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Optimization of wear behaviour of hybrid Al(6061)-Al_2O_3-B_4C composites through hybrid optimization method

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Abstract. Al-based hybrid metal matrix composites were prepared through stir casting method by reinforcing aluminium oxide or alumina (Al_2O_3) and boron carbide (B_4C) particles into Al matrix with their varying proportions. The wear analysis of prepared hybrid MMCs was performed using the Pin-on-disc method and wear parameters were also optimized with objectives of minimizing the weight loss (WL) and coefficient of friction (COF) through integrated Grey-Taguchi techniques. Morphological analysis was also performed to explain the wear mechanism through a Scanning electron microscope (SEM). The maximum improvement in the weight loss of 71.33 % and in coefficients of friction of 35.35 % was found for the hybrid composites as compared to that of Al-alloy matrix. Further, the ANOVA results suggested that compositions has the maximum contribution of 94.47 %, sliding speed has 1.06 %, sliding distance has 1.04 %, and load has 3.16 % on the wear performance of the present hybrid composites.
Keywords: metal matrix composites; hybrid composites; aluminium; wear analysis; optimization; scanning electron microscope

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Introduction

In recent decades, the demand for metal matrix composites (MMCs) has been increasingly increased in different sectors of automobile, aerospace, sporting goods, and other industries on account of their excellent properties of specific stiffness and strength, desirable coefficient of thermal expansion, and superior wear and corrosion resistance [1]. Among the available MMCs, Al is more preferred matrix material because of its low density, ease of fabrication ability and good engineering properties [2]. Aluminium-based MMCs have been utilized as newer materials in the field of high-performance tribological applications because of their improved mechanical properties, good wear resistance, higher thermal conductivity, and low coefficient of thermal expansion [3]. The aluminium based MMCs have been found to be utilized in the following parts: brake drums, pistons, connecting rods, drive shafts, cylinder liners, cylinder blocks, gears, valves, and suspension components etc. [4]. These composites can be fabricated by the following methods such as powder metallurgy, stir casting techniques, chemical vapour deposition, physical vapour deposition, and spray deposition. In

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stir casting, the particles are mechanically well distributed with the help of a stirrer in the liquid – particles mixture before the solidification [5].

Wear is one of the important material interface phenomenons that occur at an interface MMCs with hard particle reinforcement that offers superior wear resistance [6,7]. Zhang et al. [8] reported that wear resistance of MMCs varies linearly with an increase in concentrations of reinforcement. Yu et al. [9] worked on Al6061-SiC composites and found that wear rate decreased with increasing applied load. A. Martin et al. [10] suggested that a characteristics physical mechanism involved in the wear process for 6061- Al_2O_3 composites. Kumar et al. [11] prepared Al6063-10 % Si_3N_4 MMCs by the stir casting and found that the MMCs had a higher wear resistance in comparison to the base alloy. A similar type of observations was reported by Anand et al. [12] for the composite (Al6061-5SiC-4.5Porcelain). Zheng et al. [13] worked on TiB +TiC/ Ti6Al4V composites and suggested that if the reinforcement content of composites is increased the main wear mechanism is changed. Cygan et al. [14] observed a considerable change in wear rate of the composites due to changes in applied loads. A similar observation was also reported by Xiao et al. [15].

Abbas et al. [16] worked on CNTs/AZ31 composites fabricated by the stir casting process and found that the wear rate decreased substantially with rising CNT weight fraction as in both cast and aged materials because of their interfacial peeling effect of a magnesium alloy of AZ31. Ambigai and Prabhu [17] investigated the tribological behaviour of Al−Gr−Si_3N_4 hybrid composite under dry sliding conditions and they concluded that the sliding distance was significant parameters followed by the applied load. In another research work, it was suggested that the sliding velocity was found to be the most significant parameter followed by the reinforcement percentage, sliding distance, and contact stress [18]. Muthu [19] worked on LM25-SiC-Cu hybrid MMCs and observed that the sliding velocity was more dominating parameter than the load and sliding distance. It was also reported that wear rate could be significantly affected by types and concentrations of reinforcements [20,21].

From the above discussion, it is clear that a good number of works are reported on wear analysis of MMCs, and wear resistance was found to be significantly affected by concentrations and types of reinforcements, wear parameters, temperatures and fabrication process of composites. It was also observed that hybrid MMCs exhibited better wear resistance than single reinforced MMCs. However, study on the effect of variations in proportions of reinforcements on wear resistance of hybrid MMCs is not attempted so far. Therefore, wear analysis and optimization of process parameters using hybrid GRA-Taguchi method for hybrid Al-based MMCs reinforced B_4C and Al_2O_3 particles are presented in this work.

Experimental details

Materials. For the development of Al alloy (6061) based hybrid MMCs, two types of reinforcement were as such: Al_2O_3 (purity 99 % and 100-325 mesh size) and B_4C (purity 99 % and 400 mesh size). All the consumable materials were purchased from UMA Scientific traders, Prayagraj, India.

Fabrication of composites. The present hybrid MMCs containing a constant wt.% of reinforcement of 6 with varying proportions of Al_2O_3 and B_4C particles were prepared by two stages of stir casting process. The small pieces of Al alloy were placed into a graphite crucible for melting inside an electric coil furnace heated to 750 °C. Then, Al_2O_3 and B_4C particles along with empty crucible were preheated to 400 °C. Thereafter, preheated powders were mixed into molten Al alloy using a stirrer (600 rpm) in two consecutive steps of 3 wt. % each for half of 10 min. For the duration of the mixing process, there was a temperature crash of around 15–20 °C. Eventually, the mixture of reinforcements and molten Al alloy was poured into the cast iron finger die in order to prepare the specimens for wear analysis. Nomenclature given for prepared hybrid composites is provided in Table 1. Figure 1 represents the casted samples.

