiment 10 produced the largest value of the S/N ratio, signifying that 2 wt.% $CaSiO_3$ and 2.5 wt.% WS_2 composite is the most resistant material in the study.

Figure 6 shows the GRG versus experiment number. Figure 6 clearly states that experiment number 10 has the highest GRG (0.7496). Therefore, the best multi-response characteristic is achieved as the combination $A_2B_5C_1$ (2 wt.% $CaSiO_3$ and 2.5 wt.% WS_2, 70 N load and 400 m) exhibiting the highest GRG value out of the twenty-five experiments which gives minimum COF and SWR for the wear tests of epoxy composites.

3.2 Analysis of Control Parameters on SWR and COF

Taguchi analysis was performed with the GRG values using Minitab software. Figure 7 shows the main effect plot of control factors (filler content, load and sliding distance) on the mean GRG. The dotted line in Figure 7 denotes an average value of GRG whereas the values in the vertical position of the plot indicate a greater magnitude of the main effect. As shown in Figure 7, the SWR and average COF of developed composites are affected concerning load, sliding distance and filler content. The optimal combination of parameters for the considered responses was identified as filler content (2 wt.% $CaSiO_3$ + 5.5 wt.% WS_2), load (70 N) and sliding distance (2000 m). The response table for means of GRG is presented in Table 5. The highest influence of control factors on the output responses was determined from Table 5. The influence of load on SWR and COF is found to be highest followed by filler content and then the sliding distance. According to Archard's wear law, the amount of wear rate is directly proportional to the normal load. Therefore, wear occurred due to the testing of specimens at high load and speed, and increased temperature between the pin and disc. This increase in temperature softens the epoxy matrix, causing it to adhere to the surface of the disc. Moreover,

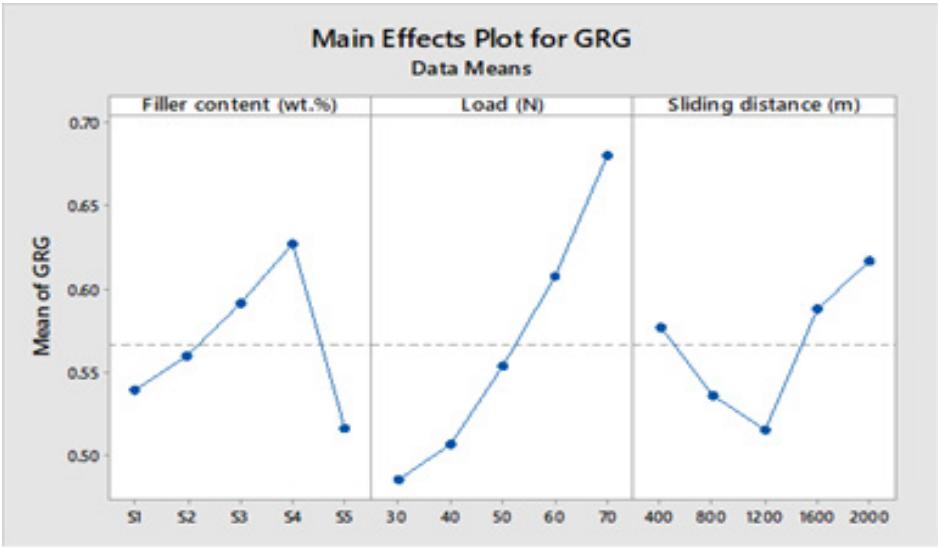


Figure 7. Main effect plot for GRG.

Table 5. Mean table for GRG

Level	Filler content (wt.%)	Load (N)	Sliding Distance (m)
1	0.5394	0.4855	0.5770
2	0.5601	0.5072	0.5363
3	0.5917	0.5542	0.5160
4	0.6273*	0.6075	0.5882
5	0.5162	0.6803*	0.6172*
Delta	0.1111	0.1948	0.1013
Rank	2	1	3

the results show that the addition of particles resulted in reduced wear. The decrease is observed because of the plastic deformation of the composite material which is caused because of increased temperature at the interface of pin and disc, due to which transfer film is formed. The transfer film formed improves the wear resistance of the polymer. Also, the result shows that the average COF increases with an increase in normal load, whereas the addition of fillers decreases the COF. The results also reveal that the increase in sliding distance increases the wear rate and COF irrespective of the increase in filler content of composite samples. Moderate sliding distance is the optimum condition for the better wear rate of samples.

