Investigations on wear behaviour of Al 6061-GNP metal matrix composites by using Taguchi L_{16} approach

R. Sivarama Krishnarao*

Department of Mechanical Engineering,
University College of Engineering,
JNTUK,
Kakinada 533003, India
Email: rsivaram.rao@gmail.com
*Corresponding author

V. Veeranna

Department of Mechanical Engineering,
St. Johns Engineering College,
Yemmiganur 518360, India
Email: Veeranna193@gmail.com

A. Gopala Krishna

Department of Mechanical Engineering,
University College of Engineering,
JNTUK,
Kakinada 533003, India
Email: Dr.a.gopalakrishna@gmail.com

Abstract: High strength Al 6061 metal matrix composites with graphene in different weight percentages were fabricated through stir-casting followed by equal channel angular pressing. Dry sliding wear tests were conducted as per Taguchi-based L_{16} orthogonal array with control factors such as: 1) reinforcement (wt. %); 2) load (N); 3) sliding speed (m/sec); 4) sliding distance (m). Wear rate and coefficient of friction (COF) was the response characteristics studied. Subsequently, analysis of variance (ANOVA) was applied to evaluate the significance of each control factor on the response characteristics. Reinforcement and load were identified as the highly influencing significant parameters on the wear rate and COF using ANOVA analysis. Furthermore, a confirmation test was also performed to verify the experimental results. Analysis of SEM of the worn surface reveals that abrasive and oxidation were the dominant wear mechanisms during the tribo-test of Al 6061-graphene composites.

Keywords: 6061 alloy; graphene; wear properties; analysis of variance; ANOVA; Taguchi design.

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Biographical notes: R. Sivarama Krishnarao is a research scholar of JNTU Kakinada and presently working in Mahindra & Mahindra Automotive R&D division in Chennai. He obtained his post-graduation from Bharath Institute of Higher Education and Research in Chennai. He has 15 years of experience in virtual validation using CAE Software's and testing of automotive components. His area of interest includes metal matrix composites, and optimisation techniques.

V. Veeranna is working as a Professor at the Department of Mechanical Engineering and Principal in St. Johns Engineering College, India. His areas of interest include metal matrix composites, optimisation techniques, and welding. He has published several research papers in national and international journals. He supervised several Master's thesis and five PhD scholars under various universities.

A. Gopala Krishna is working as a Professor at the Department of Mechanical Engineering, University College of Engineering, Jawaharlal Nehru Technological University Kakinada, Andhra Pradesh. His areas of interest include nanomaterials, sintering, machining, welding and forming. He has published nearly 100 papers in journals and conferences.

1 Introduction

Aluminium alloys possess high damping capacity and good wear resistance, hence become a favourable choice for marine, automotive and defence industries (Georgantzia et al., 2021; Miodownik, 2002). The aluminium-metal-matrix-composites (AMMCs) are one of the widely used composite in the automobile and aerospace industries to its high specific strength and good wear resistance (Bodunrin et al., 2015). Many researchers are improving the mechanical and wear properties of Al 6061 composite by reinforcing the hard ceramic particles such as SiC, Al_2O_3, Y_2O_3, B_4C and TiC (Das et al., 2014; Kumar et al., 2018).

Recently, the trend has moved towards using carbonous materials as the reinforcement phase in AMMCs (Huang et al., 2014). Graphene is an allotrope of carbon atom with a hexagonal lattice structure which possesses excellent mechanical properties and high wears resistance (Raj et al., 2020). Graphite (Gr) reinforcement in AMMCs creates a continuous layer of solid lubricant on the tribo-surface which controls the wear behaviour of the composite (Wang et al., 2012). The microstructure, electrical, mechanical and thermal properties of graphene reinforced AMMCs are studied by various authors (Khan et al., 2020; Pourmand and Asgharzadeh, 2020; Akçaml et al., 2016). Stir-casting method has become a versatile one for the fabrication of aluminium-graphene composites as compared to powder metallurgy due to its limitation in the formation of porosity and batch production (Singh et al., 2020). Research work on the tribological behaviour of aluminium metal matrix composites has been reported by several authors.

Baskaran et al. (2014) analysed the effect of reinforcement, load, velocity and distance on the wear rate of 7075-TiC composites by Taguchi method. It was reported that applied load has the highest influence on the wear rate. Pandiyan and Prabaharan (2020) investigated on AA6061-SiC composite under dry sliding wear conditions using Taguchi method and concluded that sliding distance was the dominant factor. Venkatesan and Xavior (2019) conducted wear studies on AA7050-graphene composites under tribo-test by Taguchi method. Authors concluded that load factor was a significant contributor on the wear rate when compared to sliding distance and sliding velocity.

Radhika and Subramaniam (2013) studied the wear behaviour of aluminium-alumina-GR composites using Taguchi method. The results revealed an applied load has the highest influence on wear rate and coefficient of friction (COF) followed by speed and reinforcement. Veličković et al. (2017) optimised the tribological properties of aluminium-SiC-GR composites using Taguchi design and concluded that the load has the greatest impact on specific wear rate followed by speed and reinforcement. Rahiman et al. (2020) analysed the sliding wear of Al5083-CNT-Ni-MoB using design of experiment (DOE) Taguchi method. Authors reported that the volume fraction of MoB was the most contributing parameter followed by sliding velocity and load.