Fig. 1. Casted samples

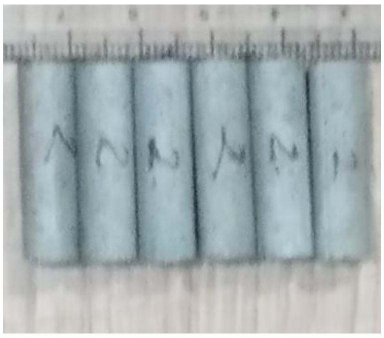
Table 1 Nomenclature used for hybrid metal matrix composites

Composites	Types of composites	Boron carbide, %	Alumina, %	Total reinforcement, wt. %
B0A0	Cast Al alloy (6061)	0	0	0
B100A0	Single B4C reinforced	100	0	6
B75A25	Hybrid	75	25	6
B50A50	Hybrid	50	50	6
B25A75	Hybrid	25	75	6
B0A100	Single Al_2O_3 reinforced	0	100	6

Wear test. The pin on disc test was employed for the analysis of dry sliding wear behaviour of prepared hybrid Al (6061)-Al_2O_3-B_4C composites in order to determine the weight loss and coefficient of friction (COF). The specification of wear test set up is given in the Table 2. Tests were conducted using $L18$ orthogonal array under dry sliding condition as per ASTM G99-95 at a temperature of 28 °C. The samples for wear test shown in the Fig. 2.

Table 2. The specifications of wear test setup for hybrid metal matrix composites

Specifications	Values
Specimen, Pin, mm	Dia-3, 4, 6, 8, 10, 12 and length- 25 to 32
Sliding speed, m/s	0.5 to 10
Normal load, N	Min–5 and Max-200
Wear disc material	EN-31 Hardened,60 HRC



(a) (b)

Fig. 2. Samples for wear test: (a) aluminium alloy and (b) hybrid composite

Table 3. The input factors for a wear test of hybrid metal matrix composites

Input parameters	Level					
	1	2	3	4	5	6
Sample code	M1 (A0B0)	M2 (B100A0)	M3 (A100B0)	M4 (B25A75)	M5 (B75A25)	M6 (B50A50)
Rotation, rpm	150	200	250	-	-	-
Sliding distance, m	1500	2000	2500	-	-	-
Load, N	15	25	35	-	-	-

Table 4. Experimental results of wear rate and coefficient of friction for hybrid metal matrix composites

S. No	Samples code	Rotation, rpm	Sliding distance, m	Load, N	Weight Loss, g	Wear rate, mg/m	COF
1	1	1	1	1	0.1756	0.117	0.595
2	1	2	2	2	0.2141	0.107	0.586
3	1	3	3	3	0.2333	0.093	0.584
4	2	1	1	2	0.0612	0.041	0.399
5	2	2	2	3	0.0772	0.039	0.396
6	2	3	3	1	0.0403	0.016	0.4
7	3	1	2	1	0.1215	0.061	0.521
8	3	2	3	2	0.1231	0.049	0.509
9	3	3	1	3	0.1323	0.088	0.506
10	4	1	3	3	0.1627	0.065	0.406
11	4	2	1	1	0.1296	0.086	0.44
12	4	3	2	2	0.1473	0.074	0.415
13	5	1	2	3	0.1054	0.053	0.372
14	5	2	3	1	0.0559	0.022	0.392
15	5	3	1	2	0.0782	0.052	0.377
16	6	1	3	2	0.0416	0.017	0.343
17	6	2	1	3	0.0749	0.05	0.337
18	6	3	2	1	0.0311	0.015	0.348

Initially, the test specimens are polished metallographically to make sample in the form of flat. The preliminary weight of specimen was measured by an electronic balance (Shimadzu Corporation, D307032807) with a precision of 0.0001 g. After the test, the specimens were removed, cleaned with acetone, dried and again specimen was weighted to find its final weight. The W_L was calculated by using the equation (1).

Weight loss = Initial weight of sample – Final weight of sample. (1)

The COF was calculated by getting a ratio of frictional force (F) and normal force (F_N) of equation (2):

$$\mu = \frac{F}{F_N}\ . \qquad (2)$$

The experiments are conducted on the prepared composites with various input parameters sample's composition, rotation (rpm), sliding distance (m) and load (N) with an objective to minimize W_L and COF. The following input parameters were used for wear test as shown in Table 3. The experiments were designed by Taguchi method and L_{18} array are used for conducting the experiments. The experimental results are shown in Table 4.

Grey Relational Analysis (GRA). It is a multi response optimization process to find the optimum combination of process parameters and the influence of each input parameters on the responses. The outputs/responses such as WL and COF are minimized so that the following the criteria "smaller the better characteristics", for signal to noise ratio can be found by the given equation (3):

$$\frac{S}{N} = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_{ij}\right] \qquad (3)$$

where n = no of observations, y_{ij} = observed response/outputs, I = 1,2,3, …, n, and j = 1, 2, 3, …, k, performance characteristics/ outputs responses.

