

Multi-Response Optimization of the Tribological Behaviour of PTFE-Based Composites via Taguchi Grey Relational Analysis

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Polymer-based composites find applications in several areas because of their exceptional properties. This article deals with Taguchi grey relational optimization method of abrasive parameters (load (L), grit size (G) and sliding distance (D)) and their influence on abrasive performance of reinforced polytetrafluoroethylene (PTFE) composites. A Taguchi L₉ orthogonal array was designed, and nine experimental tests were conducted based on the Taguchi designed experiments. A pin-on-disc tribology machine was used for the experiments. The coefficient of friction (μ) and abrasive specific wear rate (A_w) were recorded for each experiment. An analysis of variance (ANOVA) was performed to establish the significance and percentage contribution of each parameter affecting the abrasive wear performance. Results from the Taguchi-grey-relational method showed that the optimal combination of parameters was achieved at load of 10 N, grit size of 1000 mesh, and sliding distance of 350 m (coded as L3G1D3). ANOVA findings revealed that a grit size with 67.69 % as the most influential on the abrasive performance of polymer-based composites. Validation tests performed using the optimal combination parameter showed an enhancement of 55.22 % in grey relational grade.

Keywords: PTFE, carbon fibre, bronze fibre, abrasive, Taguchi, grey relational analysis

Highlights

- Optimization of abrasive tribological performance of PTFE based composites has been performed.
- Influence of load, grit size and sliding distance on coefficient of friction (μ) and specific abrasive wear rate (A_w) were studied.
- Optimization of multiple responses of μ and A_w via Taguchi-grey relational method is presented.
- Analysis of variance performed to find the most significant parameter on Taguchi grey relational grade.
- Optimal parameters found to be load and sliding distance at their third levels while grit size at its first level.
- According to the order of significance and percentage, the contribution on and to grey relational grades in abrasive performance is enumerated as grit size, load, and sliding distance.

0 INTRODUCTION

Polymer matrix composites (PMCs) are used in the automotive and aerospace sectors because of their high strength and stiffness [1]. Polytetrafluoroethylene (PTFE) is a commonly used matrix due to its antifriction property, water and chemical resistance, thermal stability, and low cost [2] to [4]. However, PTFE shows poor wear properties. It is reinforced with fibres including glass, carbon, aramid and bronze fibres to improve the wear properties [5]. PTFE and its composites are exposed to abrasive action and used in highly abrasive environments. The wear rate and coefficient of friction (μ) of PMCs are not inherent material properties and strongly rely on the system where the system will operate [6] and [7].

Experimental studies showed that reinforcing matrices with fibres improve their wear rate. Suresha and Kumar [8] reinforced PA66/PP with nano-clay and short carbon fibres. Improvement in wear rate of the P66/PP matrix was observed. In their study of abrasive property of different polymers, Shipway and Ngao [9] showed that polymers exhibited different behaviours

and concluded that the abrasive wear of polymer depends on the type of the polymer. Ravi Kumar et al. [10] studied the abrasive wear rate of glass and carbon fabric reinforced vinyl/ester composites. The results showed that vinyl/ester reinforced with carbon had lower abrasion compared to glass reinforced vinyl/ester composite and that increasing the distance decreased the abrasion. Liu et al. [11] studied abrasive performance of a filled UHMWPE matrix and found that the applied load was most significant process variable. Yousif et al. [12] studied the abrasion resistance of betelnut-filled epoxy composite. It was revealed that rougher particles and high velocity generated high μ and wear rate, respectively. Harsha and Tewari [13] studied the influence of glass fibre at different loadings, sliding distance, load, and grit size on polysulfone. The results revealed a deterioration in abrasive performance of the polysulfone. Moreover, decreasing and increasing trends of tribological behaviour were observed due to varying load, distance, speed and grit size.

