Journal of Minerals and Materials Characterization and Engineering, 2012, 11, 876-884
Published Online September 2012 (http://www.SciRP.org/journal/jmmce)

Multiple Response Optimization of Three-Body Abrasive Wear Behaviour of Graphite Filled Carbon-Epoxy Composites Using Grey-Based Taguchi Approach

K. M. Subbaya[1*], N. Rajendra[1], Y. S. Varadarajan[1], B. Suresha[2]
[1]Department of Industrial & Production Engineering, The National Institute of Engineering, Mysore, India
[2]Department of Mechanical Engineering, The National Institute of Engineering, Mysore, India
Email: *kms_coorg@yahoo.com

Received April 11, 2012; revised May 20, 2012; accepted June 8, 2012

ABSTRACT

The three-body abrasive wear behaviour of carbon fabric reinforced epoxy (C-E) composites has been evaluated by the addition of graphite (G) particles as a secondary reinforcement. Three-body abrasive wear test were conducted using dry sand rubber wheel abrasion tester as per ASTM G-65 with three process parameters load, abrading distance and filler content. To assess the abrasive wear behaviour of particulate filled C-E composites satisfying multiple performance measure, grey-based Taguchi approach has been adopted. The experiments were designed according to Taguchi's orthogonal array (L_{27}). The grey relational analysis was applied to convert a multi response process optimization to a single response. Using analysis of variance, significant contributions of process parameters have been determined. The results indicate that the addition of graphite particles into C-E composite increased the wear resistance considerably. It was observed that highest wear resistance of C-E composite was achieved with incorporation of 10 wt% of graphite filler. Results indicate that the filler content and grit size of abrasive paper were found to be the most significant factor which has influence on the abrasive wear of C-E composite. The worn surface features were examined through scanning electron microscope to probe the wear mechanism.

Keywords: Composites; Three-Body Abrasion; Grey Relational Analysis; Scanning Electron Microscope

1. Introduction

Engineering polymers have attracted much interest in structural applications for many years, because of their superior properties such as light weight, strong, ease of fabrication and low cost [1]. In recent years much attention has been devoted to explore the potential advantage of thermoset matrices for new polymer composites [2]. One of such matrix is epoxy which has found a special place in the family of thermoset engineering polymers because of its excellent mechanical properties with chemical and corrosion resistance [3]. Polymer composites are subjected to abrasive wear in many applications. Abrasive wear as defined by ASTM, is due to hard particles or hard protuberances that are forced against and move along a solid surface. Wear, in turn, is defined as damage to a solid surface that generally involves progressive loss of material and is due to relative motion between that surface and a contacting substance or substances. Abrasive wear occurs when hard asperities on one surface move across a softer surface under load, penetrates and remove material from the softer surface leaving grooves [4]. The tribological performance of composite material is usually related with the properties of their reinforcement [5]. One of the traditional concepts to improve the friction and wear behaviour of polymeric materials is to enhance their hardness, stiffness and their compressive strength and to reduce adhesion to the counterpart material [6-9]. Many investigations have shown that the incorporation of fiber reinforcement improved the wear resistance and reduced the coefficient of friction [10]. Mody *et al.* [11] in their investigation showed the simultaneous existence of parallel and perpendicular oriented carbon fibers in a woven configuration leads to a synergic effect on the enhancement of the wear resistance of composite. Carbon fiber is graphitized carbon with the hexagonal planes of its crystals aligned perpendicular to the fiber axis. The lubricating function of the graphitized carbon is thought to be responsible for the reduction of the friction coefficient and wear rate as the composite slide against the matting surface. Besides the lubricating function, carbon fiber also enhances the thermal conductivity and mechanical properties of poly-

*Corresponding author.

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mer matrix which is believed to be beneficial to the wear resistance as well [12].

