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Optimization of Tribological Properties in Aluminum Hybrid Metal Matrix Composites Using Gray-Taguchi Method

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This article investigates the optimization of dry sliding performances on the aluminum hybrid metal matrix composites using gray relational analysis in the Taguchi method. Different loads, sliding speeds and varying percentage of molybdenum disulfide are selected as control factors. The multiple responses to evaluate the dry sliding performances are specific wear rate and coefficient of friction. Using a pin-on-disk apparatus, the volume loss and frictional force are measured. Based on gray relational analysis, the optimum level parameters for specific wear rate and coefficient of friction have been identified. An L27 orthogonal array was employed for the experimental design. Analysis of Variance (ANOVA) had given the impact of individual factors and interactions on the specific wear rate as well as the coefficient of friction. The results indicated that the three test parameters had a significant role in controlling the friction and wear behavior of composites. Interaction of the control factors showed the sizable influence on tribological performance. Using Scanning Electron Microscopy (SEM) the wear surface morphology and wear mechanism of the composites have been investigated.

Keywords aluminum, gray relational analysis, hybrid metal matrix composites, self lubricated wear, Taguchi method

1. Introduction

Aluminum Metal Matrix Composites (AMMCs) are used in aerospace, electronics, and automobile sectors because of their attractive characteristics like high strength, stiffness, and wear resistance (Ref 1-3). Alumina and silicon carbide are used as reinforcements in composites to reduce wear in aluminum alloys. In the dry sliding and abrasive wear conditions, this reinforcement supports the applied load by restricting surface deformations (Ref 4-6). Yılmaz and Buytoz (Ref 7) found out that wear rates of aluminum-alumina composites (5-15% alumina) decreased with increasing size of alumina particulates (between 16 and 77 μm) in abrasive wear test. Also, he found that the composites containing 10% alumina with 5% graphite declined in the coefficient of friction produced by compocasting. Das et al. (Ref 8) concluded that Al-4.5 wt.% copper alloy showed improved hardness and abrasive wear resistance after the addition of alumina and zircon particles in stir cast composites. Akbulut et al. (Ref 9) experimented in planar-randomly oriented alumina short fiber, and reinforced Al-Si (LM 13) alloy was produced by liquid infiltration technique. According to their conclusion, the wear resistance of composites increased up to four times than that of unreinforced alloy in dry sliding wear test with the load from 5 to 60 N at a constant sliding speed of 1 m/s.

However, these kinds of reinforcements are sensitive to cracking during severe wear conditions and experience reduction in the wear resistance at higher loads. Another problem associated with ceramic reinforcements is their tendency to drop off from the matrix (Ref 10). The external addition of a lubricant is the easiest solution to reduce the friction and wear, although self-lubricating materials are preferable as they can work at higher temperatures.

Self-lubricating composites have found wide application in many special machine parts; yet oil or grease cannot lubricate inaccessible parts and contamination is not acceptable. Some previous studies on the solid lubricants for metallic materials have been carried out. Prasad and Asthana (Ref 11) reported that reinforcement of aluminum alloys with graphite solid lubricants and hard ceramic particles were used in automotive applications. Deonath and Rohatgi (Ref 12) reveal that cast aluminum-mica particulate composites and copper-coated ground mica particles have enough strength and so they are used as bearings in several applications. Jha et al. (Ref 13) reported that, in aluminum alloys LM13 and LM6, the cast composites of 2.8 and 2% of talc particles respectively, the wear rates of the composites were found to be 22-30% lower than the matrix alloys. Ramesh et al. (Ref 14) observed that dispersion of silicon carbide in the copper matrix reduced the wear rate of copper while the use of graphite, a soft phase as reinforcement in copper, resulted in increased wear rate when compared to Cu-SiC composites. However, Cu-Gr composites showed lower wear rates when compared to copper. Seah et al. (Ref 15) stated that adding graphite (1-3%) into the cast ZA-27 composites decreased wear rate. Naplocha and Granat (Ref 16) revealed that the Al-Si7 matrix and with alumina fibers

