ENGINEERING RESEARCH JOURNAL (ERJ)

Vol. 1, No. 47 Jan. 2021, pp 28-33

Journal Homepage: http://erj.bu.edu.eg

Tribological Behavior of Epoxy-Based Nan composites Reinforced with MWCNTs

Abd El-Karim M. Awad, Sayed A.E. Abd-Allah and Ahmed M. Gaafer

Faculty of Engineeringat Shoubra, Benha University, Cairo, Egypt.

Abstract. Multi-walled carbon nano tubes (MWCNTs) was used as a high-density polyethylene reinforcement material in epoxy-based nano composites. The effect of sliding conditions typically; applied load, sliding speed and volume fraction of the MWCNTs on coefficient of friction and wear rate was evaluated and optimized. Cylindrical specimens having of 0.5, 1 and 1.5% volume fraction of MWCNTs were worn using a pin on disc machine. The analysis and optimization was carried out by analysis of variance (ANOVA). L27 orthogonal array design of experiments(DOE) technique were used to determine the most influential parameter on wear rate and coefficient of friction. The results by ANOVA analysis with Taguchi (DOE) showed that parameters; volume fraction, speed and load were significant factors on coefficient of friction and wear rate. The sequence of importance of process parameters on multi-responses by (RSM) were applied the load followed by volume fraction, and finally the sliding speed.

Keywords: MWCNTs, epoxy matrix, coefficient of friction, wear rate, ANOVA.

1. INTRODUCTION

Due to their exceptional characteristics, nanocomposite materials are becoming ever more important over the years. They show a combination of properties which no other conventional family of materials could achieve. Of that reason, demand is booming and many companies are spending millions in research to better understand and leverage to the fullest their exceptional resources[1].Epoxy resins are commonly used in industrial applications thanks to their high mechanical, adhesion and chemical resistance properties, and the curability of in a variety of temperatures without volatile products emissions. They are commonly used in various applications, including paints and fabrics, adhesives, manufacturing equipment and composites, electrical and electronics, consumer automotive, marine and aviation applications[2].Carbon nanotubes CNTs composite exhibits high flexibility, low mass density, and large aspect ratio (typically>1000), whereas predicted and some experimental data indicate extremely high tensile moduli and strengths for these materials[2]. CNTs describe a family of nanomaterials made up entirely of carbon. In this family, multi-walled carbon nanotube (MWCNTs) are of special interest for the industry, structurally[3]. MWCNTs exhibit advantages such as ease of mass production, low product cost per unit, and enhanced thermal and chemical stability. It is a suitable material which used to improve the photocatalyst performance due to their unique structure and properties.In addition,MWCNTs composites have paying attention due to the mechanical, electrical and thermal properties of MWCNTs[4].

Hamed et al. [5] investigated the effect of the process parameter such as applied load, sliding distance between centers and volume percentage of nano content of MWCNTS on wear rate of epoxy composites using pin on disc machine. They found that applied load had the most significant factor on wear rate. Reda [6] studied the effect of process parameters such as applied load, sliding distance between center, sliding time and volume percentage of nano particles of CNTs, aluminum oxide (Al_2O_3) and silicon oxide (SiO_2) on tribological properties, wear rate and coefficient of friction, of polymer epoxy nano composites by using pin-on disc machine. The applied load had the most significant effect on coefficient of friction and wear rate[6]. Ahmad et al[8] studied the effect of process parameters such as applied load and volume percentage of nano of aluminum oxide (Al_2O_3) and multi-walled carbon nanotubes (MWCNTs) on wear rate by using practicing unique dispersion method. The results showed that volume percentage of nano was the most significant factor on wear rate.

The main objective of the present investigation is to study the effect of sliding wear conditions; applied load, sliding speed and sliding time on tribological properties (coefficient of friction and Wear rate) by using analysis of variance (ANOVA based on Taguchi L27 orthogonal array.

2. MATERIALS and EXPERIMENTAL PROCEDURES

In this study, Epoxy resin (KEMAPOXY 150) was used as a matrix.The epoxy resin was mixed with the hardener by (2:1) by weight. The mixing process was stirred mechanically for 20 minutes at room temperature using SUPERMIX homogenizer (model DEPOSE) at the rate of 1000 RPM. The mixture poured in a silicon moldwith standard inner dimensions according to test standards. nanocomposites were prepared by adding 0.5, 1 and 1.5% of MWCNTs nanoparticles separately to the resin and stirred mechanically for 20 minutes at room temperature, then the hardener was added to the mixture and then stirred mechanically again for 10 minutes. The epoxy/nanofillers slurry was poured in tubes. Finally, the mixture was allowed to fully harden at room temperature for 7 days according to the specification of the matrix. Experiments have been conducting according to Taguchi L27 orthogonal array. The parameters; volume fraction of MWCNTs%, speed and applied load, were selected with the level presented in Table1. Wear test were performed using pin-on-ring machine apparatus shown schematically in Fig. 1.