It is required to normalize the output responses prior to analyzing them with the grey relation theory. The normalization for every experimental result is performed by using equation (4):

$$Z_{ij} = \frac{\max(y_{ij}, i = 1,2,3,\dots,n) - y_{ij}}{\max(y_{ij}, i = 1,2,3,\dots,n) - \min(y_{ij}, i = 1,2,3,\dots,n)}\ , \qquad (4)$$

where y_{ij} is the j^{th} performance characteristics and min y_{ij} and max y_{ij} values of j^{th} performance characteristics for the i^{th} experiments respectively.

The grey relational coefficients for the individual output can be found from the normalised values by using equation (5) and coefficient constant is assumed to be $\xi = 0.5$:

$$(y_0(k), y_i(k)) = \frac{\Delta\min + \xi\Delta\max}{\Delta_{0j}(k) + \xi\Delta\max}\ , \qquad (5)$$

where

a) i = 1, 2, 3,. ..., n, k = 1, 2, ..., m, n is the number of experimental data items and m is the number of responses;

b) $y_0(k)$ is the reference sequence ($y_0(k)$ = 1, k = 1, 2, ..., m), $y_j(k)$ is the specific comparison sequence;

c) $\Delta_{0j} = \| y_0(k) - y_j(k) \|$, the absolute value of the difference between $y_0(k)$ and $y_j(k)$.

d) $\Delta_{\min} = \| y_0(k) - y_j(k) \|$, the smallest value of $y_j(k)$.

e) $\Delta_{\max} = \| y_0(k) - y_j(k) \|$, the largest value of $y_j(k)$.

f) ξ is the coefficient constant, which is defined in the range $0 \le \xi \le 1$.

The grey relational grade (GRG) for combined multi-objective can be obtained from grey relational coefficient of the responses. The grade which decides the rank or performance characteristics was obtained by using the equation (6).

$$\delta_j = \frac{1}{k}\sum_{i=1}^{m} y_{ij}\ , \qquad (6)$$

where δ_j is the values of GRG for the j^{th} experiment and k is the number of performance characteristics.

Results and Discussion

Multi-objective-GRA. The experimental results are normalised using equation (4) and the normalised results are converted into grey relational coefficient to represents the correlation between desired and actual data. At last, the grey relational grades are calculated by the equation (6). The S-N ratio and its normalised values for W_L and COF are tabulated in the Table 5.

Table 5. The signal to noise ratio and the normalized value of weight loss and coefficient of friction for hybrid metal matrix composites

S. No	S/N ratio (Wl)	S/N ratio (COF)	Normalised value (W_L)	Normalised value (COF)
1	15.1095	4.50966	0.285361	0
2	13.3877	4.64205	0.094955	0.034884
3	12.6417	4.67174	0	0.042636
4	24.2650	7.98054	0.851137	0.75969
5	22.2477	8.04610	0.772008	0.771318
6	27.8939	7.95880	0.9545	0.755814
7	18.3085	5.66325	0.552918	0.286822
8	18.1948	5.86564	0.545005	0.333333
9	17.5688	5.91699	0.499505	0.344961
10	15.7722	7.82948	0.349159	0.732558
11	17.7479	7.13095	0.512859	0.600775
12	16.6359	7.63904	0.425321	0.697674
13	19.5432	8.58914	0.632542	0.864341
14	25.0518	8.13428	0.877349	0.786822
15	22.1359	8.47317	0.767062	0.844961
16	27.6181	9.29412	0.948071	0.976744
17	22.5104	9.44740	0.783383	1
18	30.1448	9.16842	1	0.957364

Table 6. The grey relational coefficient and grey relational grade value for hybrid metal matrix composites

S.No	Deviation sequence (W_L)	Deviation sequence (COF)	GRC (W_L)	GRC (COF)	GRG	RANKS
1	0.714639	1	0.411645	0.333333	0.372489	16
2	0.905045	0.965116	0.355861	0.34127	0.348565	17
3	1	0.957364	0.333333	0.343085	0.338209	18
4	0.148863	0.24031	0.770579	0.675393	0.722986	6
5	0.227992	0.228682	0.686821	0.68617	0.686495	8
6	0.0455	0.244186	0.916591	0.671875	0.794233	4
7	0.447082	0.713178	0.527937	0.412141	0.470039	14
8	0.454995	0.666667	0.523563	0.428571	0.476067	13
9	0.500495	0.655039	0.499753	0.432886	0.466319	15
10	0.650841	0.267442	0.434465	0.651515	0.54299	11
11	0.487141	0.399225	0.506513	0.556034	0.531274	12
12	0.574679	0.302326	0.465255	0.623188	0.544222	10
13	0.367458	0.135659	0.576397	0.786585	0.681491	9
14	0.122651	0.213178	0.803018	0.701087	0.752053	5
15	0.232938	0.155039	0.682186	0.763314	0.72275	7
16	0.051929	0.023256	0.905914	0.955556	0.930735	2
17	0.216617	0	0.697723	1	0.848861	3
18	0	0.042636	1	0.921429	0.960714	1

In the next section, the grey relational coefficient is calculated by equation (5) to present association between the ideal (best) and specific normalised experimental results. Finally the grey relational grades are calculated by equation (6) to represent the level of correlation between the reference sequence and the comparability sequence. The higher value of GRG indicates that the comparability sequence has a stronger correlation to reference sequence. In other words, the higher the value of GRG corresponds to better performance. Here, the reference sequence was selected as "smaller the better" characteristics and the comparability sequence with larger value of GRG gives smaller W_L and COF. The GRC, GRG values and their ranks are shown in the Table 6.