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reinforcement improved wear resistance property, and graphite improved seizure resistance. Daoud et al. (Ref 17) reported that aluminum alloy 7075 reinforced with alumina with an increased volume fraction increases wear resistance. Yen and Ishihara (Ref 18) examined the tribological behavior of the Al-Si alloy-graphite (55 vol.%) composite under 30 to 1% relative humidity, and found that the coefficient of friction and wear rate increased more than those of the base alloy. Dhanasekaran and Gnanamoorthy (Ref 19) observed that iron-copper-carbon-sintered steel containing solid lubricant of 3% of molybdenum disulfide which is used in gears and bearings showed a significant decline in the friction and wear in comparison to the base alloy. Morimoto (Ref 20) researched that, silicon nitride and cemented carbide blocks against a bearing steel ring in the load of 1600 N under molybdenum disulfide lubrication gave better results than oil lubricants. Kato et al. (Ref 21) examined that in sintered copper-tin-molybdenum disulfide composites, coefficient of friction decreased with increasing molybdenum disulfide until 20 vol.% of molybdenum disulfide. However, from 20 to 40 vol.% molybdenum disulfide, the wear rates of the composites increased. From the above literature reviews, it was found that solid lubricant helped in reducing friction and wear; it further improved seizure resistance of the composites. On the other hand, limited information is available about the characterization of this hybrid aluminum-alumina-molybdenum disulfide composite.

As the relation between the parameters in dry sliding wear is complex and interdependent, selection of the optimal factors of combination is important. Design of experiments, response surface method, and genetic algorithm are the procedures that are used to decide the optimum parameters' settings. Taguchi method has been used in industries for nearly three decades for the optimal factor with a single response. Many researchers have been using Taguchi method to identify the effect of parameters on dry sliding with composites. Basavarajappa et al.'s (Ref 22) investigation on Al 2219-SiC and Al2219-SiC-Graphite hybrid composites showed that the sliding distance, load, as well as sliding speed parameters were significant factors for wear by using Taguchi and ANOVA techniques. Modi et al. (Ref 23) had inferred that the effect of load was significant for aluminum-10% alumina composite using factorial design of experiment method. Also, the combined effect of abrasive size and sliding distance caused not only increased wear of matrix alloy but also helped to reduce the wear of composite. Sahin (Ref 24) studied the abrasion resistance of 10 and 20 wt.% SiC particle-reinforced 2014 aluminum and he found that abrasive grain size was the most powerful factor on the abrasive wear between weight fraction and abrasive size. Then, he conducted a set of experiments by combining orthogonal arrays and analysis of variance techniques to study the abrasive wear behavior of Al-2014 alloy-10 wt.% SiC composites (Ref 25). In this experiment, he found that the introduction of SiC particle reinforcement in the alloy exerted the greatest effect on abrasive wear, followed by the applied load, but the sliding distance had a much lower effect. Response surface method was used by Kumar and Balasubramanian (Ref 26) to evaluate dry sliding wear behavior of AA7075 aluminum-SiC composites produced by powder metallurgy. From their study, they found that the sliding speed is directly proportional to wear rate and the particle size, and volume fraction was inversely proportional to wear rate.

Optimization of multiple performance characteristics is much more complicated than single performance characteristics. Taguchi method coupled with gray relational analysis was used to solve the multiple performance characteristics of wear rate. Gray theory forwarded by Deng Ju-long from China (Ref 27, 28) was a new theory and the method applicable was the study of unascertained problems with a few data but poor information. The gray theory works on the unascertained, but partially known as well as unknown information by extracting valuable information from partially known and developing it further. In this theory, "black" is to represent unknown information and "white" is for known information, besides "gray" that represents that information that is partially known and partially unknown. Gray theory is applied to various fields of optimization like injection moulding and rapid prototyping parameters' optimization (Ref 29, 30). Recently, some researchers have used gray-based Taguchi method for the selection of optimum parameters for tribological performance evaluation. Sahoo and Pal (Ref 31) used Taguchi method with gray relational analysis to the multiple tribological performance characteristics of electroless Ni-P Coatings. Peng and Kirk (Ref 32) used the theory of gray relational grades to classify six types of metallic wear debris for wear particle analysis for machine condition monitoring and fault diagnosis. Fung (Ref 33) used a gray relational analysis for injection molding process parameters' optimization for the wear property of 15 wt.% short fiber-reinforced polybutylene terephthalate composites.