A notable advance in the polymer industry has been the use of fiber and particulate fillers as reinforcements in polymer matrices. Many researchers found that glass fiber and carbon fibers were effective reinforcements for distinct effect on the friction and wear behaviour of polymer composites [13]. The advantage of glass fiber includes low cost, high strength as well as high chemical resistance. On the other hand its low modulus, low fatigue resistance. Its self-abrasiveness and its poor interaction with some matrices limit this type of fiber for some tribological applications. Carbon fibers not only show a high strength and modulus but also have an excellent heat stability and chemical inertness [14]. Furthermore, carbon fiber is preferred as reinforcement/filler in tribo-composites because it imparts reinforcement, conductivity and better friction. However, these fibers have some disadvantages such as difficulty of uniform distribution, poor interfacial adhesion etc. [15]. The modification of tribological behaviour of fiber reinforced polymers by the addition of functional fillers has been reported by many researchers [16,17]. Particulate fillers are of considerable interest, not only in the economic point of view but also as modifiers especially in respect to improve physical properties of polymer. It is well documented in the literature that majority of fillers have a positive influence on mechanical properties [18]. Inorganic fillers like SiC, SiO_2, Al_2O_3, MoS_2, graphite, addition into polymer composite can promote hardness, wear resistance and thin film formation on the counterpart during sliding wear process. Most of the findings are based on randomly oriented, unidirectional oriented or woven fabric reinforced polymer composites. Surface treatment of carbon fibers [19-21] is commonly used to improve the fiber-matrix adhesion, interfacial shear strength, etc. However, only few works are focussed on the effect of surface modification of filler on abrasive wear properties of fiber reinforced polymer composites. It is reported that silane coupling agent promotes the interfacial adhesion and interfacial toughness between glass fibers and polytetrafluoroethylene (PTFE) and largely enhance the tensile and tribological properties of glass PTFE composites [22,23].

Majority of research studied detailed experimental work with effect of one factor by keeping all other factors fixed, this approach is not advisable because in actual environment there will be combined effects of interacting factors influencing the abrasive wear. Hence in this study an attempt is being made to study the interacting effects of factors along with the main effect. To achieve this, design of experiments based on Taguchi method is adopted. This method is advocated by Taguchi and Konishi [24]. Taguchi's technique uses special design of orthogonal arrays to study the entire parameter space with only a small number of experiments. Taguchi's technique also helps in optimizing the critical parameters [25].

Carbon fabric reinforcement and graphite filler are good choice since in many applications both high modulus and high strength are desired. In the present work, the carbon fabric and graphite particles were treated with silane coupling agent and their effect on Tree-body abrasive wear of epoxy composites have been evaluated using multi response grey-based Taguchi method. The purpose of this work is to study the abrasion resistance of C-E composite with silane treated graphite particles under three-body abrasion using silica sand of angular shape. It is expected that this research work can be helpful to the use of epoxy composites in practice.

2. Experiment

2.1. Materials

The composites investigated in the present study, consists of bi-directional carbon fabric of about 6 - 8 μm diameter as reinforcement (T300). The carbon fiber surface is treated with silane coupling agent to improve adhesion between the matrix and fiber. Epoxy resin (LY556) with room temperature curing hardener (HY951 grade) with diluent DY021 (supplied by Hindustan Ciba Geigy) mix was employed for the matrix material. The graphite particles of average size of about 20 - 25 μm were employed as filler material. The details of composites selected, measured density and hardness are listed in **Table 1**. Three-body wear test samples of size 25 × 75 × 2.5 mm^3 were prepared from the laminate using a diamond tipped cutter.

2.2. Barcol Hardness

ASTM D2583 Barcol hardness test method [26] is used to determine the hardness of reinforced thermosets. The specimen is placed under the indentor of Barcol hardness tester and a uniform pressure is applied to the specimen until the dial indication reaches a maximum. The depth of penetration is converted in to absolute Barcol numbers. At least three specimens of each composition were tested and the average values were listed in **Table 1**.

Table 1. Composites selected for study.