Similar results were obtained by Alagarsamy S.V, Ravichandran M and Meignanamoorthy M[27]. The authors reported an increase in wear rate with an increase in applied load whereas reinforcement of fillers reduced the wear rate. Aashish Kumar *et al.*[28], examined the wear behaviour of Gr-Al-Si_3N_4 composites at various applied loads, sliding velocities and sliding distances. They reported a significant decrease in wear rate after the addition of fillers. P. Hariharasakthisudhan *et al.*[29], developed Si_3N_4 nano particles reinforced AA6061/ Al2O3/graphite hybrid nano composites. and reported that the increasing wt.% of Si_3N_4 nanoparticles reduced the values of friction coefficient and wear rate.

3.3 Analysis of Variance (ANOVA) for GRG

ANOVA is a statistical technique used to identify the most significant factors that influence a response variable. This analysis involves quantitatively evaluating the percentage contribution of each design factor using ANOVA[11]an effort is made to manufacture a tractor pedal shaft using two different materials En8D and SAE1018. The shaft was made by using a Gas Metal Arc Welding technique.

Table 6. ANOVA for GRG

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P- Value	% Contribution
Filler Content	4	0.03817	0.03817	0.009542	2.35	0.113	15.63%
Load	4	0.12426	0.12426	0.031065	7.65	0.003	50.87%
Sliding Distance	4	0.03310	0.03310	0.008276	2.04	0.153	13.55%
Error	12	0.04872	0.04872	0.004060			19.95%
Total	24	0.24425					100.00%

R-Sq = 80.05%; R-Sq (adj) = 60.10%

* Significant parameter

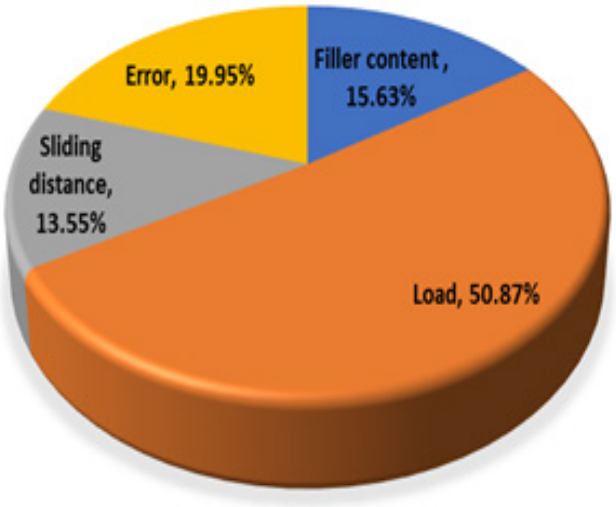


Figure 8. Contribution plot for GRG.

The welded shaft was then tested for ultimate tensile strength along with radiographic NDT testing to detect the welding defects in the shaft. Furthermore, the study uses Taguchi technique to optimize welding parameters like welding current, welding voltage, gas pressure, wire feeding rate, and nozzle to work piece distance in order to achieve high strength, defect-free welding for a tractor pedal shaft. A standard Taguchi experimental plan with notation L9 was chosen. Finally, the most significant design factor affecting the tensile strength of the shaft was investigated using Analysis of Variance (ANOVA).