On the basis of the literature survey, it was noticed that very limited knowledge-base on the influence of four control factors on the wear properties of aluminium composites. No work has been conveyed to study the influence of the weight fraction of graphene on the wear properties of aluminium composites. This research work is an attempt to analyse the influence of wt. % graphene, applied load, sliding velocity and sliding distance on the wear characteristics of Al 6061-graphene composites through Taguchi technique. Wear rate is tested under different levels of control factors on a pin-on-disc tribo-tester with Taguchi L_{16} orthogonal array (OA).

2 Experimental procedure

2.1 Materials and fabrication

The high purity Al 6061 ingot supplied from Matrix Metal and Alloys, India was chosen as the base matrix material. The graphene particles (< 10 μm, > 99.7%, platelet) supplied by Alfa Aesar, India were selected for the reinforcement material. In this investigation, graphene was varied from 0 wt. % to 0.75 wt. % for the fabrication of Al 6061-GNP composites using stir-casting and equal channel angular pressing (ECAP). Al 6061 ingots were melted inside of the crucible and the appropriate volume fractions of graphene platelets were mixed to fabricate the different composition of the composites. The Al 6061-GNP composites after stir-casting were subjected to ECAP using a 100° die for six passes.

2.2 Wear test

The dry sliding wear test was conducted on the Al 6061-graphene composites using a pin-on-disc tribometer (Ducom make). The test specimens are finished as per ASTM G-99 standard. The surface of test pin is polished with 400 grit abrasive and pressed against the rotating disc. The final weight of the test pin is measured at the end of each experiment using an electronic weighing machine having a sensitivity of 0.1 mg. The weight loss due to wear is the difference between initial and final weight of the pin. The volumetric loss due to wear is determined by considering the corresponding density values of the pin. The wear rate of the composite specimens in mm^3/m is the ratio of volumetric loss to sliding distance.

2.3 Taguchi experimental design

The number of experiments was attained as per Taguchi standard L_{16} OA. The weight fraction of reinforcement (R), normal load (N), sliding velocity (V) and sliding distance (D) was studied as the wear parameters and their levels are shown in Table 1. The repeatability of each experiment is confirmed by performing the test for three times. The test values are analysed with MINITAB-19 software using analysis of variance (ANOVA) for smaller is better criteria. The correlation between wear rate and corresponding significant parameters is validated experimentally with the specific combination of parameters. The wear track surface of various test pins was characterised by scanning electron microscopy (SEM).

Table 1 Control factors and levels

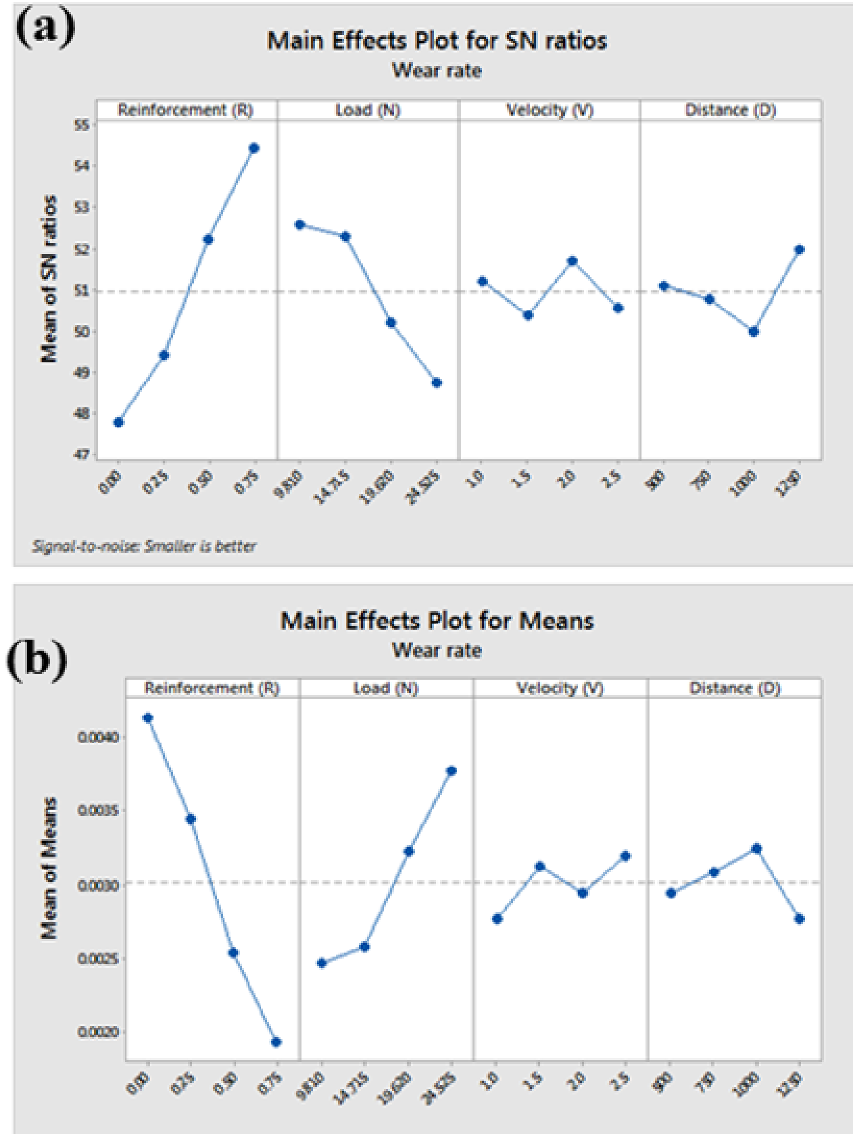
Control parameters	*Unit*	*Levels*			
		I	*II*	*III*	*IV*
Reinforcement (R), wt. %	--	0	0.25	0.5	0.75
Load (N), N	N	9.81	14.715	19.62	24.525
Sliding velocity (V), m/sec	m/sec	1	1.5	2	2.5
Sliding distance (D), m	m	500	750	1,000	1,250