Taguchi Method. It is an integrated approach to discover the best range of designs for quality, computational cost and performance. The traditional experimental design procedure focuses on the average process performance characteristics but this method concentrated on the effect of variation of the process quality characteristics rather than on its averages. It used a statistical measure of performance called signal to noise ratio (S/N) which is logarithmic function of outputs/ responses. The S-N ratio considers both mean and variability and is defined as the ratio of the mean (signal) to the standard deviation (noise). The ratio (S/N) depends on the quality characteristic of the product/ process to be optimized. Here, the Taguchi optimization technique is employed on the basis of GRG values. The outcome of this optimization is presented in the Table 7. Generally, a higher GRG value offers better output/ response. The multi-objective (minimum weight loss and coefficient of friction) optimum condition could be found from the response table: sample code of level 6, rotation of level 3, sliding distance of level 3 and load of level 1.

Table 7. Response Table of wear test for hybrid metal matrix composites (Means)

Level	Samples code	Rotation, RPM	Sliding distance, m	Load, N
1	0.3531	0.6201	0.6108	0.6468
2	0.7346	0.6072	0.6153	0.6242
3	0.4708	0.6377	0.6390	0.5941
4	0.5395			
5	0.7188			
6	0.9134			
Delta	0.5603	0.0305	0.0283	0.0527
Rank	1	3	4	2

Analysis of Variance (ANOVA). ANOVA is performed using a Minitab version 17 to find which parameters significantly affect the quality/ multi-objective/responses. The mean data of overall grey relational grade is used to analyse the effect of sample code, rotational speed sliding distance and load on the total variance of the results. The result of the ANOVA is tabulated in the Table 8. The ANOVA table shows the percentage contribution of each and every parameter. The percentage contributions of parameters were found 94.47 % for sample code, 1.06 % for rotation, 1.04 %, for sliding distance, and 3.16 %, for the load. The main effect plot for grey relational grade values for means are given in the Fig. 3. The optimal combination of factors and their levels is abbreviated as SC6R3SD3L1 based on the mean effect plot. Sahoo and Pal [22] performed similar work on the tribological performance on the electroless Ni-P coatings and found that the three test parameters, load, speed and time have a significant influence on the friction and wear behaviour at the confidence level of 95 % within the specific test range. Paranthaman et al. found that the applied load is significant parameter and wt % of reinforcement and sliding distance are insignificant for studying tribological behaviour Al metal matrix composites [23].

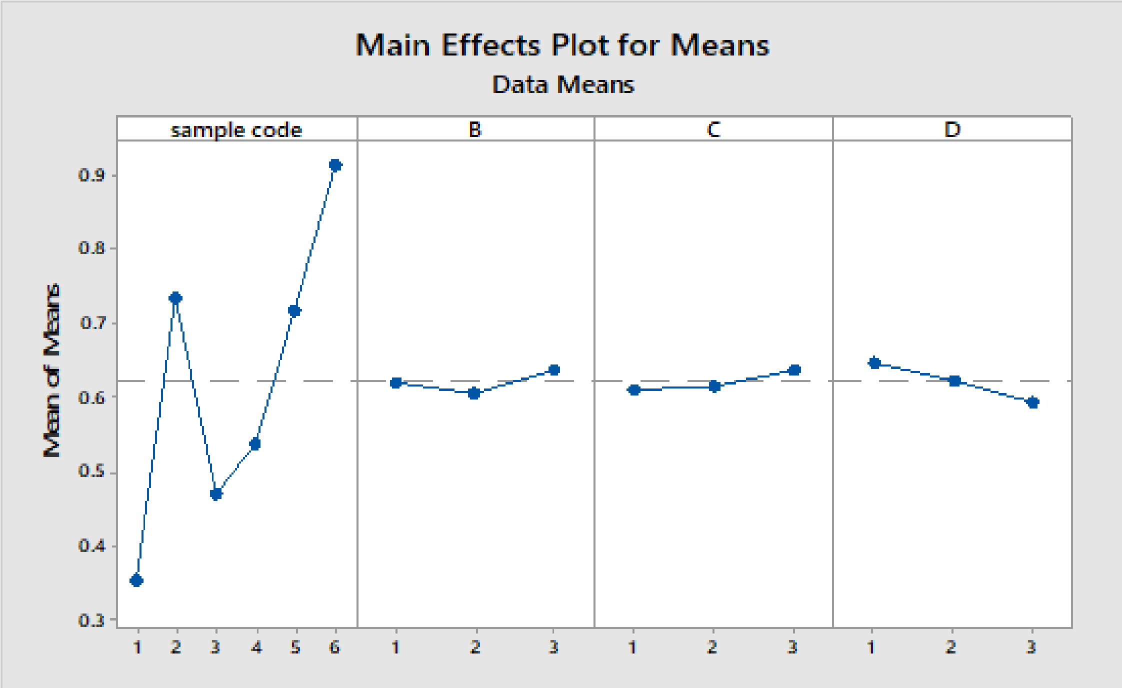


Fig. 3. Main effect plot for means- wear rate of hybrid metal matrix composites (higher is better)