In this study, gray relational analysis and L27 orthogonal array are integrated to analyze the experimental results of dry sliding performances obtained from 27 experiments by changing the control parameters like load, sliding speed, and percentage of molybdenum disulfide. The optimum combinations of these control factors can be determined from this study. Analysis of Variance (ANOVA) was used to find out the contribution of each parameter and their interactions on the dry sliding performances. The worn surfaces were observed by Scanning Electron Microscopy (SEM) to understand the wear mechanisms.

2. Details of Experiment

2.1 Materials

Al-Si10Mg (British Standard: LM9) was used as the matrix, alumina as hard reinforcement and molybdenum disulfide as soft reinforcement. This matrix alloy was used for intricate, thin-walled castings that demand high strength, such as castings for the automotive industry and general engineering. It has very good castability and is suitable for sand, gravity die-casting, and high-pressure die casting. Nominal composition of the aluminum alloy is shown in Table 1. To produce composites, the stir casting technique was used. Particle size of 10-20 μm alumina and 1.5 μm particle sizes of molybdenum disulfide reinforcements were used in this composite. Molybdenum disulfide in varying amounts ranging between 2 and 4 wt.% was mixed with aluminum-5 wt.% alumina composite. The densities of the composites were measured using Archimedes' principle. The weight of the composite sample in air and water were measured with the help of an electronic balance. The hardness of the composite was measured using Vickers micro hardness tester with a 100-g load in different locations on the surface of the composite. The density and average hardness of the composites are given in Table 2. The SEM micrographs of

Table 1 Nominal composition of the Al-Si10Mg alloy (wt.%)

Cu	Mg	Si	Fe	Mn	Zn	Al
0.2	0.2-0.6	10-13	0.6	0.3-0.7	0.1	Balance

Table 2 Density and hardness of the composites

Designation	Density, g/cm^3	Vickers hardness, VHN
Al-Si10Mg-5 wt.% Alumina	2.65	108
Al-Si10Mg-5 wt.% Alumina-2 wt.% molybdenum disulfide	2.67	114
Al-Si10Mg-5 wt.% Alumina-4 wt.% molybdenum disulfide	2.68	113

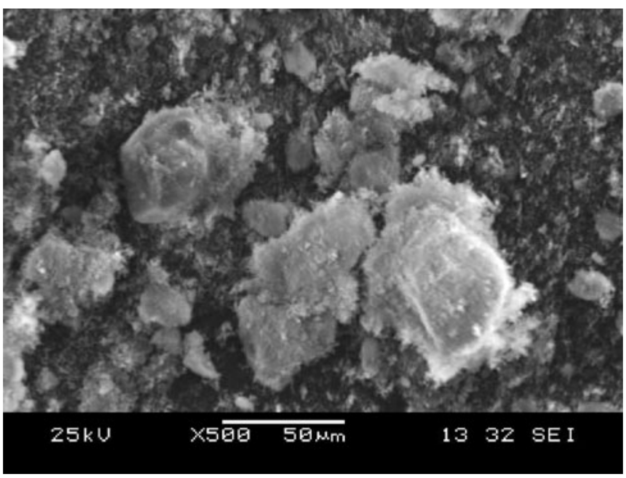

Fig. 1 SEM image of molybdenum disulfide particles

molybdenum disulfide and alumina particles are shown in Fig. 1 and 2. The composite was solidified in a cast iron die in the form of cylindrical pin of diameter of 14 mm and length 73 mm. Composite and wear test specimens are shown in Fig. 3.

2.2 Experimental Setup

Dry sliding wear test performed on the pin-on-disk apparatus that linked to a data collection system is shown in Fig. 4. The apparatus consists of a stationary pin sliding on a rotating disk driven by an electric motor. The disk material is EN32 steel having a hardness value of HRC65. Wear test specimen were machined from cast composites to obtain cylindrical pins having a diameter of 10 mm and height 40 mm, which are metallographically polished, their weights being 8.3250 ± 0.2 g. The wear tests were carried out at room temperature (30 ± 3 °C, RH $55 \pm 5\%$) under dry sliding condition in accordance with the ASTM G 99-95 standard. Before the test, all the contacting surfaces were polished, cleaned in acetone, and dried. The wear losses of the specimens were measured using an electronic balance of 0.0001 g precision. The sliding distance was fixed as 3000 m. Before and after wear testing, samples were cleaned with acetone to remove wear debris. The