Material (designation)	Epoxy (wt%)	Filler (wt%)	Density (g/cm^3)	Hardness (barcol)
Carbon-epoxy (C-E)	40	-	1.412	73
Graphite filled carbon-epoxy (5G-C-E)	35	5	1.431	74
Graphite filled carbon-epoxy (10G-C-E)	30	10	1.465	76

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2.3. Three-Body Wear Test

Three-body abrasive wear experiment was conducted using dry sand/rubber wheel abrasion test set up as per ASTM G65 standard [27]. The schematic diagram of the test set up is shown in **Figure 1**.

Initially the samples were cleaned with acetone, dried and its initial weight was determined using a high precision digital electronic balance (0.0001 g accuracy). The naturally deposited silica sand of grain size 212 μm in angular particle shape was used as abrasive. The abrasive was fed at the contacting face between the rotating rubber wheel and test sample. The tests were conducted at a rotational speed of 200 rpm. The rate of feeding abrasive was maintained at 255 ± 5 g/min. The parameters and levels are given in **Table 2**. The experiment was carried out for three loads viz., 11 N, 23 N and 35 N. The abrading distances were maintained at 300 m, 600 m and 900 m. After testing, the specimens were removed, cleaned, dried and again weighed. The difference between the initial weight and final weight of the specimen was computed, this gives the material wear in terms of weight loss, was then converted into volume loss using measured density data. Further specific wear rate (K_s) was calculated from equation [28]:

$$K_s = \frac{\Delta V}{L \times D} \ \mathrm{m}^3 / \mathrm{N} \cdot \mathrm{m} \tag{1}$$

where; ΔV is the volume loss in m^3, L is the load in Newton and D is the abrading distance in meters.

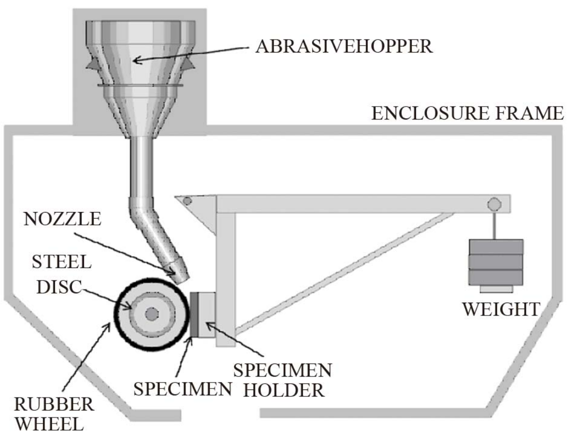

Figure 1. Dry sand/rubber wheel abrasive test rig.

Table 2. Control factors and levels.

Factor	Description	Level 1	Level 2	Level 3
A	**Filler (wt%)**	0	5	10
B	**Load (N)**	11	23	35
C	**Sliding distance (m)**	300	600	900

In unlubricated sliding wear the value of wear coefficient (k) is the dimensionless quotient [29] of the specimens was calculated according to the equation:

$$k = \frac{\Delta VH}{LD} \tag{2}$$

where ΔV is volumetric wear, H is hardness of the wearing material, L is the normal load in Newton, and D is abrading distance in metres.

2.4. Design of Experiments

Wear properties are highly dependent on its material composition and variables under which it has to be performed [30]. This study was selected as the target qualities for optimization of the weight loss of composite material using 212 grain size silica sand of angular shape as abrasive. Three body abrasive wear test were conducted to determine weight loss. Taguchi uses a special design of orthogonal arrays to study the entire process parameter space with only a small number of experiments [31-33]. Twenty seven experimental runs, based on Taguchi orthogonal arrays were used to find the best factor level condition given in **Table 3**. The factor levels were assessed according to selected wear loss. The influence of the controllable process factors on the weight loss was studied, based on the correlation between the process factors. By analyzing the grey relational grade matrix, the most influential factors were identified. Finally the worn surfaces were observed by scanning electron microscopy (SEM) to understand wear mechanisms.