The single response optimization Taguchi method has been used for the tribological performance of

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PMCs. Thakur and Chauchan [14] studied the wear and friction behaviour of submicron size cenosphere particle-reinforced vinyl ester composites using Taguchi L₂₇. Load, roughness, filler size, speed, and distance (each at three levels) were considered as parameters controlling the tribological behaviour of the vinyl ester composite. Different optimal combinations of parameters for desired μ and A_w were found for the two responses. ANOVA showed that load at 68.33 % and 63.89 % was the most significant factor controlling the μ and A_w . Pogosian, Cho, and Bahadur [15] used the Taguchi method to optimize polyphenylene sulphide reinforced with MoS₂, Al₂O₃ particles. The optimal Taguchi combination of parameters was found to be PPS+17 % Vol. MoS₂+10 % Vol. PTFE, speed 1.5 ms⁻¹ and roughness 0.1 μ m for minimum wear rate. ANOVA indicated that MoS₂ exhibited the greatest effect on wear rate of the composites. Chang et al. [16] optimized load, distance, counterface roughness, and amount of fibre as parameters influencing the abrasive wear of kenaf-reinforced polyester composite via Taguchi L₉(3⁴). The results showed that the optimal combination for minimum wear was obtained at a load of 30 N, composition B, and distance 2,500 m and that applied load was the most influential parameter on wear rate. Şahin [1] optimized control the factors of abrasive wear of glass- and carbon-reinforced PTFE composites through the Taguchi method. Load, grit size, distance, and compressive strength were the investigated parameters. For minimum volume loss, it was found that a load of 5 N, a grit size of 1200 mesh, a distance of 45 m, and a compressive strength of 9.8 MPa were the optimal parameters.

To study multiple responses related to tribological behaviours of composites, several decision-making methods, including data envelopment analysis (DEA), analytic hierarchy process (AHP), and grey relational analysis (GRA) have been proposed. Of these, GRA, introduced by Deng in 1989 [17], is the most commonly used when the nature of the information is uncertain and incomplete. Ramesh and Suresha [18] integrated Taguchi with the grey relational method to establish the optimal levels of abrasive performance of carbon-epoxy hybrid composites. It was found that grit size and filler loading were the most influential parameters. Based on the Taguchi-grey relational analysis, Subbaya et al. [19] investigated the wear assessment of SiC-filled epoxy composites; the results showed that the optimal combination for minimum wear was obtained at filler content of 10 wt. %, grit size of 320 mesh, load of 10 N, and distance of 75 m. Filler with 70.09 % was the found

to be most significant parameter influencing the GRG. Dharmalingam et al. [20] combined Taguchi with GRA to determine the optimal parameter settings of multiple responses of abrasive wear aluminium hybrid metal composites. The optimal parameters were found to be load of 20 N, sliding speed of 1.5 m/s, and the amount of molybdenum disulphide at 2 wt.%. An integrated Taguchi with GRA has been adopted for optimization of μ and wear rate of co-long composite by Sylajakumar et al. [21] combined Taguchi with GRA. Using this method, optimal parameter settings of were found to be an applied load of 60 N, a sliding speed of 1 ms⁻¹, and a sliding distance of 1000 m. Validation testing showed an improvement of 35.25 % in GRA. Savaran and Thanigaivelan [22] coupled Taguchi-particle component analysis and GRA to optimize the dimple geometry of stainless steel (SS36L). The results indicated that optimum parameter values for the highest GRG peak value of 0.2642 were an average power of 12 W, a pulse duration of 1500 ns, and a frequency of 15 Hz.

Even though the Taguchi approach is simple, efficient, and economical, it is limited to optimizing a response at a time. The need for a method that can optimize multiple responses cannot be overemphasized. Therefore, this study is aimed at optimizing multiple responses of the coefficient of friction (μ) and specific abrasive wear rate (A_w) of reinforced PTFE composites using a Taguchi-GRA method. Moreover, abrasive wear performance should be optimized to prevent detrimental consequences on output performance.

1 EXPERIMENTAL

1.1 Materials

In this study, PTFE reinforced with carbon 25 % wt. and bronze 40 % wt. has been used. The materials fabricated by compression moulding process were supplied by Polymer Chemical Industry Ltd, Turkey in the form of square plates (100 mm × 100 mm × 6 mm). Selected properties of the materials are shown in Table 1. All samples have been cut from the same lot to minimize variations in the production technique.