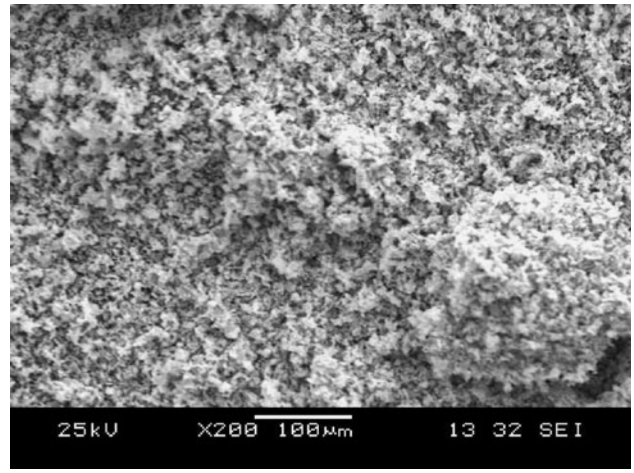

Fig. 2 SEM image of alumina particles

Fig. 3 Photograph of composite casting and pins

Fig. 4 Photograph of pin-on-disk apparatus

differences in the weight measured before and after the test gave the dry sliding wear loss of the composites, which was converted into the volume loss. The specific wear rate (W_s) was calculated using Eq 1. where V is the volume loss, L is the applied load, and D is the sliding distance.

$$\text{Specific wear rate, } W_s = \frac{V}{L \times D} \text{mm}^3/\text{N m} \quad \text{(Eq 1)}$$

The coefficient of friction (μ) is calculated by the ratio between tangential forces (F_T) and the normal force (F_N) using Eq 2. The tangential force is obtained from the load cell fitted in the pin-on-disk apparatus.

$$\text{Coefficient of Friction, } \mu = \frac{F_T}{F_N} \quad \text{(Eq 2)}$$

2.3 Taguchi Method

Based on the Taguchi method, an orthogonal array was used to reduce the number of experiments for finding out the optimum test parameters (Ref 34). The orthogonal array provided the shortest possible matrix of combinations in which all the parameters were used to consider their direct effect as well as interactions simultaneously. The main factors are applied load (A), sliding speed (B), and molybdenum disulfide weight percentage (C). Details of the design factors and their levels are shown in Table 3. Standard L27 orthogonal array used in this study is shown in Table 4. The first column was assigned for applied load (A), the second column for sliding speed (B), and the fifth column for the percentage of the molybdenum disulfide (C), and the other columns were assigned for their interactions (Ref 35). The other response variables are the specific wear rate and the coefficient of friction of composites. In Taguchi method, signal-to-noise (S/N) ratio is used to represent quality characteristics, and the largest value of S/N ratio is required. There are three types of S/N ratio—the lower the better, the higher the better, and the nominal the better. The S/N ratio with lower-the-better characteristics (like wear, coefficient of friction, etc.) can be calculated using Eq 3

$$\eta_{ij} = -10 \log\left(\frac{1}{n}\sum_{j=1}^{n} y_{ij}^2\right) \quad \text{(Eq 3)}$$

where y_{ij} is the ith experiment at the jth test, and n is the total number of tests.

Table 3 Design factors along with their levels

Design factors	Unit	Levels 1	2	3
Applied load (A)	N	10	30	50
Sliding speed (B)	m/s	2	3	4
Percentage of molybdenum disulfide (C)	%	0	2	4

3. Details of Gray Relational Analysis

3.1 Data Preprocessing

During data preprocessing, the experimental results (specific wear rate, and coefficient of friction) are normalized in the range between zero and one. Gray relational analysis depends

Table 4 L27 orthogonal array with design factors and interactions

Test No.	Arrays: 1 (A)	2 (B)	3 (A × B)	4 (A × B)	5 (C)	6 (B × C)	7 (B × C)	8 (A × C)	9	10	11 (A × C)	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

on the quality characteristics of a data sequence. Various methods of data preprocessing are available (Ref 36). For higher-the-better characteristic, the original sequence is normalized as follows:

$$x_i^*(k) = \frac{x_i^o(k) - \min x_i^o(k)}{\max x_i^o(k) - \min x_i^o(k)} \quad \text{(Eq 4)}$$