2.5. Grey System

Deng [34] proposed Grey relational analysis (GRA) which is part of grey system. GRA is suitable for solving problems with complicated inter relationships between multiple factors and variables. According to Moran *et al*. [35] grey relational analysis solves multi-attribute decision making problems by combing the entire range of performance attribute values being considered for every alternative into one single value. This reduces the original problem into a single decision making problem. This method quantifies the influences of various factors and their relation which is called the whitening of factor relation. The information that is either incomplete or undetermined is called grey. The system having incomplete information is called grey system. Grey based Taguchi method follows the optimization method developed by Dr. Genichi Taguchi. Taguchi method works for optimization of a single performance characteristic. GRA is used to combine the entire considered performance characteristic in optimization problem [36]. Grey relational analysis requires less data and can analyze many factors that can overcome the disadvantages of statistical methods.

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Table 3. Experimental layout using $L_{27}(3^{13})$ orthogonal Array and performance results.

Expt. No.	Load, *A* (N)	Distance, *B* (m)	Filler, *C* (wt%)	Specific wear rate (K_s) × 10^{-5} (m^3/N·m)	Wear coef. (*k*) × 10^{-3}	Hardness (*H*)
1	11	300	0	6.6545	6.1887	73
2	11	300	5	6.312	5.9333	74
3	11	300	10	5.2757	5.0647	76
4	11	600	0	3.6818	3.424	73
5	11	600	5	3.3984	3.1945	74
6	11	600	10	3.1696	3.0429	76
7	11	900	0	2.6615	2.4753	73
8	11	900	5	2.4282	2.2825	74
9	11	900	10	2.2737	2.1827	76
10	23	300	0	3.6898	3.4315	73
11	23	300	5	3.2492	3.0543	74
12	23	300	10	3.1115	2.9871	76
13	23	600	0	1.9854	1.8465	73
14	23	600	5	1.7782	1.6715	74
15	23	600	10	1.7057	1.6375	76
16	23	900	0	1.4801	1.3765	73
17	23	900	5	1.3226	1.2433	74
18	23	900	10	1.183	1.1357	76
19	35	300	0	2.7257	2.5349	73
20	35	300	5	2.3876	2.2443	74
21	35	300	10	2.2076	2.1193	76
22	35	600	0	2.0547	1.9109	73
23	35	600	5	1.6923	1.5908	74
24	35	600	10	1.5114	1.4509	76
25	35	900	0	1.7698	1.6459	73
26	35	900	5	1.3346	1.2545	74
27	35	900	10	1.1892	1.1416	76

3. Results and Discussion

3.1. Abrasive Wear Volume

The wear volume of unfilled C-E, 5G-C-E and 10G-C-E composites tested with varying load 11 N, 23 N and 35 N are shown in **Figures 2(a)-(c)**. The wear volume tends to increase with increasing abrading distance from 300 m to 900 m as well load from 11 N to 35 N. The higher filler loaded, 10 wt% graphite filled C-E exhibited lowest wear volume at all abrading distances and loads. Wear volume data revealed that wear volume of unfilled C-E at higher load is higher than that obtained at lower load. Severe damage to matrix and fiber is the main reason for higher wear at higher load. Higher contact pressure and elongation of softened matrix caused more debris and micro cracks in the matrix. Softened polymer matrix could not effectively protect the carbon fiber from peeling off which aggravated the fiber removal. This resulted in the decline of the wear resistance of unfilled C-E composite. Additions of graphite filler considerably decreased the wear volume.

3.2. Data preprocessing

Data pre-processing is a process of transferring original sequence to a comparable sequence. For this experimental research, data is normalized between zero and one. Depending on characteristics of data sequence various methodologies of data pre-processing available. In this study the response to be optimized is specific wear rate, wear coefficient and Hardness.

To obtain the optimal wear performance lower-the-better quality characteristic has been used to minimize the specific wear rate and wear coefficient, and can be expressed as:

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

where $x_i^*(k)$ and $x_i(k)$ are sequences after data pre-processing and comparability sequence respectively, k = 1, 2 for wear rate and wear coefficient. i = 1, 2, 3, ⋯, 27 for experiment number 1 to 27.