3 Results and discussion

3.1 Statistical analysis on wear rate and COF

Table 2 represents the estimated wear characteristics such as wear rate and COF for the L_{16} OA to identify the high wear resistance composites from the wide range of process parameters. Signal to noise (S/N) ratio identified the wear rate and COF based on the 'smaller is better' option. The highest values of S/N ratio describe the optimum wear process factors (Navaneethakrishnan and Athijayamani, 2015). The average values of the response characteristics of the composite were measured from the 16 experiments. Figures 1(a) and 1(b) display the impact plots of various input factors on wear rate of Al 6061-graphene composites. The investigation of these main effects plots using S/N ratio provides the optimal parameter combination for minimum wear.

Figure 1 Main effect plot of control factors on wear rate (see online version for colours)



From Figure 1, it can be noted that graphene reinforcement (R) of 0.75 wt. %, load (N) of 9.81 N, sliding velocity (V) of 2 m/sec and sliding distance (D) of 1,250 m gave the optimal wear rate. The amount of wear decreases with the increase in the reinforcement (graphene) concentration and decrease in the applied load (Khatkar et al., 2020). The optimal combination of input factors for minimising the COF as shown in Figures 2(a) and 2(b) are R = 0.75, N = 9.81 N, V = 1.5 m/sec and D = 750 m. Tables 3 and 4 shows the ranking of different control factors using S/N ratio obtained at different range of values for the amount of wear and COF. From the response tables, it is to be noted that the graphene content is the influencing parameter on the amount of wear (Table 3) and applied load is the influence parameter on the COF (Table 4).

Table 2 DOE using L_{16} OA for wear rate and COF

Exp. no.	*Reinforcement (R)*	*Load (N)*	*Velocity (V)*	*Distance (D)*	*Wear rate (mm³/m)*	*S/N ratio*	*COF*	*S/N ratio*
1	0.00	9.810	1.0	500	0.00323	49.8159	0.360	8.8739
2	0.00	14.715	1.5	750	0.00394	48.0901	0.350	9.1186
3	0.00	19.620	2.0	1000	0.00441	47.1112	0.484	6.3031
4	0.00	24.525	2.5	1250	0.00496	46.0904	0.523	5.6300
5	0.25	9.810	1.5	1000	0.00325	49.7623	0.349	9.1435
6	0.25	14.715	1.0	1250	0.00254	51.9033	0.362	8.8258
7	0.25	19.620	2.5	500	0.00372	48.5891	0.421	7.5144
8	0.25	24.525	2.0	750	0.00427	47.3914	0.482	6.3391
9	0.50	9.810	2.0	1250	0.00163	55.7562	0.324	9.7891
10	0.50	14.715	2.5	750	0.00234	52.6157	0.314	10.0614
11	0.50	19.620	1.0	1000	0.00281	51.0259	0.369	8.6595
12	0.50	24.525	1.5	500	0.00336	49.4732	0.510	5.8486
13	0.75	9.810	2.5	750	0.00178	54.9916	0.302	10.3999
14	0.75	14.715	2.0	500	0.00149	56.5363	0.349	9.1435
15	0.75	19.620	1.5	1250	0.00196	54.1549	0.321	9.8699
16	0.75	24.525	1.0	1000	0.00251	52.0065	0.464	6.6696