Table 1. Selected properties of materials used

Materials	Code	ρ [gcm ⁻³]	σ [kgcm ⁻²]
Polytetrafluoroethylene	PTFE	2.10	380
Carbon-filled composite	CF25	2.05	210
Bronze-filled composites	BF40	3.05	280

1.2 Abrasive Test

An abrasive test was conducted according to ASTM G99 on a pin-on-disc tribometer (Model: Arton Paar, Switzerland), shown in Fig. 1. The counterface material for the wear test is a steel of disc 140 mm in diameter and thickness of 10 mm that has been heat-treated to obtain a surface hardness of 55 RC to 60 RC. This is ground to a surface finish of nearly 0.12 μm centreline average. The square samples (20 mm × 20 mm) were cut from the plates using computer numerical control water machining for the pin-on-abrasive testing. A specially designed fixture for holding the rectangular samples was designed and fabricated. The samples were inserted into the fixture and bolted and then loaded against SiC abrasive papers fixed to the hardened steel holder by means of liquid adhesive. Control parameters and their levels are shown in Table 2. The experimental design is as shown in Table 3 and was performed at 0.15 ms⁻¹. In all the experiments, mass before (*m*₁) and mass after (*m*₂) was measured using digital weighing balance (Model: PS 1000.RS RADWAG, made in Poland) with 10⁻³ g precision accuracy. Testing was performed at room temperature (29 °C and relative humidity 55 %). Samples were cleaned with a brush before and after the experiment to remove debris and then weighed. The specific abrasive wear rate (*A*_w) was then computed from Eq. (1):

$$A_w = \frac{m_1 - m_2}{L\rho D}, \quad (1)$$

where *m*₁ – *m*₂ is mass loss [g], *L* load [N], *ρ* density [gcm⁻³] and *D* sliding distance [m], respectively. Two replicates were performed for each run and the average reported. The tribometer is connected to a computer with a data acquisition system that collects and transmits to software for processing and generation of results. The coefficient of friction (*μ*) is obtained from this process.

Table 2. Control parameters and their levels

Parameters	Symbol	Level 1	Level 2	Level 3
Load [N]	L	5	8	10
Grit size (mesh)	G	1000	320	220
Distance [m]	D	150	250	350

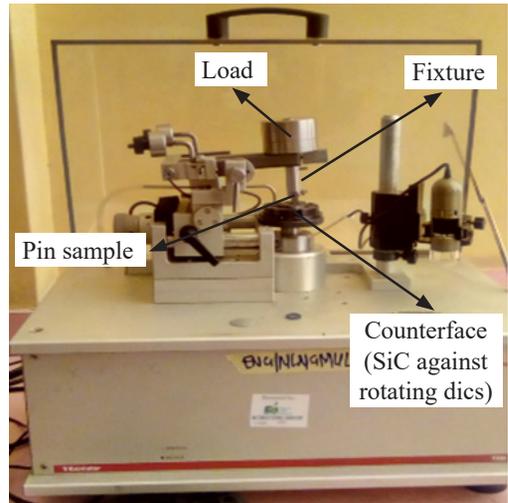


Fig. 1. Arton Paar Tribometer used for the experiment

1.3 Taguchi Design of Experiment (DOE)

The Taguchi design of the experiment is a tool which optimizes process parameters, keeping the process under control by managing variations while improving quality. In this study, based on literature, three parameters (i.e., load (*L*), grit size (*G*), and sliding distance (*D*)) at three levels were optimized. The experiment was designed based on a Taguchi L₉ (3³) orthogonal array (OA) and conducted according to Table 2. Although the Taguchi design is simple, cost-effective, and improves the process, it is limited to optimizing a single response. For the optimization purpose, Taguchi uses the signal-to-noise ratios (*SNRs*) to determine the optimum combination of parameters and followed Eq. (2).

$$(SNRs)_{STB} = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n y_i^2 \right), \quad (2)$$

where *n* is repetition of number of each trial and *y*_{*i*} outcome of the *i*th experiment for each trial. *SNR* of *μ* and *A*_w were computed as per Eq. (2).