Table 8. ANOVA results for hybrid metal matrix composites

Source	Degree of freedom	Sum of square	Mean square	Percentage Contribution	P Value
Sample code	5	0.626851	0.125370	94.47	0.0
Rotation (RPM)	2	0.002817	0.001409	1.06	0.968
Sliding distance, m	2	0.002770	0.001385	1.04	0.968
Load, N	2	0.008402	0.004201	3.16	0.906
Residual Error	6	0.002002	0.000334	0.25	
Total	17			100	

Confirmation Tests. After the optimum level of wear behaviour parameters is identified, a confirmation test was performed for checking the accuracy of the analysis. The predicted grey relational grade γ_{pre} value may be found by the following equation:

$$\gamma_{\text{Pre}} = \gamma_m + \sum_{i=1}^{n} (\bar{\gamma} - \gamma_m) \quad , \tag{7}$$

where, γ_m is the total mean of the grey relational grade, $\bar{\gamma}$ is the mean of grey relational grade values at the optimum level and n is the number of main parameters that significantly affect the overall quality characteristics.

Table 9 shows the comparison between predicted value of grey relational grade and experimental value of grey relational grade obtained by combination of optimal parameters. The confirmation test was performed and it was found that the experimental GRG value for response characteristics increased by 0.063656. The W_L and COF were decreased by 0.0061 g and 0.021 respectively from the initial to optimal parameters. Hence, the integrated Grey Taguchi approach improved the multiple performance characteristics in terms of W_L and COF by 8.05 % and 6.18 %, respectively.

Table 9. Results of the confirmation test for hybrid metal matrix composites

Sources	Initial testing parameters	Optimum testing parameters	
		Prediction	Experimental
Combination of testing parameters	SC6R2SD1L3	SC6R3SD3L1	SC6R3SD3L1
Weight loss	0.0749		0.0688
COF	0.337		0.316
GRG	0.84886	0.970814	0.912516

Parametric effect on the outputs/ responses (weight loss and coefficient of friction). Figure 4 represents the weight loss at different wear parameters, whereas variations of coefficient of friction and wear rate with load at different rotations and sliding distances for hybrid composites in presented in Figs. 5 and 6 respectively. It can be observed that the Al-alloy A0B0 has the highest weight loss in comparison to all the hybrid composites samples of B100A0, A100B0, A75B25, B75A25 and B50A50 for all the variable wear parameters. The phenomenon is happened due to lower asperities to asperities contact between two counter surfaces or particles of reinforcements (i.e. Al_2O_3 & B_4C) are harder, and unreinforced al alloy (6061) is softer than the reinforced composites which causes heavy plastic deformation on the surface also. Bardeswaran et al. [24] found that COF decreases on increases the B_4C particles content and wear resistance of the composites increased on increasing the contents of B_4C particles in the matrix materials.

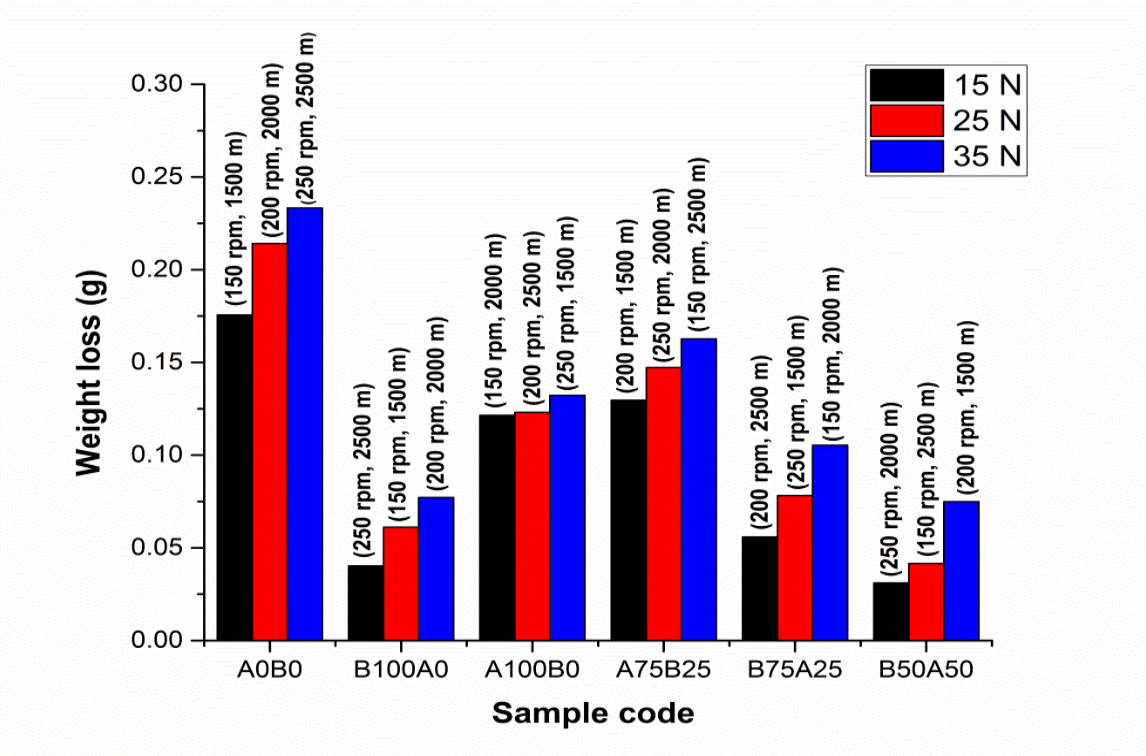


Fig. 4. Variations of weight loss with load at different rotation and sliding distance for hybrid composites