In case of lower-the-better characteristic, the original sequence is normalized as follows:

$$x_i^*(k) = \frac{\max x_i^o(k) - x_i^o(k)}{\max x_i^o(k) - \min x_i^o(k)} \quad \text{(Eq 5)}$$

For instance, for nominal-the-better characteristic, the original sequence is normalized as follows:

$$x_i^*(k) = 1 - \frac{\left|x_i^o(k) - x^o\right|}{\max x_i^o(k) - x^o} \quad \text{(Eq 6)}$$

Or, the values of original sequence are divided by the first value of the sequence:

$$x_i^*(k) = \frac{x_i^o(k)}{x_i^o(1)} \quad \text{(Eq 7)}$$

where $i = 1,\ldots, m$; $k = 1,\ldots, n$. m is the number of experimental data items, and n is the number of parameters. $x_i^o(k)$ denotes the original sequence, $x_i^*(k)$ the sequence after the data preprocessing, max $x_i^o(k)$ is the largest value of $x_i^o(k)$, min $x_i^o(k)$ is the smallest value of $x_i^o(k)$ and x^o is the preferred value.

3.2 Gray Relational Coefficient and Gray Relational Grade

After data preprocessing, the gray relational coefficient $\xi_i(k)$ for the kth performance characteristics in the ith experiment is calculated as

$$\xi_i(k) = \frac{\Delta_{\min} + \zeta\,\Delta_{\max}}{\Delta_{oi}(k) + \zeta\,\Delta_{\max}} \quad \text{(Eq 8)}$$

whereas Δ_{oi} is the deviation of sequence between the reference sequence and the comparability sequence, where $0 < \xi_i(k) \leq 1$; $\Delta_{oi} = \left\|x_o^*(k) - x_i^*(k)\right\|$; $\Delta_{\min} = \min\limits_{\forall j \in i} \min\limits_{\forall k} \left\|x_o^*(k) - x_j^*(k)\right\|$; $\Delta_{\max} = \max\limits_{\forall j \in i} \max\limits_{\forall k} \left\|x_o^*(k) - x_j^*(k)\right\|$.

Reference sequence is denoted by $x_o^*(k)$ and $x_i^*(k)$ is the comparability sequence. ζ is the distinguishing coefficient, which is defined in the range $0 \leq \zeta \leq 1$. $\zeta = 0.5$ is generally used. The average value of the gray relational coefficients is the gray relational grade. Therefore, the gray relational grade is defined as follows:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \quad \text{(Eq 9)}$$

The gray relational grade γ_i represents the correlation between the reference sequence and the comparability sequence, with a higher gray relational grade.

4. Analysis and Discussion

Experimental values of specific wear rate and coefficient of friction are listed in Table 5. The calculated values of S/N ratio for a given response using Eq 3, are listed in Table 6. The normalized S/N ratio values were obtained by Eq 4-7 based on the quality of the characteristics. In general, the larger normalized S/N ratio corresponds to the better performance. The deviation sequence Δ_{oi} is calculated as follows:

Table 5 Experimental results for specific wear rate and coefficient of friction

Exp. No.	Applied load (A), N	Sliding speed (B), m/s	MoS_2 wt.% (C), wt.%	Specific wear rate, $\times 10^{-5}$ mm^3/N m	Coefficient of friction
1	10	2	0	15.334	0.483
2	10	2	2	11.2742	0.450
3	10	2	4	10.787	0.423
4	10	3	0	13.9284	0.457
5	10	3	2	7.6758	0.435
6	10	3	4	6.7516	0.410
7	10	4	0	8.2675	0.445
8	10	4	2	4.70199	0.411
9	10	4	4	3.9342	0.380
10	30	2	0	9.4133	0.669
11	30	2	2	5.7084	0.598
12	30	2	4	4.9748	0.555
13	30	3	0	8.7744	0.645
14	30	3	2	5.0288	0.564
15	30	3	4	3.7988	0.520
16	30	4	0	5.4009	0.617
17	30	4	2	4.0502	0.523
18	30	4	4	3.1328	0.487
19	50	2	0	8.5640	0.714
20	50	2	2	5.7492	0.645
21	50	2	4	4.5056	0.608
22	50	3	0	7.1073	0.692
23	50	3	2	5.0968	0.603
24	50	3	4	3.9143	0.560
25	50	4	0	5.4972	0.673
26	50	4	2	4.1447	0.564
27	50	4	4	3.4046	0.522