Table 3. Taguchi L₉ (3³) OA Design

Run	<i>L</i> [N]	<i>G</i> (mesh)	<i>D</i> [m]
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

1.4 Grey Relational Analysis (GRA)

The Taguchi design approach is limited to single response optimization. For multi-objective optimization, GRA has been developed exploiting the Taguchi design to estimate the degree of correlation between test trials (series) via grey relational grade (GRG). To reduce data inconsistency, the data is normalized to a comparable range between 0 and 1 [22]. Different objective functions exist, such as larger is better and smaller is better. The objective of this study is to minimize wear rate. Therefore, the smaller is better function is chosen, and the data are normalized according to (Eq. (3)):

$$X_i^*(k) = \frac{\max\varphi_i(k) - \varphi_i(k)}{\max\varphi_i(k) - \min\varphi_i(k)}, \quad (3)$$

where $X_i^*(k)$ is normalized for the i^{th} experiment and $\varphi_i(k)$ initial sequence of the average responses.

1.5 Calculation of Grey Relational Coefficient (GRC) and Grade (GRG)

The next step after data normalization is the computation of the deviation sequence using (Eq. (4)):

$$\Delta_{oi}(k) = X_0^*(k) - X_i^*(k), \quad (4)$$

where $\Delta_{oi}(k)$ stands for deviation, $X_0^*(k)$ denotes normalized data and $X_i^*(k)$ refers to comparability sequence. GRC is thus estimated through (Eq. (5)):

$$\xi_i(k) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{oi}(k) + \zeta\Delta_{max}}, \quad (5)$$

where $\xi_i(k)$ is a GRC of each response calculated as a function of Δ_{min} and Δ_{max} the lowest and the highest deviations of each target factor, respectively. Differentiating or identification coefficient is symbolized by ζ and is demarcated within the range of $\zeta \in [0,1]$. This is usually set at one half to assign equivalent weights to every variable. As indicated in (Eq. (6)), GRG is then determined by taking mean of GRG of each response:

$$\gamma_i = \frac{1}{n} \sum_{i=1}^n \xi_i(k), \quad (6)$$

where γ_i is a GRG obtained for i^{th} test run, and n summation count of performance attributes. As soon as optimal level of variables is established via GRG, the last phase is to predict and confirm the quality attributes by (Eq. (7)):

$$\gamma_{predicted} = \gamma_m + \sum_{i=1}^q \gamma_0 - \gamma_m. \quad (7)$$

1.6 Analysis of Variance (ANOVA)

ANOVA is traditionally utilized to determine the significance of parameters on responses. Generally, Taguchi-GRA in combination with ANOVA is used to ascertain the percentage contribution of each factor to responses. The parameter with the largest percentage contribution is the most significant parameter and vice versa.

3 RESULTS AND DISCUSSION

The results of the experiment based on Table 3 with corresponding SNRs of μ and A_w are presented in Table 4; these results are used for the Taguchi GRA. From Table 4, it was seen that run 4 produced the largest value of SNRs, signifying that BF40 composite is the most resistant material in the study.

3.1 Effect of Load on μ and A_w

Fig. 2 shows the changes in A_w of reinforced PTFE composites as a function of load, grit size and distance. It is seen that A_w decreased with increasing applied load. The decrease in A_w of the PTFE based composites is because as the load increases the contact between samples, and the SiC counterface increases. This decreases the contact pressure, which allows particles of samples cooperating with the interface to share the stress. Additionally, a uniform, thin, and adherent transfer film in-between the samples and the counterface, which prevented direct contact with SiC counterface is another reason for the lower A_w . However, at lower load A_w was high. This is related to high contact pressure in-between and the ineffective tribo-layer between samples and counterface leading to direct contact of the samples with the counter surface. Fig. 3 presents the variation in μ of PTFE based composites as a function L , G , D and S . It is observed in Fig. 3 that μ shows increasing and decreasing trends as the load increased from 5 N to 8 N and from 8 N to 10 N, respectively. The low μ due to increasing the load is related to formation of layers by the fibres at the counterface and their viscoelastic properties. These layers act as lubricants between samples and SiC surface. High μ occurred, owing to destruction of these tribo-layers. These findings were in agreement with literature data [22] to [24].