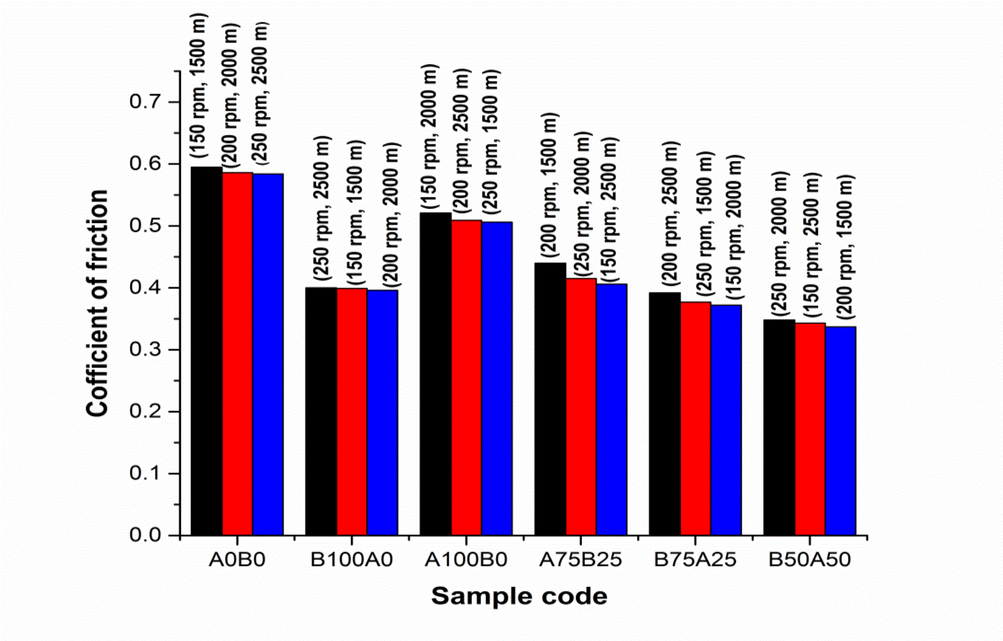


Fig. 5. Variations of coefficient of friction with load at different rotation and sliding distance for hybrid composites

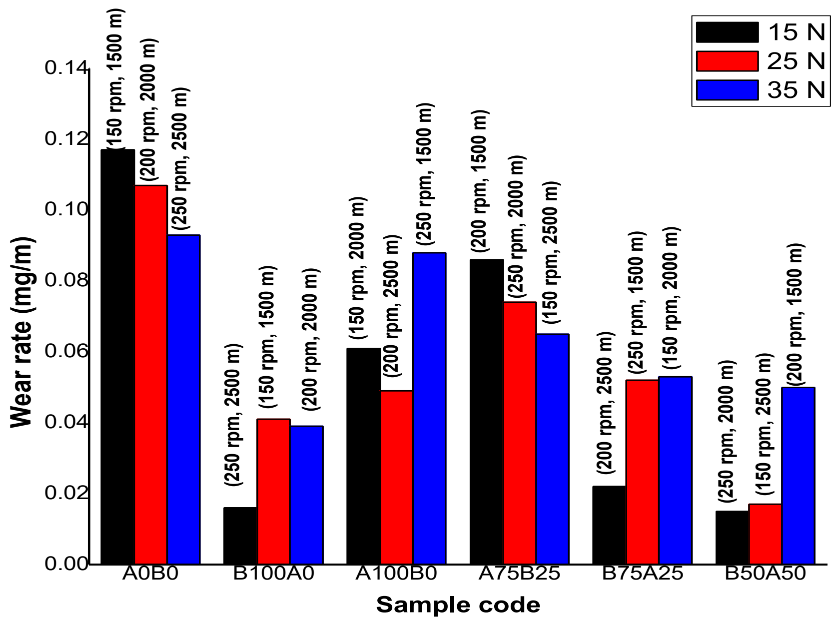


Fig. 6. Variations of wear rate with load at different rotation and sliding distance for hybrid composites

The weight losses were found to be increased with increase in loads for all the composites due to increased plastic deformation of asperities to asperities contact between the contacting surfaces at wear parameters. Also the similar trend was followed by weight loss with rotation of disc or sliding distance for all the composites at different wear parameters. For B50A50 sample, the weight loss was the lowest among all the composites due to contribution of hard ceramic particles as reinforcements and its better interfacial bonding between the matrix of al alloy 6061 with dispersed particles of alumina and boron carbide.

For the samples A0B0 and A100B0, the weight loss was increased with increasing rotation of disc or sliding distance due to softening of materials. The composites B100A0 and B50A50 showed lower weight loss at higher rotation of disc or sliding distance due to formation of tribo-layer between the sample and counter surface body. Also, for the composites A75B25 and B75A25, the weight loss was higher at lower speed than the other speed due to delimitation of particles taking place for all particular wear parameters. On comparing with Al alloy A0B0, all the composites offer a higher coefficient of friction at all the conditions. This happened due to addition of dispersed particles of alumina and boron carbide in the matrix material. For all the composites including alloy, initially the coefficient of friction was high because of sharp asperities on the counter face that deformed the material then decreased with increasing load (15N-35N) due to deformation of asperities, which also causes work hardening of matrix material.