$$\Delta_{o2}(1) = \left|x_o^*(1) - x_2^*(1)\right| = |1.00 - 0.194| = 0.806$$

$$\Delta_{o2}(2) = \left|x_o^*(2) - x_2^*(2)\right| = |1.00 - 0.732| = 0.268$$

So, $\Delta_{o2} = (0.806, 0.268)$.

The same calculation method is used for $i = 1\text{-}27$, and the results of all Δ_{oi} for $i = 1\text{-}27$ are given in Table 6. $\Delta_{\max}$ and $\Delta_{\min}$ obtained from Table 6 are as follows:

$$\Delta_{\max} = \Delta_{01}(1) = \Delta_{019}(2) = 1.00$$

$$\Delta_{\min} = \Delta_{018}(1) = \Delta_{09}(2) = 0.00$$

The gray relational coefficients and grade values for each experiment is calculated using Eq 8 and 9 as given in Table 7. Average gray relational coefficient and grades for each level of a testing parameter calculated as per Taguchi method. The symbol (*) has been used to denote the optimum value of gray relational coefficient and grade in Tables 8-10.

It is clearly observed from Table 8 and Fig. 5 that optimum factors for the lowest specific wear rate are 30 N applied load (level 2), 4 m/s sliding speed (level 3), and 4 wt.% of molybdenum disulfide (level 3) is obtained.

From, Table 9 and Fig. 6, the optimum factors for the lowest coefficient of friction obtained are 10 N applied load (level 1), 4 m/s sliding speed (level 3), and 4 wt.% of molybdenum disulfide (level 3).

Table 6 S/N ratio values, normalized S/N ratio values, and deviation sequences

Expt. No.	S/N ratios		Normalized S/N ratio		Deviation sequences (Δ_{oi})	
	Specific wear rate	Coefficient of friction	Specific wear rate	Coefficient of friction	Specific wear rate	Coefficient of friction
1	−23.713	6.321	0.000	0.620	1.000	0.380
2	−21.042	6.936	0.194	0.732	0.806	0.268
3	−20.658	7.473	0.221	0.830	0.779	0.170
4	−22.878	6.802	0.061	0.707	0.939	0.293
5	−17.702	7.230	0.436	0.786	0.564	0.214
6	−16.588	7.744	0.517	0.880	0.483	0.120
7	−18.347	7.033	0.389	0.750	0.611	0.250
8	−13.446	7.723	0.744	0.876	0.256	0.124
9	−11.897	8.404	0.857	1.000	0.143	0.000
10	−19.475	3.491	0.307	0.103	0.693	0.897
11	−15.130	4.466	0.622	0.281	0.378	0.719
12	−13.936	5.114	0.709	0.399	0.291	0.601
13	−18.864	3.809	0.352	0.161	0.648	0.839
14	−14.029	4.974	0.702	0.374	0.298	0.626
15	−11.593	5.680	0.879	0.503	0.121	0.497
16	−14.649	4.194	0.657	0.232	0.343	0.768
17	−12.150	5.630	0.838	0.494	0.162	0.506
18	−9.919	6.249	1.000	0.607	0.000	0.393
19	−18.654	2.926	0.367	0.000	0.633	1.000
20	−15.192	3.809	0.618	0.161	0.382	0.839
21	−13.075	4.322	0.771	0.255	0.229	0.745
22	−17.034	3.198	0.484	0.050	0.516	0.950
23	−14.146	4.394	0.694	0.802	0.306	0.198
24	−11.853	5.036	0.860	0.385	0.140	0.615
25	−14.803	3.440	0.646	0.094	0.354	0.906
26	−12.350	4.974	0.824	0.374	0.176	0.626
27	−10.641	5.647	0.948	0.497	0.052	0.503

Based on the gray relational grade values given in Table 10 and Fig. 7, the optimum factors for both the specific wear rate and the coefficient of friction obtained for the hybrid composite are 10 N load (level 1), 4 m/s sliding speed (level 3), and 4% of molybdenum disulfide (level 3) combination. In Table 10, the rank indicates the strongest factor on the dry sliding performance so that molybdenum disulfide percentage has the strongest effect on dry sliding parameters in comparison to other factors. This reveals that the dry sliding performance is strongly affected the molybdenum disulfide percentage.