3.2 Effect of Grit Size on μ and A_w

As seen in Fig. 2, increasing grit size causes a decrease in A_w . The minimum A_w at higher G is due to

deposition of debris from the samples and formation of transfer film between samples and counterface. This resulted in reduction of cutting efficiency of the SiC particles leading to lower A_w loss. At smaller grit size, say 220 mesh, the particles are rough and penetrated deeply into samples. This caused large plastic deformation, leading to removal of more materials by micro-ploughing action. As seen in Fig. 3, μ exhibited a linear decreasing trend with an increase in grit size. μ is related to smoothness and roughness of surfaces. The high μ at smaller grit size is related to roughness of the SiC particle, which offered significant resistance. However, decrease in μ when the grit size is large is attributed to smoothness of the SiC particles leading to the formation of protective layer (lubricant) at the contact surface, preventing direct contact of the samples with the abrasive surfaces. This finding agrees with the finding of [1] when bronze and carbon filled PTFE was studied.

3.3 Effect of Sliding Distance on μ and A_w

As seen in Fig. 2 A_w linearly decreases when the sliding distance increases. Also, μ follows the same trend as A_w (Fig. 3). In other words, both μ and A_w reduced due to increasing sliding distance. This could be explained on the basis that the sliding distance acts as lubrication to the contact surfaces thereby separating the pin samples from the abrasive counterface. More so, the lower wear rate of the reinforced PTFE composites could be linked to pull out or fracture of abrasive particles owing to the presence of fibres. Also, wear debris is transferred from the matrix leading to reduced wear rate. Similar findings were reported by [25] and [26] when nylon 6 was reinforced with glass fibre at varied proportions.

3.4 Main Effect and Percentage Contribution of Factors on μ and A_w

To determine the optimal combination of parameters for minimum μ and A_w , the SNRs computed were obtained using Eq. (2). The largest SNRs give the desired value. SNRs' mean response table for μ is provided in Table 4, and the main effect plot depicted in Fig. 4. From Fig. 4, the optimum predicted maximum SNRs for L , G and D are obtained at 10 N, 1000 mesh, and 350 m, respectively. In Table 5, the desired corresponding level values are bolded to facilitate understanding. The optimum combination of process parameters for desired μ is coded as L3G1D3. To estimate the significance (contribution) of each parameter on the μ , ANOVA (Table 6) was

executed. As observed from Table 6, grit size with the percentage contribution of 69.34 %, shows the greatest effect on μ , followed by load with 14.62 % and the distance with 9.10 %. More so, it can be seen that the error is less than 10 %. Similarly, the same optimal combination of parameters was obtained for A_w (L1G1D3) for the lowest A_w using the main effect plot (Fig. 5). From the ANOVA results (Table 8), it can be implied that the grit size is the most significant parameter (42.65 %), followed by load (15.05 %), and distance shows the least significance (7.50 %) on A_w .

Table 4. Taguchi L_9 (3⁴) OA results with SNRs

Run	μ	μ SNRs [dB]	A_w [mm ³ N ⁻¹ m ⁻¹]	A_w SNRs [dB]
1	0.11	19.54	8.5714E-07	121.34
2	0.28	10.96	2.4390E-06	112.26
3	0.53	5.47	1.7237E-06	115.27
4	0.22	13.07	5.1639E-07	125.74
5	0.30	10.34	4.0816E-07	127.78
6	0.56	5.08	3.5366E-06	109.03
7	0.03	29.50	4.1115E-07	127.72
8	0.28	11.04	1.2568E-06	118.01
9	0.40	7.90	9.8095E-07	120.17