Table 1. The factors and their levels

Parameter	Unit	Level 1	Level 2	Level 3
Speed	RPM	300	600	900
Load	N	17.1	20.1	24.1
MWCNTs	Vol. %	0.5	1	1.5

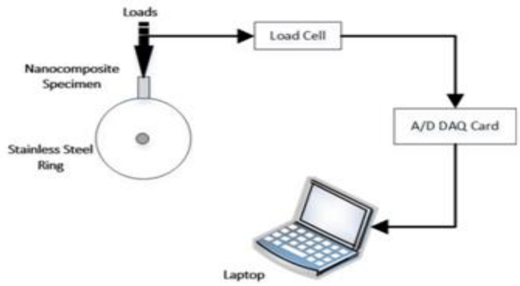

Fig. 1. A schematic illustration of the pin-on-ring wear tester.

3 Results and discussion

The results of wear rate and coefficient of friction at defferent process paramters are listed in table 2.

Table2. Measuement results of wear rate and coefficient of frictions

No.	%	V	F	Wear	μ	No.	%	V	F	Wear	μ
1	0.5	300	300	2	0.149	15	1	600	1000	65	0.44
2	0.5	300	300	2.5	0.167	16	1	900	300	130	0.27
3	0.5	300	300	5	0.149	17	1	900	300	317	0.27
4	0.5	600	600	6	0.19	18	1	900	300	23.9	0.26
5	0.5	600	600	9	0.28	19	1.5	300	1000	3	0.126
6	0.5	600	600	7.5	0.23	20	1.5	300	1000	5	0.124
7	0.5	900	1000	16	0.39	21	1.5	300	1000	10	0.126
8	0.5	900	1000	4.5	0.32	22	1.5	600	300	104	0.26
9	0.5	900	1000	8.5	0.39	23	1.5	600	300	73	0..22
10	1	300	600	1.4	0.127	24	1.5	600	300	54	0.28
11	1	300	600	5.5	0.142	25	1.5	900	600	183	0.2
12	1	300	600	3.5	0.127	26	1.5	900	600	240	0.23
13	1	600	1000	22	0.44	27	1.5	900	600	280	0.24
14	1	600	1000	57.5	0.38						

3.1 Taguchi design of experiment (DOE) optimization by ANOVA

3.1.1 Analysis of main effect for coefficient of friction

The dependence of the main effect plot for SN ratio of coefficient of friction on percentage of MWCNTs, speed and applied load is presented in Fig. 2. The results revealed that the most significant parameter affects the coefficient of friction is percentage of MWCNTs.

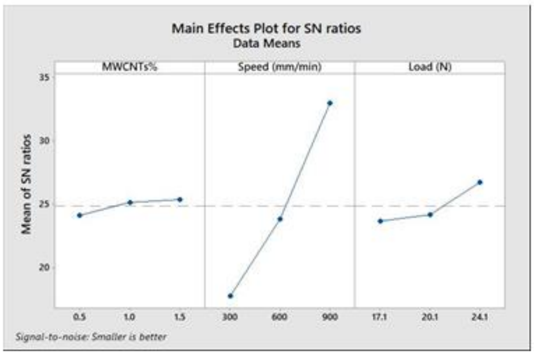

Fig2. Main effects plot for SN ratio for coefficient of friction.

In this study, analyses of variance for the response surface were performed. Results of ANOVA for each parameter are shown in Table3. From the table, fraction of MWCNTs, speed and applied load seem to have most dominance influence. The model of high F-value indicate to this model is significant. P-values less than 0.0500 indicate model terms are significant. In this case, load, speed and MWCNTs% were most significant model terms.

Table3. The results of ANOVA for coefficient of friction

Source	DF	Adj SS	Adj MS	F-Val	P-Val
MWCNTs, vol.%	2	0.001984	0.000992	19.14	0.000
Speed, RPM	2	0.053621	0.026811	517.21	0.000
Load, N	2	0.003221	0.001610	31.06	0.000
Error	20	0.001037	0.000052		
Lack-of-Fit	2	0.000072	0.000036	0.67	0.523
Pure Error	18	0.000965	0.000054		
Total	26	0.059863			

3.1.2 Analysis of main effect for wear rate

Figure3. Shows the main effects plots for SN ratios for wear rate with respect to process parameters.Table4 summaries the results of ANOVA analysis of wear rate. The results from Figure3 and Table4 revealed that parameters load, speed and percentage of MWCNTs were significant factors on wear rate.