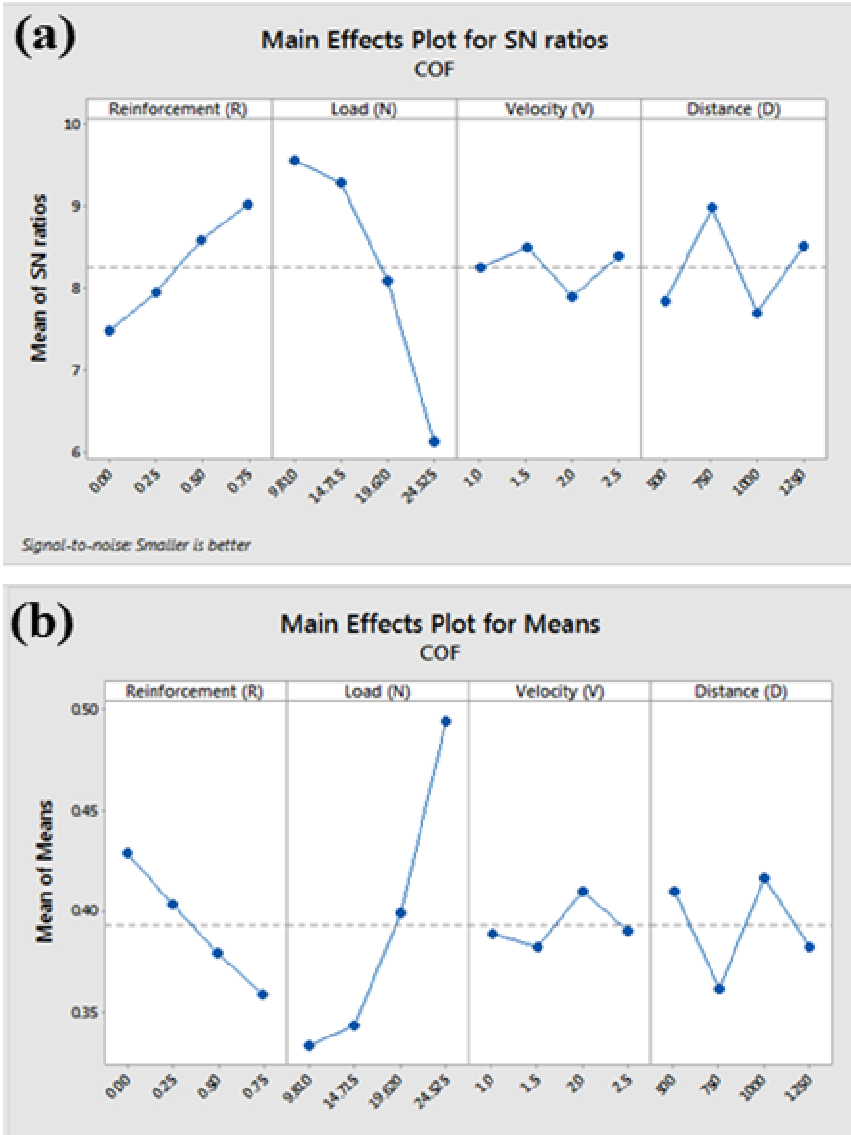
Table 3 Response table for S/N ratios-smaller is better (wear rate)

Level	*Reinforcement (R)*	*Load (N)*	*Velocity (V)*	*Distance (D)*
1	47.78	52.58	51.19	51.10
2	49.41	52.29	50.37	50.77
3	52.22	50.22	51.70	49.98
4	54.42	48.74	50.57	51.98
Delta	6.65	3.84	1.33	2.00
Rank	1	2	4	3

Table 4 Response table for S/N ratios-smaller is better (COF)

Level	*Reinforcement (R)*	*Load (N)*	*Velocity (V)*	*Distance (D)*
1	7.481	9.552	8.257	7.845
2	7.956	9.287	8.495	8.98
3	8.59	8.087	7.894	7.694
4	9.021	6.122	8.401	8.529
Delta	1.539	3.43	0.601	1.286
Rank	2	1	4	3

Figure 2 Main effect plot of control factors on COF (see online version for colours)



3.2 Analysis of variance

In order to investigate the dominant parameter over series input factors, ANOVA is conducted with 95% confidence level. ANOVA table is framed using the MINITAB-19 software and the results are listed in Tables 5 and 6. The results reveal that wt. % of graphene have the highest influence with a contribution of 67.20% on wear rate. Therefore, wt. % of graphene is an important input factor to be considered during wear test followed by a load of contribution as 25.39% and distance of contribution as 4.49%. Sliding velocity is the least contributing factor with 2.82%.

Table 5 ANOVA for wear rate

Source	*DF*	*Seq. SS*	*Contribution (%)*	*Adj. SS*	*Adj. MS*	*F-value*	*P-value*
Reinforcement	3	1.38376	67.20%	1.38376	0.461253	682.86	0.000
Load	3	0.52289	25.39%	0.48009	0.160031	236.92	0.000
Velocity	3	0.05813	2.82%	0.05641	0.018803	27.84	0.011
Distance	3	0.09248	4.49%	0.09248	0.030826	45.64	0.005
Error	3	0.00203	0.10%	0.00203	0.000675		
Total	15	2.05929	100.00%				