The wear rate of Al alloy A0B0 is highest in comparison to all the composites B100A0, A100B0, A75B25, B75A25 and B50A50 due to softer nature of matrix materials of Al alloy or higher asperities to asperities contact between counter surfaces or presence of harder Al_2O_3 and B_4C powder particles in the composites for all wear parameters.

For Al alloy A0B0 (at all the wear conditions), B100A0 (200 rpm, 2500 m) and A100B0 (200 rpm, 2500 m), there is formation of oxides which spreads and form a layer on the pin surfaces. Once, the oxide later are formed there were spalling, distortion and fractures of that layer may be happened between mating surfaces during sliding but all the oxides are not dislodge from the mating surfaces. Hence, it may prevent metal to metal or particles to metal contacts leads to reduction in wear rate.

For A75B25 composites, the wear rate is decreased with increasing load from 15-35 N because of better interfacial bonding between reinforcing and matrix materials for all wear conditions. The wear rate of composites B75A25 and B50A50 are increased with increasing applied load from 15 to 35 N due to increasing temperature leads to no longer formation of mechanically mixed layer. A larger load produces large uncertainties in the formation of mechanically mixed layer. Similar trends followed by the composites B100A0 and A100B0.

Morphological study of wear surfaces. Figure 7 shows the micrographs of worn surfaces for hybrid metal matrix composites at different loads: A0B0 at 15 N, A50B50 at 35 N, B100A0 at 25 N, and A100B0 at 25 N. It was seen that longitudinal grooves and some pits are present in each of the specimens. The grooves refer to the occurrence of plastic deformation. The fine scratches were visible along with the sliding direction for hybrid composites A50B50, B100A0, and A100B0. However, the grooves and scratches have been reduced to a relatively finer form for hybrid composite A50B50. The presence of grooves indicates the micro-cutting and micro-ploughing effect. It is the indication of abrasive wear. From the SEM images, the pits and heavy flow of material along the sliding direction could also be observed, so there is adhesive wear. Severe abrasive wear along with adhesive wear was observed for the hybrid composites. The present result was found in line with the reported result by Zhu et al. [25].