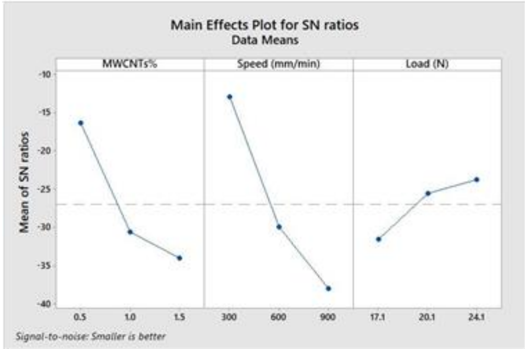

Fig3. Main effects plot for SN ratio for wear rate.

Table4. The results of ANOVA for wear rate

Source	DF	Adj SS	Adj MS	F-Val	P-Val
MWCNTs, vol.%	2	45159	22579	6.40	0.007
Speed, RPM	2	79065	39533	11.21	0.001
Load, N	2	21010	10505	2.98	0.074
Error	20	70558	3528		
Lack-of-Fit	2	19319	9660	3.39	0.056
Pure Error	18	51239	2847		
Total	26	215792			

3.2. Multi optimization response using GRA

The optimization of complex multi-response features can be converted to optimization of a single response feature through the Gray relational grade as the objective function by using Grey relational analysis associated with the Taguchi process. thus, the objectives are to minimize wear rate and coefficient of friction by using grey relational analysis.

3.2.1.Grey relational generation:

GRA is the most suitable technique to obtain the optimal process parameters on multi- response characteristics, the first step is to perform the grey relational generation in which the results of the experiments for wear rate and coefficient of friction are normalized corresponding to smaller-the-better criterion can be expressed as :

$$X_i(k) = \frac{\max Y_i(k) - Y_i(k)}{\max Y_i(k) - \min Y_i(k)} \quad (1)$$

k = 1, 2, ..., n, i = 1, 2, 3, ..., m; m is the number of experimental data and, n is the number process responses. Yi (k) the original sequence, Min Yi (k) is the smallest value of Yi (k). Max Yi (k) is the largest value of Yi (k). Xi (k) is the value after Grey relational generation. The normalized values of wear rate and coefficient of friction are calculated by Eq. (1) and are shown in Table 5

3.2.2.Grey relational coefficient

The grey relational coefficient shown in Table5 is calculated by the following equation (2):

$$\boldsymbol{\xi_i(k) = \frac{\Delta_{min} + \zeta\, \Delta_{max}}{\Delta_{0i}(k) + \zeta\, \Delta_{max}}} \quad \textbf{(2)}$$

where, $\Delta_{0i}$is the deviation sequence of the reference sequence and the comparability sequence and$\Delta_{0i}(k) = \|x_0(k) - x_i(k)\|$ where $x_0(k)$implies the reference sequence and $x_i(k)$ termed as comparability sequence. Δ min and Δ max are the minimum and maximum values of the absolute differences (Δ0*i*) of all comparing sequences. ζIs distinguishing or identification coefficient and the range is between 0 to 1. Usually, the value of $\zeta$is taken as 0.5.The Grey relation coefficient of each performance characteristic is shown in Table5.

3.2.3.Grey relational grade (GRG)

The (GRG) shown in Table5.Is calculated by averaging the grey relational coefficient corresponding to each experiment as it shown from equation (3):

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k) \ (3)$$

ξi(k) is the Grey relational coefficient and *n* is the number of responses. The higher value of GRG corresponds to an intense relational degree between the reference sequence *x*0(*k*) and the given sequence *x*i (*k*).