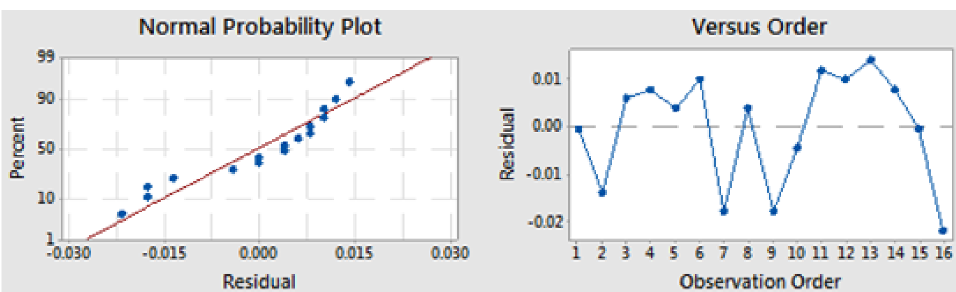
S = 0.0259899, R-sq. = 99.90%, R-sq.(adj.) = 99.51%

Table 6 ANOVA for COF

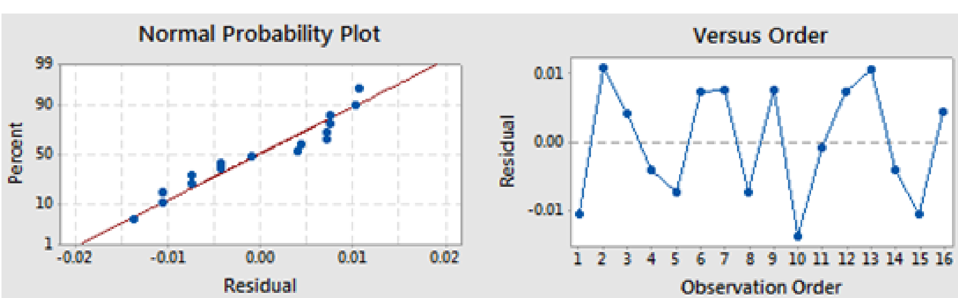
Source	*DF*	*Seq. SS*	*Contribution (%)*	*Adj. SS*	*Adj. MS*	*F-value*	*P-value*
Reinforcement	3	0.016712	20.66%	0.016712	0.005571	16.12	0.024
Load	3	0.049652	61.38%	0.044713	0.014904	43.12	0.006
Velocity	3	0.00475	5.87%	0.001574	0.000525	1.52	0.37
Distance	3	0.008743	10.81%	0.008743	0.002914	8.43	0.057
Error	3	0.001037	1.28%	0.001037	0.000346		
Total	15	0.080895	100.00%				

S = 0.0185915, R-sq. = 98.72%, R-sq.(adj.) = 93.59%

Figure 3 Residual plots for (a) wear rate and (b) COF (see online version for colours)

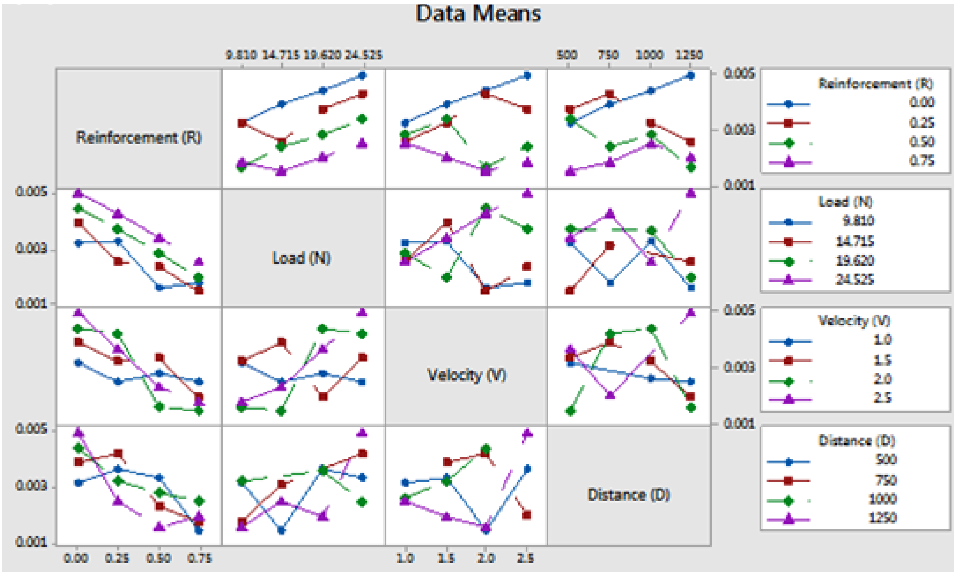


(a)