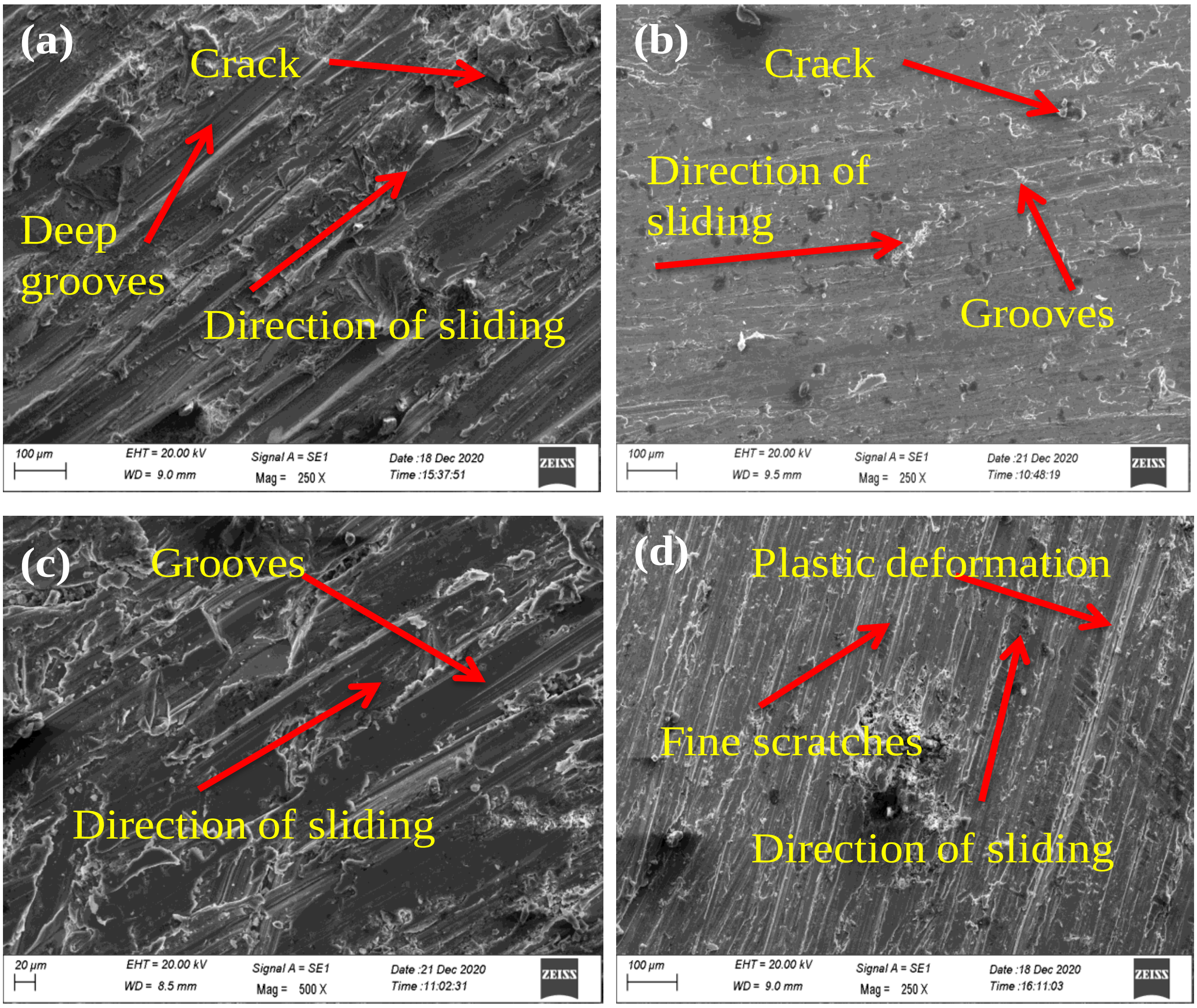


Fig. 7. Micrographs of worn surfaces for hybrid metal matrix composites: (a) A0B0 at 15 N, (b) B100A0, (c) B0A100 at 25 N, and (d) B50A50 at 35 N for different rotation of the disc and sliding distance

The degree of the grooves formed for a specimen (A0B0) at a load of 15 N was higher than the specimens A50B50 at a load of 35 N, B100A0 and A100B0 at a load of 25 N. The grooves formed in composites were reduced with the addition of hard alumina and boron carbide particles, indicating lower material loss for hybrid composite. At the beginning of the wear test, the material may be subjected to abrasive wear. Later, when the sliding distance increases, the adhered reinforcements may come out from the composites material and act as abrasive between pin and disc material (EN-31, hardened), leading to three-body abrasion behaviour. The EDS analysis of worn surfaces of Al-Al_2O_3/B_4C composites is shown in Figure 8. The presence of Si, Mn, Cu, Cr, Fe, B, C, O and Mg particulates can be seen by EDS analysis. The EDS images of fabricated Al6061-Al_2O_3/B_4C composites show the presence of B, C, O along with monolithic Al alloy constituents (Al-Mg-Si). Thus, it can be confirmed about reinforcements in the samples by the EDS analysis.

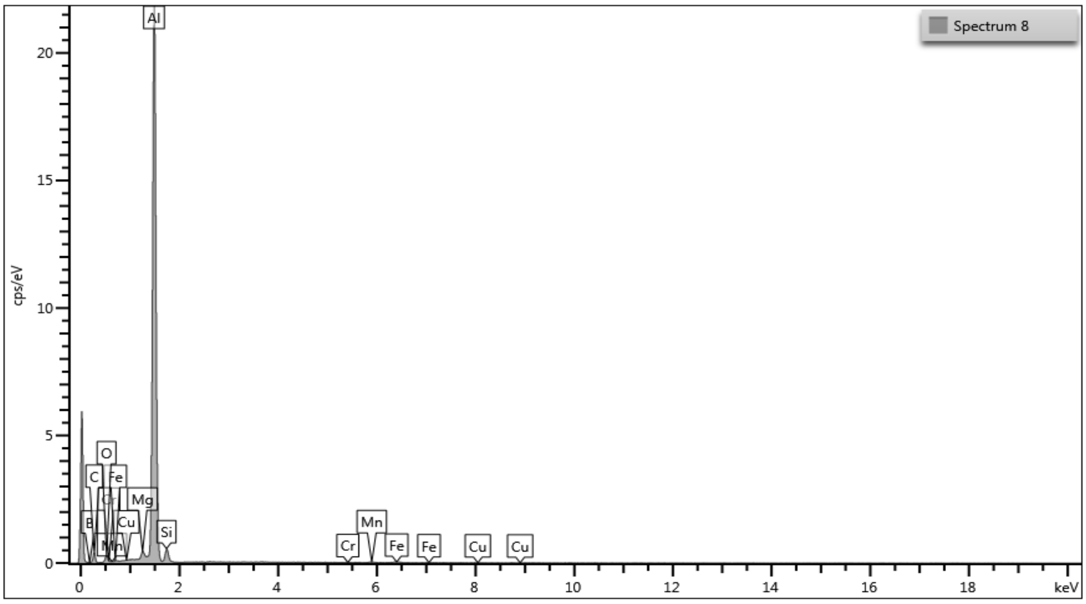


Fig. 8. EDS spectrum of Al-Al_2O_3/B_4C metal matrix composites

Conclusions

The wear analysis of the prepared hybrid MMCs was performed using the pin-on-disc method and wear parameters were also optimized with objectives of minimizing the weight loss and coefficient of friction through integrated Grey-Taguchi techniques. The main findings are as follows:

1. In comparison with Al alloy matrix and single reinforced MMCs, the minimum values of weight loss and coefficient of friction were seen for the hybrid composite with equal percentages of reinforcements.
2. The optimum values of weight loss and coefficient of friction through an integrated GRA-Taguchi analysis were reported as such: sample composition of B_4C= 50 % and Al_2O_3 = 50 %, rotation (sliding speed) of 250 RPM, the sliding distance of 2500 m and the load of 15 N.
3. The results of the ANOVA indicated the percentage contribution of each input factor as such: compositions of 94.47 %, rotation (sliding speed) of 1.06 %, sliding distance of 1.04 %, and load of 3.16 %.
4. The abrasive along with adhesive wear mechanism was found in the composites through SEM analysis.
5. Based on experimental outcomes from wear analysis of hybrid metal matrix composites, it can be concluded that better wear resistance was offered by hybrid composites than Al matrix and single reinforced composites which makes the hybrid composites more suitable for applications where economical and high wear resistance materials are required.

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