In the present work, ANOVA analysis was used to determine the percentage contribution of each parameter that affects the performance. ANOVA for GRG is performed based on a 95% level of confidence using Minitab software. The ANOVA table shows the

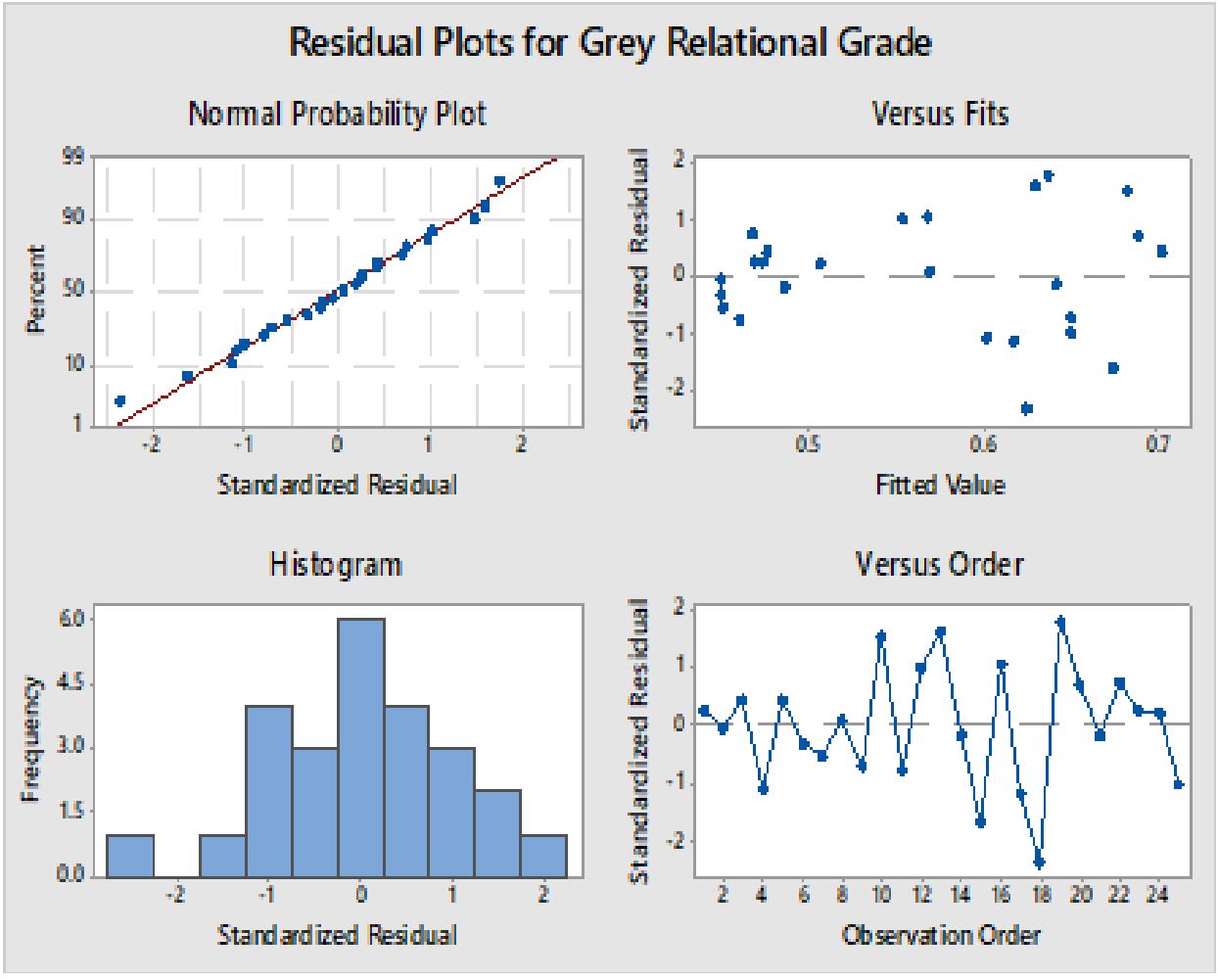


Figure 9. Residual plots for GRG.