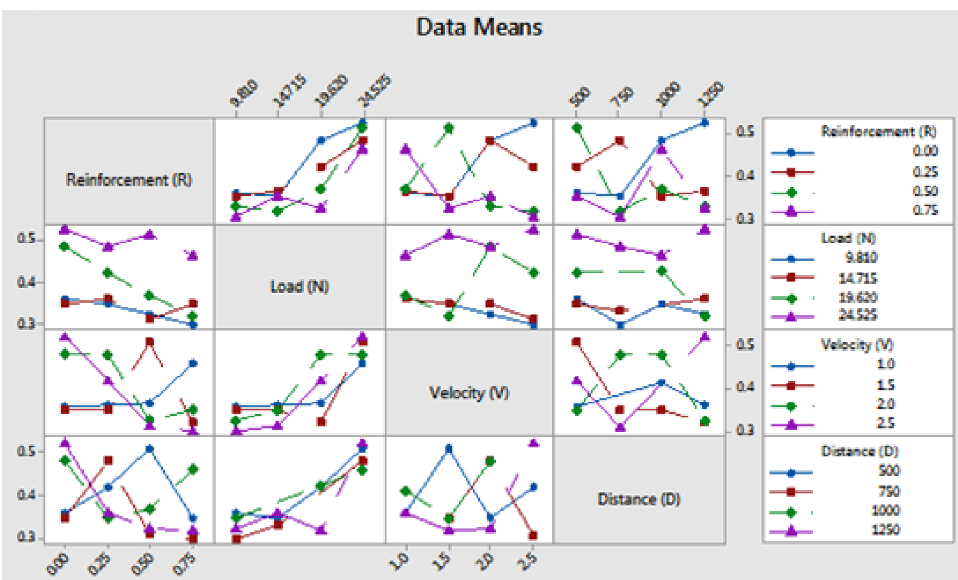


(b)

Figure 4 Interaction plot of control factors for (a) wear rate and (b) COF (see online version for colours)



(a)

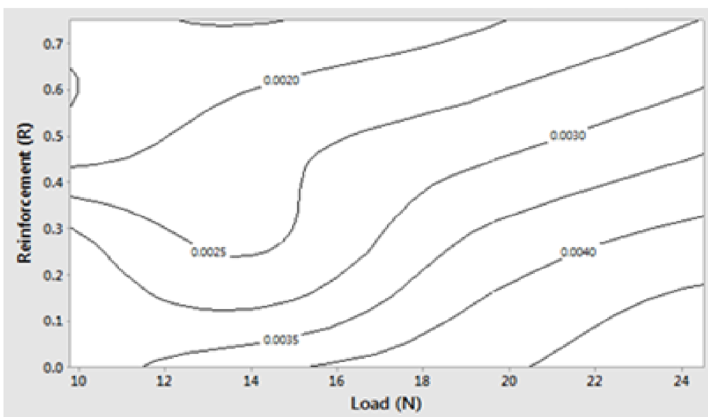


(b)

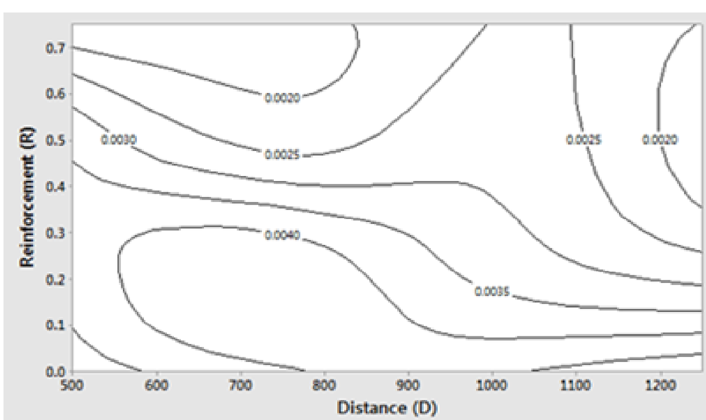
Similarly, the ANOVA table (Table 6) for COF confirmed that applied load has the highest influencing parameter with a contribution of 61.38%. Hence, applied load is an important input factor to minimise the COF followed by graphene reinforcement (contribution as 20.66%), distance (contribution as 10.81%) and velocity (contribution as 5.87%). The R-sq. and R-sq.(adj.) values for wear and COF are above 93% and are closer to each other. This represents that the formulated models are able to predict the response characteristics with high accuracy (Rajesh et al., 2014).

The residual plot for wear and COF is presented in Figure 3. The plotted points are noted to be normally distributed along the straight line. Figure 4 shows the interaction plot for influence of input factors on wear rate and COF. The volume fraction of graphene and load are the most significant factors on wear characteristics of Al 6061-GNP composites. Figures 5(a) and 5(b) show the contour plot, wherein the interaction between graphene reinforcement, load and distance on wear rate is specified. It was noted that the amount of wear reduces with the increase in graphene reinforcement and decrease in applied load. In Figures 5(c) and 5(d), the contour plot of COF for load, reinforcement and distance is given. It was found that the COF increases with increase in load and decrease in graphene reinforcement. From the contour plots, it was figured that the wear rate and COF is minimal at higher graphene content of 0.75% and lower applied load of 9.81 N.