Hardness of composite should follow higher—the better criterion which can be expressed as:

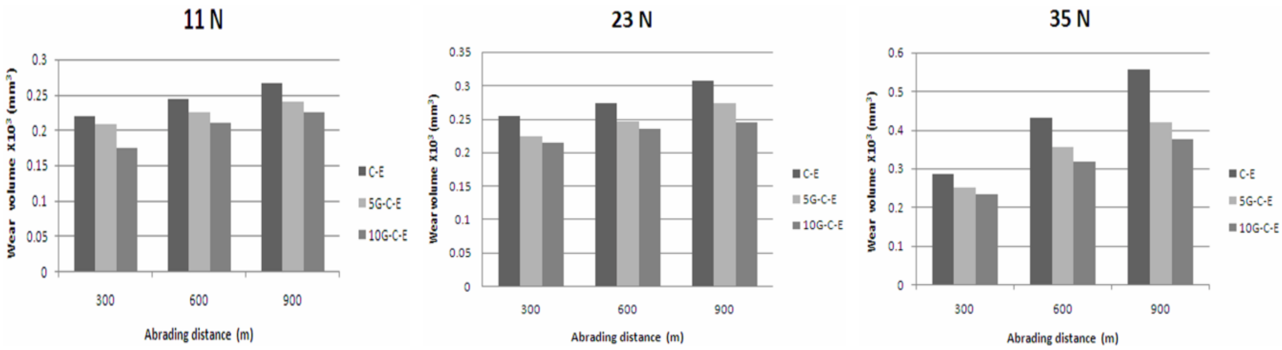
$$x_i^*(k) = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)} \tag{4}$$

where $x_i^*(k)$ and $x_i(k)$ are sequences after data pre-processing and comparability sequence respectively, k = 3 for hardness. i = 1, 2, 3, ⋯, 27 for experiment number 1 to 27.

$\Delta_{oi}(k)$ is deviation sequence of reference sequence $x_0^*(k)$ and comparability sequence $x_i^*(k)$. Deviation sequence Δ_{oi} can be calculated using equation:

$$\Delta_{oi}(k) = \left| x_o^*(k) - x_i^*(k) \right| \tag{5}$$

Table 4 represents the normalized data and deviation sequence for 27 experimental runs.



(a) (b) (c)

Figure 2. Effect of abrading distance on wear volume of composites at (a) 11 N; (b) 23 N; (c) 35 N.

Table 4. Normalized data and deviation sequences.

Expt No.	Normalized data			Deviation sequences (Δ_{oi})		
	$K_s \times 10^{-4}$	$(k) \times 10^{-3}$	H	$K_s \times 10^{-4}$	$(k) \times 10^{-3}$	H
1	0.0000	0.0000	0.0000	1.0000	1.0000	1.0000
2	0.0625	0.0505	0.3333	0.9375	0.9495	0.6667
3	0.2519	0.2224	1.0000	0.7481	0.7776	0.0000
4	0.5433	0.5471	0.0000	0.4567	0.4529	1.0000
5	0.5951	0.5925	0.3333	0.4049	0.4075	0.6667
6	0.6369	0.6225	1.0000	0.3631	0.3775	0.0000
7	0.7297	0.7348	0.0000	0.2703	2652	1.0000
8	0.7724	0.773	0.3333	0.2276	0.227	0.6667
9	0.8006	0.7927	1.0000	0.1994	0.2073	0.0000
10	0.5418	0.5456	0.0000	0.4582	0.4544	1.0000
11	0.6223	0.6203	0.3333	0.3777	0.3797	0.6667
12	0.6475	0.6336	1.0000	0.3525	0.3664	0.0000
13	0.8533	0.8593	0.0000	0.1467	0.1407	1.0000
14	0.8912	0.8939	0.3333	0.1088	0.1061	0.6667
15	0.9044	0.9006	1.0000	0.0956	0.0994	0.0000
16	0.9457	0.9523	0.0000	0.0543	0.0477	1.0000
17	0.9744	0.9787	0.3333	0.0256	0.0213	0.6667
18	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000
19	0.7180	0.7230	0.0000	0.2820	0.2770	1.0000
20	0.7798	0.7806	0.3333	0.2202	0.2194	0.6667
21	0.8127	0.8053	1.0000	0.1873	0.1947	0.0000
22	0.8406	0.8465	0.0000	0.1594	0.1535	1.0000
23	0.9069	0.9099	0.3333	0.0931	0.0901	0.6667
24	0.9399	0.9376	1.0000	0.0601	0.0624	0.0000
25	0.8927	0.899	0.0000	0.1073	0.1010	1.0000
26	0.9722	0.9764	0.3333	0.0278	0.0236	0.6667
27	0.9988	0.9988	1.0000	0.0012	0.0012	0.0000