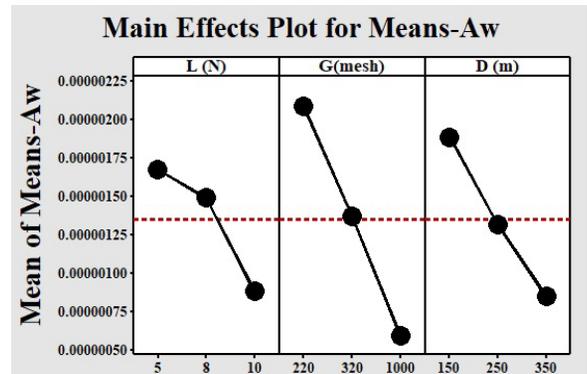


Fig. 2. Effect of process variables on A_w

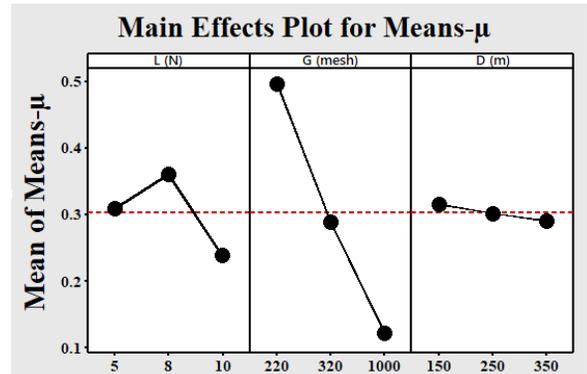


Fig. 3. Effect of process variables on μ

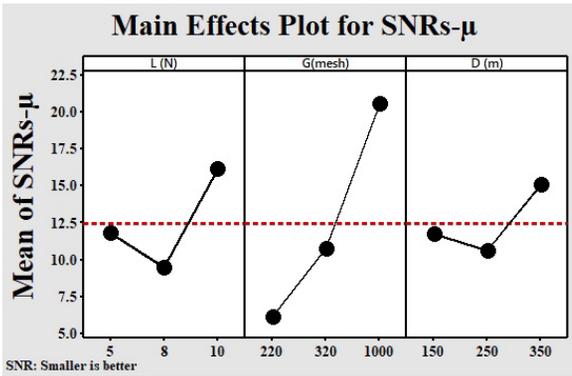


Fig. 4. Main effect plot for SNRs of μ

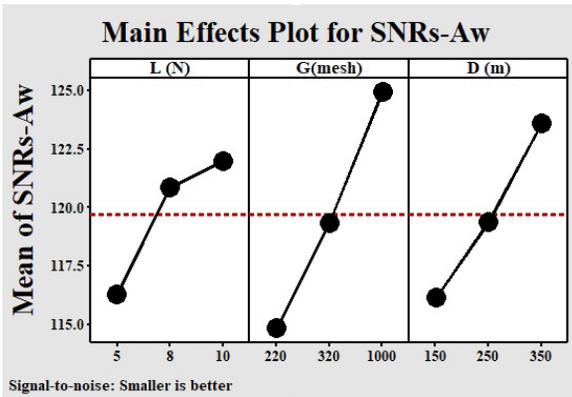


Fig. 5. Main effect plot for SNRs of A_w

Table 5. Response table for SNRs of μ (STB)

Factors	L1	L2	L3	Delta	Rank
L [N]	11.83	9.45	16.15	6.65	2
G [mesh]	6.15	10.78	20.54	14.39	1
D [m]	11.73	10.65	15.10	4.46	3

Table 6. ANOVA for μ

Source	DF	SSS	AMS	Contribution [%]
L [N]	2	68.3	34.15	14.62
G [mesh]	2	323.81	161.9	69.34
D [m]	2	32.41	16.2	6.94
Error	2	42.5	21.25	9.10
Total	8	467.01		100.00

Table 7. Response table for SNRs of A_w (STB)

Factors	L1	L2	L3	Delta	Rank
L [N]	116.30	120.90	122.00	5.7	3
G [mesh]	114.80	119.40	124.90	10.10	1
D [m]	116.10	119.40	123.60	7.50	2