Figure 5 Contour plot of wear rate and COF for control factors, (a) contour plot of wear rate vs. reinforcement (R), load (N) (b) contour plot of wear rate vs. reinforcement (R), distance (D) (c) contour plot of COF vs. load (N), reinforcement (R) (d) contour plot of COF vs. load (N), distance (D)

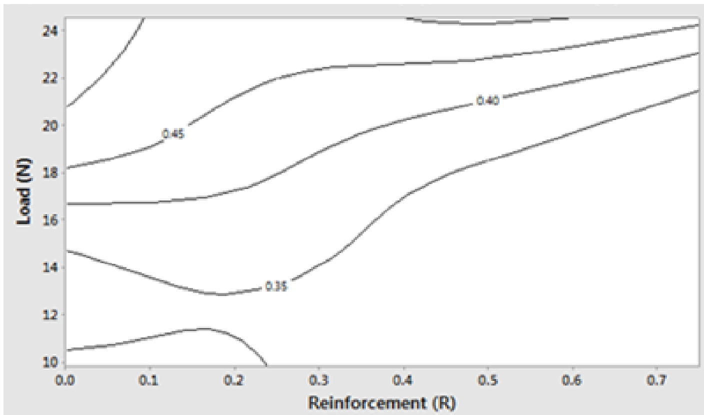


(a)

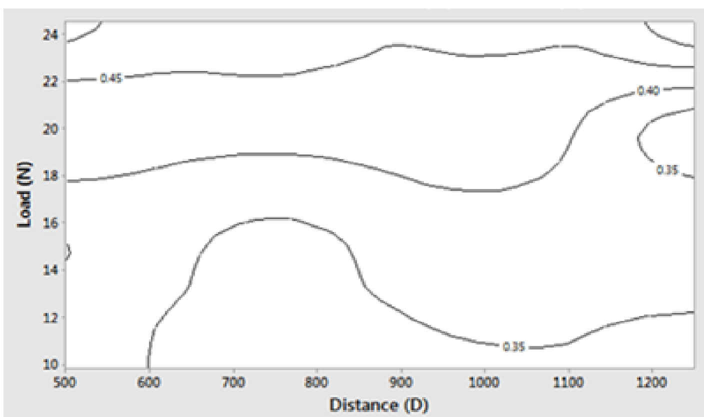


(b)

Figure 5 Contour plot of wear rate and COF for control factors, (a) contour plot of wear rate vs. reinforcement (R), load (N) (b) contour plot of wear rate vs. reinforcement (R), distance (D) (c) contour plot of COF vs. load (N), reinforcement (R) (d) contour plot of COF vs. load (N), distance (D) (continued)



(c)



(d)

3.3 *Multiple linear regression models*

Four independent factors with four levels considered in the present work were used to develop a multiple linear regression models. Regression equations are generated by the linear correlation between the four independent factors, i.e., graphene % (R), applied load (N), sliding speed (V) and sliding distance (D) with the wear rate and COF of fabricated Al 6061-GNP composite.

The regression equation for wear rate is elaborated as below:

$$\begin{aligned}\text{Wear rate} = 0.002329 - 0.003004 \text{ reinforcement (R)} + 0.000093 \text{ load (N)} \\ +0.000208 \text{ velocity (V)} - 0.000000 \text{ distance (D)}\end{aligned} \quad (1)$$

The regression equation for COF is elaborated as below:

$$\begin{aligned}\text{COF} = {} & 0.2115 - 0.0598 \text{ reinforcement (R)} + 0.01152 \text{ load (N)} \\ & +0.0014 \text{ velocity (V)} + 0.000012 \text{ distance (D)}\end{aligned} \tag{2}$$

From the above equations (1) and (2), it can be inferred that the negative sign of the coefficient of reinforcement exposes that increase in graphene reinforcement decreases the wear rate and COF. The influence of applied load (N) is directly proportional to wear rate and COF. Similar observations were reported by Girish and Anandakrishnan (2020) and Khare et al. (2019).

3.4 *Confirmation test*

A confirmatory experiment is performed to validate the statistical analysis of response characteristics using a specific combination of input factors and levels. Table 7 shows the combination of different set of input factors for conducting the wear test. The results of confirmation test for experimental and predicted values are listed in Table 8. The wear rate of experimental values is noted to be varying from wear rate of predicted values by error percentage between 3.82% and 11.84%. However, for COF, it is between 2.47% and 8.93%. The error associated with these response characteristics is less. Therefore, the developed regression model confirmed a feasible and effective way to predict the wear rate and COF of the Al 6061-graphene composites.

Table 7 Confirmation experiment

Test. no.	*Reinforcement (R)*	*Load (N)*	*Velocity (V)*	*Distance (D)*
1	0.25	19.62	2	1,000
3	0.5	24.525	2	1,250
4	0.75	19.620	1.5	1,000
5	0.75	24.525	2	750