4.1 Analysis of Variance (ANOVA)

ANOVA is used to find the significant factor by statistical method. It helps to do formal tests for the significance of the main factors and their interactions by comparing the mean square against an estimate of the experimental errors at specific confidence levels. In the analysis, "F-ratio" is a ratio of mean square error to residual is used to determine the significance of a factor. Thus, the percentage of contribution is defined as the significant rate of process parameters on a particular quality characteristic.

From Table 11, it is possible to note that molybdenum disulfide percentage (40.0941%) followed by sliding velocity (30.4939%) and applied load (21.0608%) exert a significant influence at the confidence level of 95% on the specific wear rate of aluminum composites. Even though interactions between factors are of small percentage, yet they may be statistically insignificant.

From Table 12, applied load (63.4293%) followed by molybdenum disulfide percentage (13.6123%) and sliding velocity (5.3839%) exerted has a significant influence, at a confidence level of 95%, on the coefficient of friction. Although interactions between factors are of a small percentage, yet they may be statistically insignificant.

From Table 13, molybdenum disulfide percentage (50.6583%) followed by sliding velocity (30.5377%) and applied load (5.1965%) exerted has the significant influence at the confidence level of 95% on the both specific wear rate and coefficient of friction of aluminum composites. Although interactions between factors are of small percentage, yet they may be statistically insignificant.

4.2 Confirmation Experiments

The predicated gray relational grades of using the optimum level of the dry sliding parameters are calculated using Eq 10.

$$\hat{\gamma} = \gamma_{\mathrm{m}} + \sum_{i=1}^{q} (\bar{\gamma}_i - \gamma_{\mathrm{m}}) \qquad \text{(Eq 10)}$$

where γ_{m} is the total mean gray relational grade, $\bar{\gamma}_i$ is the mean gray relational grade at the optimum level, and "q" is the number of main design parameters that significantly affect the coefficient of friction and specific wear rate. Tables 14-16 show the comparison of the estimated gray relational grade with the calculated gray relational grade obtained in an experiment using the optimum test parameters. Thus, compared to

Table 7 The calculated gray relational coefficient and gray relational grade

For both coefficient of friction and specific wear rate			For specific wear rate			For coefficient of friction		
Expt. No.	Gray relational grade	Rank	Expt. No.	Gray relational coefficient	Rank	Expt. No.	Gray relational coefficient	Rank
9	0.889	1	18	1.000	1	9	1.000	1
18	0.780	2	27	0.905	2	6	0.806	2
8	0.731	3	15	0.805	3	8	0.801	3
27	0.702	4	24	0.781	4	3	0.746	4
23	0.668	5	9	0.777	5	23	0.716	5
6	0.657	6	17	0.756	6	5	0.700	6
15	0.653	7	26	0.739	7	7	0.666	7
17	0.626	8	21	0.686	8	2	0.651	8
24	0.615	9	8	0.662	9	4	0.631	9
26	0.592	10	12	0.632	10	1	0.568	10
5	0.585	11	14	0.627	11	18	0.560	11
3	0.569	12	23	0.620	12	15	0.501	12
7	0.558	13	16	0.593	13	27	0.498	13
21	0.544	14	25	0.585	14	17	0.497	14
12	0.543	15	11	0.570	15	12	0.454	15
14	0.535	16	20	0.567	16	24	0.449	16
2	0.517	17	6	0.508	17	14	0.444	17
16	0.494	18	22	0.492	18	26	0.444	18
11	0.490	19	5	0.470	19	11	0.410	19
4	0.489	20	7	0.450	20	21	0.402	20
25	0.470	21	19	0.441	21	16	0.394	21
20	0.470	22	13	0.435	22	13	0.373	22
1	0.451	23	10	0.419	23	20	0.373	23
22	0.418	24	3	0.391	24	10	0.358	24
13	0.404	25	2	0.383	25	25	0.356	25
10	0.389	26	4	0.347	26	22	0.345	26
19	0.387	27	1	0.333	27	19	0.333	27