Table 8. ANOVA for A_w

Source	DF	SSS	AMS	Contribution [%]
L [N]	2	54.31	27.15	15.05
G [mesh]	2	153.9	76.95	42.64
D [m]	2	84.59	42.01	23.4
Error	2	68.59	34.29	19.00
Total	8	360.81		100.00

3.5 Optimization via GRA

Principally, GRA is used to unravel real problems comprising a bounded amount of data. It is commonly employed to approximate the properties of indefinite systems having no black and white solutions. In a grey system, black signifies being without information whereas white connotes being with information. This technique is largely utilized to maximize or minimize problems involving multiples parameters and responses [27] and [28]. The data in Table 3 are pre-processed in the range of 0 to 1 according to Eq. (3). Thereafter, post-data processing was performed to obtain the deviation sequences using Eq. (4). Table 9 reveals the results of the post-data processing models. GRC for μ and A_w was computed using Eq. (5). Eventually, the mean of GRC is calculated to establish the GRG . As enumerated in Table 10, the calculated values of GRG were employed to produce equivalent SNR . A larger magnitude of SNR is useful, provided that the tests are close to the normalized magnitudes of GRG . Fig. 6 depicts the plot of GRG against $SNRs$. It indicates that seventh experimental run possesses the highest SNR . Correspondingly, the first rank was assigned to the seventh run. The straggling disposition of the GRG , below the plot of SNR in Fig. 6 adds to the discussion above.

Once the ranks are obtained, the GRG response table was developed. Each factor of GRG at the chosen level was selected and the average computed to obtain the mean GRG for different parameters. To obtain mean GRG values, of each parameter from Table 9, for instance, parameter L at L1 in the 1st, 2nd and 3rd runs. The corresponding GRG values from Table 9 was used for computation as depicted in Eq. (8).

$$L_1 = \frac{0.7737 + 0.4735 + 0.4435}{3} = 0.5336. \quad (8)$$

The mean of chosen GRG was computed utilizing technique above and put together to generate the response table (Table 11). The grades in the response table are used as a degree of correlation between the normalized and comparability sequence of GRA. Higher values of GRG show strong correlation

[29]. Hence, from Table 11, it is possible to achieve a combination of optimal parameters capable of maximizing the overall response. As observed in Table 10, the maximum *GRG* exists at L3, G1, and D3. Therefore, the optimal levels for useful abrasive tribological property of reinforced PTFE composites are $L = 10 \text{ N}$, G at 1000 mesh and $D = 350 \text{ m}$.

Table 9. Reference and deviation sequences post data processing

Run	X_i^*		Δ_{oi}	
	μ	A_w	μ	A_w
1	0.8510	0.8565	0.1490	0.1435
2	0.5234	0.3508	0.4766	0.6492
3	0.0458	0.5795	0.9542	0.4205
4	0.6399	0.9654	0.3601	0.0346
5	0.4833	1.0000	0.5167	0.0000
6	0.0000	0.0000	1.0000	1.0000
7	1.0000	0.9990	0.0000	0.0010
8	0.5282	0.7287	0.4718	0.2713
9	0.2951	0.8169	0.7049	0.1831

Table 10. Computed *GRC* and *GRG* with *SNRs*

Run	$X_i^*(k)$		γ_i	γ_i SNR [dB]	Rank
	μ	A_w			
1	0.7704	0.7770	0.7737	-2.2285	2
2	0.5120	0.4351	0.4735	-6.4929	7
3	0.3438	0.5432	0.4435	-7.0619	8
4	0.5813	0.9353	0.7583	-2.4030	3
5	0.4918	1.0000	0.7459	-2.5465	4
6	0.3333	0.3333	0.3333	-9.5424	9
7	1.0000	0.9981	0.9990	-0.0083	1
7	0.5145	0.6483	0.5814	-4.7107	5
8	0.4150	0.7320	0.5735	-4.8297	6
9	0.7704	0.7770	0.7737	-2.2285	2