F-value, P-value and percentage contribution of each factor affecting the response. Table 6 shows the ANOVA for GRG of wear and COF. These results of the ANOVA analysis imply that all three noted control factors- load, sliding distance and filler content will affect wear and COF. Based on analysis, it is evident that load (B) has the maximum substantial impact on the responses, followed by filler content (A) and sliding distance (C). It is observed that load (P = 0.003) has the highest influence of 50.87%, filler content (P = 0.113) has an influence of 15.63% and sliding distance (P = 0.153) has an influence of 13.55% (shown in Figure 8). With an R^2 value of 0.8005, it can be inferred that the model is capable of reasonably explaining 80.05% of the variability observed in the GRG.

Residual plots for GRG are shown in Figure 9. The plots include normal probability plots, versus fits, histograms and order for GRG values.

The normal probability plot shows that the standardized residuals follow an approximately straight line. The histogram shows highest frequency is around zero in the residuals and an outlier exists in the data. The residual versus fits plots show an increasing trend in the residuals indicating nonconstant variance. The residuals versus order graph does not show any fixed pattern. The residuals are randomly around the center line indicating that the residuals are independent from one another. Similar results for ANOVA and residual plots for GRG are plotted after conducting the wear behaviour of SiC-reinforced aluminium composites by Narendra Kaushik and Sandeep Singhal[30].

3.4 Regression Equation Model

The mathematical equations for COF and SWR are as follows:

$$COF = 0.5136 - 0.00107\ A - 0.000740\ B + 0.000018\ C \quad (6)$$

$$SWR = 0.001038 - 0.000012\ A - 0.000007\ B - 0.000001\ C \quad (7)$$

The equation represents the relation between responses (Coefficient of fraction and Specific wear rate) and control factors (A- filler content, B- load, C- sliding distance).

3.5 Confirmation Experiment

To verify the experimental results, confirmation tests were conducted by evaluating the response of GRG. According to the ranking in Table 4, the initial ideal combination of parameters for maximum GRG is $A_2B_5C_1$ and the optimal parameter combination is $A_4B_5C_5$. The Equation (8) used to determine GRG is as follows[31]:

$$\gamma_{opt} = \gamma_m + \sum_{i=1}^{p}(\gamma_i - \gamma_m) \quad (8)$$

Where represents the total mean of GRG, p represents the number of process parameters that significantly affect the performance of polymer composites and represents the average GRG at the optimal parameter level. Table 6 displays the comparisons between the predicted and actual values of GRG. The computational value of GRG is 0.7892 whereas the experimental value is 0.8294. The results demonstrate a high level of agreement between the estimated and experimental values. An improvement of 0.0798 (10.64%.) in GRG from the initial ideal condition to the optimal factor combination was obtained. Similar results which showed an improvement in experimental GRG for optimal parameter conditions were observed. Okwuchi Smith Onyekwere *et al.*[32] implemented a multi-response optimization technique for polyester composites and reported a 51.1% improvement in GRG concerning initial parameter conditions. R. Ganesh *et al.*[16] used the Taguchi-GRA on Mg-TiO2 nanocomposite, and reported an increase in GRG from 0.825 to 0.8314, achieving an improvement of 0.77%.

Table 6. Results of the confirmation test

	Initial ideal condition	Optimal Control Parameters	
	$A_2B_5C_1$	Prediction $A_4B_5C_5$	Experimental $A_4B_5C_5$
GRG	0.7496	0.7892	0.8294