3.3 Grey Relational Coefficient and Grey Relational Grade

Grey relational coefficient (GRC) expresses relationship between ideal and actual normalized experimental results and is given by:

$$\xi_i\left(k\right)=\frac{\Delta_{\min}+\zeta\,\Delta_{\max}}{\Delta_{oi}\left(k\right)+\zeta\,\Delta_{\max}} \tag{6}$$

where $\Delta_{oi}(k)$ is deviation sequence of reference sequence $x_0^*\left(k\right)$ and comparability sequence is $x_i^*\left(k\right)$, ζ distinguishing or identification coefficient. The purpose of grey relational coefficient is to expand or compress the range of grey relational coefficient [37]. If all parameters are given equal preference, ζ is taken as 0.5. Grey relational coefficient (GRC) **Table 5** for each experiment can be calculated using Equation (6).

After obtaining GRC, the Grey relational grade (GRG) is computed by averaging GRC corresponding to each performance characteristic. Overall evaluation of multiple performances characteristic is based on GRG is given by:

$$\gamma_i=\frac{1}{n}\sum_{k=1}^{n}\xi_i\left(k\right) \tag{7}$$

Table 5. Grey relational coefficient and grey relational grade.

Expt. No	Grey Relational Coefficient			GRG
	K_s	k	H	
1	0.3333	0.3333	0.3333	0.3333
2	0.3478	0.3449	0.4285	0.3737
3	0.4006	0.3913	1.0000	0.5973
4	0.5226	0.5247	0.3333	0.4602
5	0.5525	0.5509	0.4285	0.5106
6	0.5793	0.5698	1.0000	0.7163
7	0.6490	0.6534	0.3333	0.5452
8	0.6871	0.6877	0.4285	0.6011
9	0.7148	0.7069	1.0000	0.8072
10	0.5218	0.5238	0.3333	0.4596
11	0.5696	0.5683	0.4285	0.5221
12	0.5865	0.5771	1.0000	0.7217
13	0.7731	0.7803	0.3333	0.6289
14	0.8212	0.8249	0.4285	0.6915
15	0.8394	0.8341	1.0000	0.8911
16	0.9020	0.9129	0.3333	0.7478
17	0.9512	0.9591	0.4285	0.7796
18	1.0000	1.0000	1.0000	1.0000
19	0.6393	0.6435	0.3333	0.5387
20	0.6942	0.695	0.4285	0.6059
21	0.7274	0.7197	1.0000	0.8157
22	0.7582	0.7651	0.3333	0.6188
23	0.8430	0.8473	0.4285	0.7062
24	0.8926	0.889	1.0000	0.9272
25	0.8233	0.8319	0.3333	0.6628
26	0.9473	0.9549	0.4285	0.7769
27	0.9976	0.9976	1.0000	0.9984

It is evident from the **Table 5** that experiment 18 has the best multiple performance characteristic among the twenty seven experiments since having the highest grey relational grade. The process parameters are converted in to signal to noise ratio. **Figure 3**, graphically represents-the effect of three control factor in GRG. The combination factor that optimizes wear process was identified as A3B3C3. Parameter combination of 10 wt% graphite filled carbon-epoxy composite abraded for 900 m under a load of 35 N results in least wear. Total mean of grey relational grade for twenty seven experiments are given in **Table 6**. The rank in the last column of the table represents the significance of each parameter.