Table 11. Response table for *GRGs*

Factors	L1	L2	L3	Delta	Rank
L [N]	0.5636	0.6125	0.7189	0.1544	3
G [mesh]	0.4501	0.6003	0.8437	0.3936	1
D [m]	0.5628	0.6018	0.7295	0.1667	2

Table 12. ANOVA for *GRG*

Source	DF	SSS	AMS	Contribution [%]
L [N]	2	7.22	3.61	10.37
G [mesh]	2	47.12	23.56	67.69
D [m]	2	7.96	3.98	11.44
Error	2	7.32	7.32	10.51
Total	8	69.61		100.00

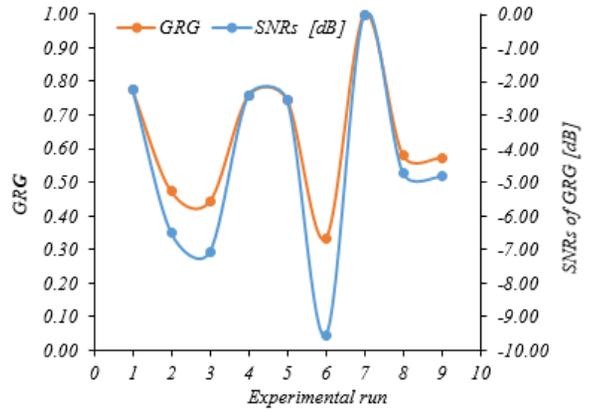


Fig. 6. Plot of *GRG* versus *SNRs*

3.6 ANOVA for *GRG*

To study the significance and percentage contribution of each parameter on the multiple A_w of reinforced PTFE composites, an ANOVA was executed for *GRG*. Taking into account the responses of μ and A_w , Table 12 depicts that grit size has the maximum influence of 67.69 % on the *GRG*, load has 12.37 %, and distance with lowest effect of 10.53%.

3.7 Confirmatory Tests

When the identities of optimum levels were established, the concluding phase in GRA is to predict and validate performance enhancement of the responses. The prediction of *GRG* was conducted based on Eq. (8). Confirmatory tests were performed to validate the results of the analysis and mean of *GRG* of two trials was computed. For the optimal conditions, the μ and A_w were determined to be $(0.04$ and $1.40 \times 10^{-7}) \text{ mm}^3\text{N}^{-1}\text{m}^{-1}$, respectively. Moreover, it can be implied from Table 13 that the outcomes of the validation experiment are in concordance with the predicted results. Furthermore, an improvement of 55.22 % in *GRG* is also achieved. This enhancement in the experimental outcomes over the initial design parameter asserts the validity of the Taguchi-GRA method for improving the abrasive wear performance of reinforced PTFE composites.

Table 13. Results of the confirmatory tests

Initial design parameters	Optimal design parameters	
	Prediction	Experiment
Setting levels	L1G3D3	L3G1D3
GRA	0.4435	1.0000
Improvement in <i>GRG</i> [%]	55.65	55.22

5 CONCLUSIONS

This study presents the results of optimal parameters that influence the abrasive performance of reinforced PTFE composite involving multiple responses. Initially, the result of varying three factors (i.e., load, grit size, and sliding distance) on multiple responses of specific wear rate and coefficient of friction was investigated using a Taguchi L₉ orthogonal array and grey relational analysis. As seen in the response table of the grey relational grades, the optimum combination of parameters for improved abrasive performance of the reinforced PTFE composites was found to be load at 10 N, grit size at 1000 mesh, and sliding distance at 350 m. Analysis of variance for grey relational grade showed that grit size with 67.69 % is the most influential parameter followed by applied load with 12.37 %, and sliding distance indicated the least effect having 10.52 % on the grey relational grade. Finally, validation tests were conducted to validate the improvement 55.22 % in grey relational grade from 0.4435 for the initial design parameters (L1G3D3) to 0.9903 for the optimal combination of parameters (L3G1D3). It is recommended that heavy conditions of parameters should be studied. The presented Taguchi-grey relational analysis results has proven to be capable of dealing with several responses in the optimization of tribological wear study of PTFE matrix composites.

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