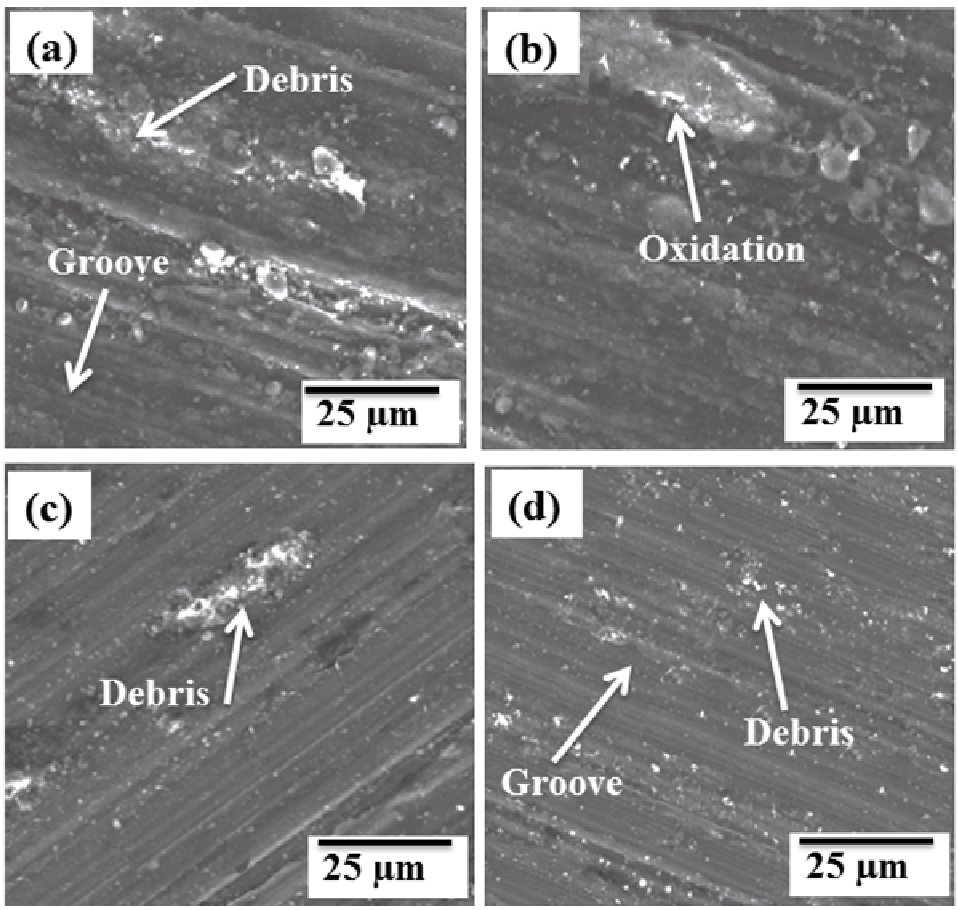
Table 8 Confirmation experiment results

Test. no.	*Wear rate (mm^3/m)*		*Error (%)*	*COF*		*Error (%)*
	Experimental	*Predicted*		*Experimental*	*Predicted*	
1	0.003898	0.0036315	6.84	0.486125	0.448791	7.68
3	0.002684	0.0025817	3.82	0.482379	0.439303	8.93
4	0.002696	0.0023768	11.84	0.370778	0.347567	6.26
5	0.002604	0.0023891	8.24	0.391727	0.382051	2.47

3.5 *Worn out surface analysis*

The worn out specimens of graphene reinforced Al 6061 composites are analysed under SEM to comprehend the wear mechanism at different conditions. The wear track of composites at 0% GNP and a load of 24.525 N [Figure 6(a)] reveal deep grooves with debris due to more material deterioration. The worn out surface of the graphene reinforcement at different volume fractions shows [Figures 6(b)–6(d)] the existence of fine grooves and scratches with oxidative area. This indicates the involvement of abrasive and oxidation wear mechanism. These findings are similar with the observations reported by several authors (Bartolucci et al., 2011; Chen et al., 2018; Pradhan et al., 2020). The increase in graphene reinforcement led to increase in wear resistance due to strong interfacial bonding strength between the reinforcement and matrix element (Boostani et al., 2015).

Figure 6 Worn surface at, (a) 0% GNP and 24.525 N load (b) 0.25% GNP and 19.62 N load (c) 0.5% GNP and 9.81 N load (d) 0.75% GNP and 14.715 N load



4 Conclusions

The tribological behaviour of Al 6061-graphene metal matrix composites was analysed by Taguchi statistical approach. Experiments were conducted successfully with four control factors as per L_{16} OA to analyse the wear rate and COF of the Al 6061 composite. The following conclusions were emerging from the above study:

1 The S/N ratio obtained for different levels of control factors from response table specifies that graphene reinforcement and load as the major contributors during the wear process.

2 The optimal combination of control parameters by S/N ratio analysis for minimum wear rate was 0.75 wt. %. graphene, 9.81 N applied load, 2 m/s sliding speed and 1,250 m sliding distance. Also, the optimal control parameters for minimising the COF were 0.75 wt. %. graphene, 9.81 N applied load, 1.5 m/s sliding speed and 750 m sliding distance.

3 ANOVA table demonstrated that graphene reinforcement (67.2%) has the highest influence on the wear rate followed by load, distance and velocity. On the other hand, applied load (61.38%) has the highest influence on the COF followed by graphene reinforcement, distance and velocity.

4 The regression model constructed based on experimental observations fits in evaluating the wear characteristics of the fabricated composite. The dominant wear mechanisms during wear test of Al 6061-graphene metal matrix composites by SEM analysis was abrasive and oxidation wear.

The wear rate and COF of Al 6061-graphene composite increases with increasing load and decreases with the increasing weight fraction of reinforcement. The incorporation of 0.75 wt. % graphene as a reinforcement phase in the Al 6061 matrix improves the tribological characteristics.

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