3.4 Analysis of Variance

The purpose of analysis of variance (ANOVA) is to investigate parameters which significantly affect the performance characteristic. This is established by separating the total variability of the grey relational grades, which is measured by sum of the squared deviations from the total mean of the grey relational grade, into contributions by each wear parameters and listed in **Table 7**.

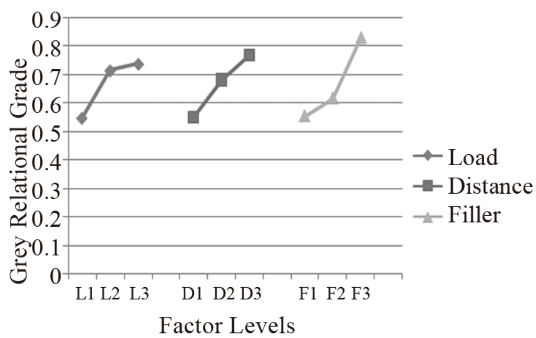


Figure 3. Effect of wear process parameter levels on grey relational grade.

Table 6. Response table for grey relational grade.

Symbol	Parameter	GRG			Main effect (max − min)	Rank
		Level 1	Level 2	Level 3		
A	Load	0.5494	0.7158	0.7390	0.1895	3
B	Distance	0.5520	0.6834	0.7688	0.7688	2
C	Filler	0.5550	0.6186	0.8305	0.2755	1

Table 7. ANOVA results.

Symbol	Parameter	DOF	Sum of Square	Contribution %
A	Load	2	0.192408	24.170
B	Distance	2	0.214650	26.970
C	Filler	2	0.374583	47.070
A*B	Load*Distance	4	0.010234	1.290
A*C	Load*Filler	4	0.002567	0.322
B*C	Distance*Filler	4	0.000220	0.028
Error		8	0.001202	0.150

According to ANOVA the percentage of contributions indicate the relative power of a factor to reduce variation. The factor with high percent contribution has greatest influence on the performance. The percentage contribution of filler content (47.07%) was found to be the major factor affecting the wear performance. Whereas the abrading distance (26.97%) found to be second influential factor followed by Load (24.17%) as shown in **Figure 4**. Suresha *et al*. [38] investigated the effect of SiC filler addition on two-body abrasive wear and concluded that the maximum wear resistance was obtained for 7.5 wt% SiC in G-E composite. The present work data by Grey relational analysis are in good agreement with the experimental investigations.

3.5. Surface Morphology

The worn surface of unfilled C-E composite **Figures 5(a)** and **(b)**, 10% graphite filled C-E composite **Figures 6(a)** and **(b)** are examined foe two loads 11 N and 35 N at 900 m abrading distance. Unfilled C-E sample **Figure 5(a)** showed higher degree of worn surface features compared to 10% graphite filled **Figure 5(b)**. The same observations hold good for samples subjected to higher load of35N shown in **Figures 6(a)** and **(b)**. These are supportive to wear volume shown in **Figure 2**. Filled C-E composites at a load of 11 N, exhibited number of broken fiber with minimum debris as compared to unfilled C-E composites. Filled C-E composites subjected to higher load of 35 N, markings of fibers were noticed where as unfilled C-E **Figure 5(b)** show large number of broken fibers with lot of distortion in the matrix with higher degree of debris formation. The application of higher load has resulted in the deformation in the form of disorientation of fibers perpendicular to the abrading direction.