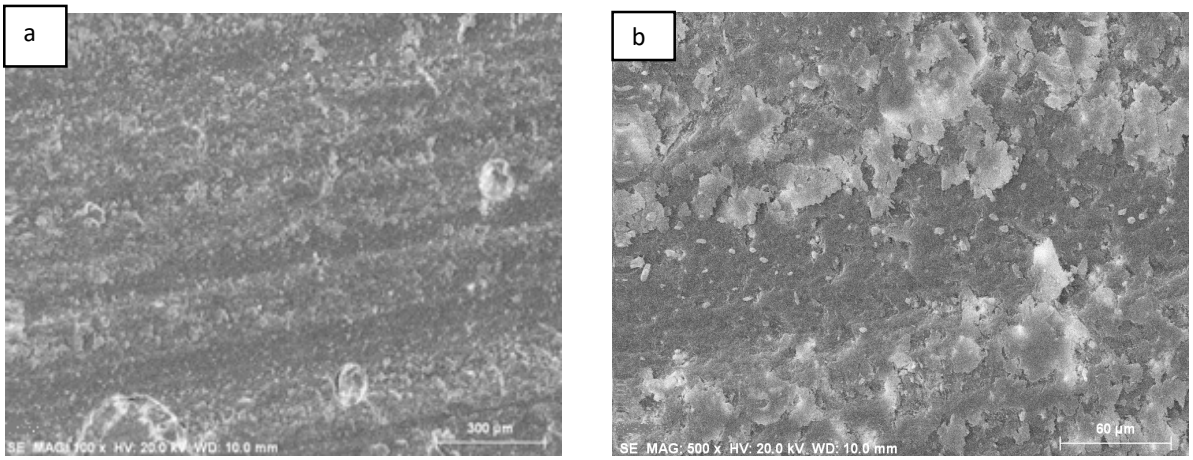


Figure 10. SEM images of worn surfaces at **(a)** 100 × magnification **(b)** 500 × magnification.

3.6 Scanning Electron Microscopy (SEM)

The morphology of wear tracks in $CaSiO_3$ and WS_2-filled epoxy matrix composite specimens is examined using SEM micrographs. The composite surfaces are observed on a JEOL JSM 6360 microscope. Figure 10 shows micrographs of worn surfaces at two different magnifications for the optimal conditions.

The micrographs reveal that the sliding surface is predominantly characterized by ploughing lines, which result from the micro-cutting sliding action between the specimen and the counter face. Also, the magnified images show that the wear mechanism exhibits a combined adhesive and abrasive nature. Figure 10 (b) illustrates torn-out surfaces that indicate adhesive wear. This wear occurs due to the testing of specimens at high load and speed, increasing temperature between the pin and disc. This increase in temperature softens the epoxy matrix, causing it to adhere to the surface of the disc.

4.0 Conclusions

This work focussed mainly on the optimization of parameter settings to obtain $CaSiO_3/WS_2$/Epoxy composites of improved properties. Initially, the composites are prepared by the magnetic stirring process and investigated for friction and wear on a pin-on-disc setup using five different levels of factors (i.e., filler content, load, and sliding distance). The result of varying three factors on multiple responses of COF and SWR was investigated using a Taguchi L_{25} OA and GRA. As seen in the response table of grey relational grades, the ideal combination of parameters for minimum COF and SWR of $CaSiO_3/WS_2$/Epoxy composites was found to be $A_2B_5C_1$ (2 wt.% $CaSiO_3$ and 2.5 wt.% WS_2, 70 N load and 400 m). Taguchi analysis showed that sliding distance of 2000 m, filler content of 2 wt.% $CaSiO_3$ and 5.5 wt.% WS_2 and applied load of 70 N ($A_4B_5C_5$) at 15 min are the optimum parameter conditions for better wear rate. ANOVA for GRG showed that the percentage contribution of load, sliding distance and filler content were 50.87%, 13.55%, and 15.63%, respectively. The most effective parameter on wear and COF was found to be the design factor load followed by sliding distance and filler content being the least effective. Finally, the confirmation tests were performed to validate the improvement of 10.64 % in GRG concerning initial parameter settings after the optimization by Grey relational analysis. SEM analysis of the worn surface revealed enhancement in tribological properties at the optimal setting of parameters.

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Abbreviations

Abbreviations	Description
A	Filler Content (wt.%)
ANOVA	Analysis of variance
B	Load (N)
C	Sliding Distance (m)
COF	Coefficient of Friction
$CaSiO_3$	Wollastonite
DOF	Degrees of Freedom
GRA	Grey Relational Analysis
GRC	Grey Relational Coefficient
GRG	Grey Relational Grade
OA	Orthogonal Array
SEM	Scanning Electron Microscopy
SWR	Specific Wear Rate (mm^3/Nm)
WS_2	Tungsten Disulphide