Table 5 Grey relational generation, Grey relational coefficient and grey relational grade values

no	Normalizing value of response		Deviation sequences		Grey relationalcoefficient		Grey relation grade
	Coefficient friction	Wear rate (mg/min)	Coefficient friction	Wear rate (mg/min)	Coefficient friction	Wear rate (mg/min)	GRG
1	0.946	0.998	0.054	0.002	0.902	0.996	0.949
2	0.923	0.997	0.077	0.003	0.867	0.993	0.930
3	0.946	0.989	0.054	0.011	0.902	0.978	0.940
4	0.000	0.985	1.000	0.015	0.333	0.972	0.653
5	0.277	0.976	0.723	0.024	0.409	0.954	0.681
6	0.088	0.981	0.912	0.019	0.354	0.963	0.658
7	0.894	0.954	0.106	0.046	0.825	0.915	0.870
8	0.882	0.990	0.118	0.010	0.809	0.981	0.895
9	0.894	0.978	0.106	0.022	0.825	0.957	0.891
10	0.974	1.000	0.026	0.000	0.950	1.000	0.975
11	0.955	0.987	0.045	0.013	0.917	0.975	0.946
12	0.974	0.993	0.026	0.007	0.950	0.987	0.968
13	0.579	0.935	0.421	0.065	0.543	0.885	0.714
14	0.428	0.822	0.572	0.178	0.467	0.738	0.602
15	0.579	0.798	0.421	0.202	0.543	0.713	0.628
16	0.793	0.593	0.207	0.407	0.708	0.551	0.629
17	0.793	0.000	0.207	1.000	0.708	0.333	0.520
18	0.806	0.929	0.194	0.071	0.721	0.875	0.798
19	1.000	0.995	0.000	0.005	1.000	0.990	0.995

20	1.000	0.989	0.000	0.011	1.000	0.978	0.989
21	1.000	0.973	0.000	0.027	1.000	0.948	0.974
22	0.378	0.675	0.622	0.325	0.446	0.606	0.526
23	0.353	0.773	0.647	0.227	0.436	0.688	0.562
24	0.126	0.833	0.874	0.167	0.364	0.750	0.557
25	0.882	0.425	0.118	0.575	0.809	0.465	0.637
26	0.844	0.244	0.156	0.756	0.762	0.398	0.580
27	0.844	0.117	0.156	0.883	0.762	0.362	0.562

The effects of each variable at different levels and mean GRG is presented in Table 6. The optimal parametric combination is chosen based on higher mean GRGvalues which calculated by take the average values for each level of process parameter from table 6 and its values are shown in Table6 . Rank indicate to the most influencing parameters during the process, the higher value of GRG implies a stronger correlation to the reference sequence and better performance. Thus, the optimal settings for multi-responses are applied load0.840N, speed 0.963mm/min and MWCNTs vol.% of 0.830. The higher values of mean grey relational grade gives the minimum values of wear rate and coefficient of friction. The difference of maximum and minimum values of mean GRG for turning parameters were as 0.121for MWCNTsvol.%, 0.343for speed and 0.128for applied load respectively Table 6. This result indicates that the applied load has the most influencing effect on multi-responses compared to other factors during process. The sequence of importance of process parameters on multi-responses are appliedspeed>load >MWCNTs

Table 6Main effects on mean grey relational grade.

Name	G R grade			Mean (max-min)	Rank
	Level 1	level 2	level 3		
MWCNTs,%	*0.830	0.753	0.709	0.121	3
Speed, RPM	*0.963	0.620	0.709	0.343	1
Load, N	0.712	0.740	*0.840	0.128	2
Total mean value of grey relation grade is				0.592	

* corresponding to optimum level

3.3.Applying (ANOVA) analysis

Considering GRG, ANOVA results are shown in Table 8. The significance of process parameters on multi-responses. From the ANOVA Table 7, it is revealed that fraction of MWCNTs, speed and applied load were significant process parameters affecting multi responses as its p-value is less than 0.05 at 95% confidence level.

Table7. The results of ANOVA (GRG)

Source	DF	Adj SS	Adj MS	F-Val	P-Val
MWCNTs, %	2	0.06388	0.031940	8.86	0.002
Speed, RPM	2	0.05865	0.029325	8.14	0.003
Load, N	2	0.008012	0.040060	11.11	0.001
Error	20	0.07209	0.003605		
Lack-of-Fit	2	0.02098	0.010492	3.70	0.045
Pure Error	18	0.05111	0.002839		
Total	26	0.27474			

4.Conclusion

The process parameters;applied load, sliding speed and volume percentage of MWCNTs wereoptimized via two different optimization

approaches; Taguchi and multi-response technique via GRA with ANOVA. The wear rate and coefficient of friction wereselected to be the control parameters during experimental work. Based on the results we can conclude:

1 Based on Taguchi analysis, the most influence parameter affects the coefficient of friction was the speed. While, the percentage of MWCNTs and speed were the significant factors on wear rate.
2 On the bases of gray relation analysis, the sequence of importance of process parameters were applied load >percentage of MWCNTs> speed. The optimul level for each parameter is, 24.1N, 1.5 vol.% and 900mm/min for applied load, percentage of MWCNTs and speed, respectively.

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