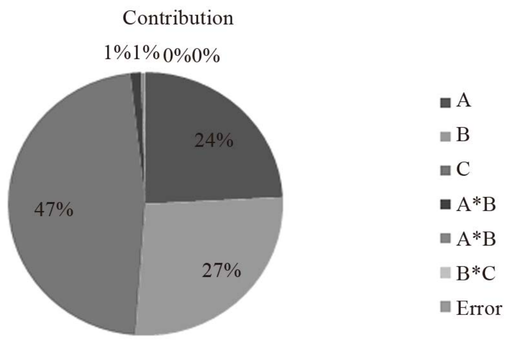
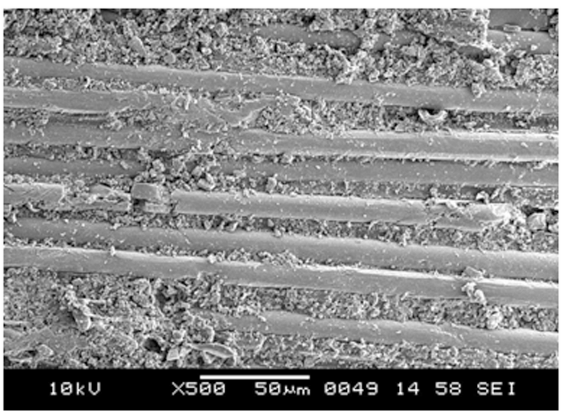
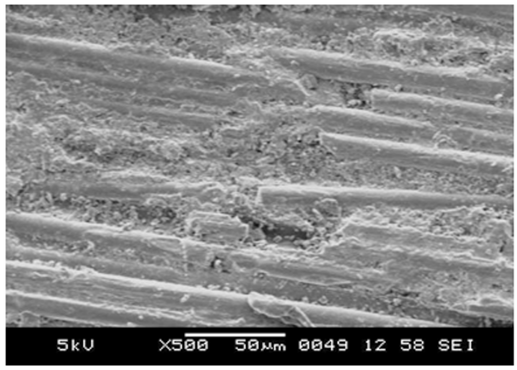


Figure 4. Percentage contribution of factors on grey relational grade.

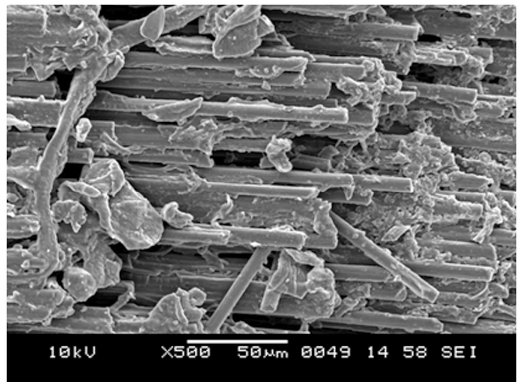


(a)

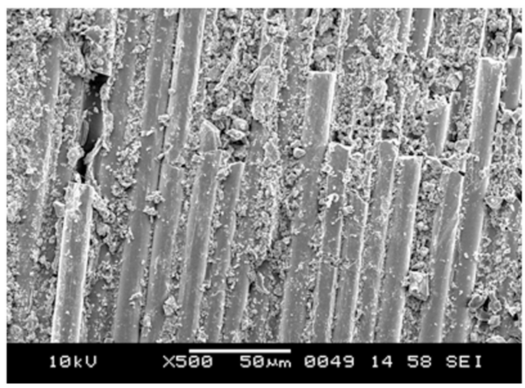


(b)

Figure 5. SEM micrograph of worn surface of unfilled C-E subjected to load (a) 11 N; (b) 35 N.



(a)



(b)

Figure 6. SEM micrograph of worn surface of 10 wt% graphite filled C-E subjected to (a) 11 N; (b) 35 N.

4. Conclusions

The grey based Taguchi multi response method was applied in this study to optmize the three-body abrsive wear of unfilled and graphite filled carbon-epoxy composites. The results are summarized as follows:

- Taguchi method, a simple systematic and efficient methodolgy used for optimizing three control factors to set optimal levels for meeting the objective with minimum number of experimental runs, to study the abrasive wear characteristics of composites.
- Optimal wear parameters have been determined by Grey relational grade for multiperformance charateristics: specific wear rate, wear coefficient and hardness.
- ANOVA of GRG for multiperformance charateristics revealed that factors like filler content (C), abrading distance (B) and applied load (A) are significant in order of priority to minimize the wear.
- Controlling factors with A3B3C3 combination caused minmum wear and higer hardness.
- Graphite filler found to possess good filler characteristics and increases the wear resistance of C-E composite.

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