Table 8 Response table for specific wear rate

	A	B	C
Level			
1	0.4802	0.4913	0.4553
2	0.6485*	0.5650	0.5991
3	0.6463	0.7186*	0.7206*
Delta	0.1683	0.2273	0.2653
Rank	3	2	1

Average gray relational coefficient: 0.5917

the early testing parameters, gray relational grade has improved. Therefore, this approach for optimum testing parameters for multiple responses is feasible.

4.3 Correlation of Optimum Results with Surface Morphology of Specimens

The optimized results can be correlated with the SEM micrographs of the worn surface of aluminum composite specimens. In aluminum-5 wt.% of alumina-4 wt.% of molybdenum disulfide clearly shows the fine grooves with fewer plastic deformations when sliding speed at 4 m/s at the applied load of 10 N as shown in Fig. 8(a). When sliding speed at 4 m/s at the applied load of 50 N grooves on the worn surface on the composites are large and the plastic deformation at the

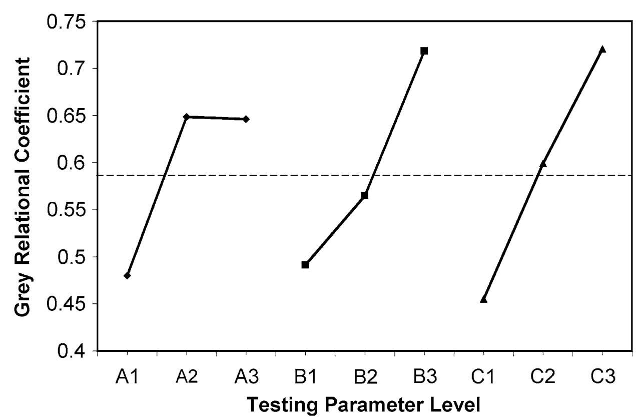

Fig. 5 Effects of dry sliding parameter levels on the specific wear rate

Table 9 Response table for coefficient of friction

	A	B	C
Level			
1	0.7299*	0.4773	0.4472
2	0.4436	0.5517	0.5596
3	0.4351	0.5795*	0.6018*
Delta	0.2948	0.1022	0.1546
Rank	1	3	2

Average gray relational coefficient: 0.5362

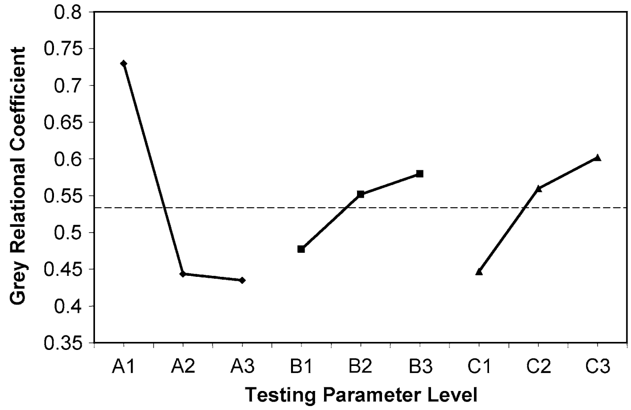

Fig. 6 Effects of dry sliding parameter levels on the coefficient of friction

Table 10 Response table for both specific wear rate and coefficient of friction

	A	B	C
Level			
1	0.6050*	0.4843	0.4512
2	0.5460	0.5584	0.5794
3	0.5407	0.6491*	0.6612*
Delta	0.0643	0.1647	0.2100
Rank	3	2	1

Average gray relational grade: 0.5639

edge of grooves high as shown in Fig. 8(b). Many researchers stated the dominance of oxidative wear during dry sliding wear of aluminum composites (Ref 37, 38). The oxide layer of lubricant phenomena is improved with the increase in an amount of molybdenum disulfide suggesting that the worn out surface is oxidized. In aluminum-alumina-molybdenum disulfide composites, more oxide is formed at higher sliding speed with constant applied load, which leads to metal and molybdenum disulfide contact is increased, thus lowering the specific wear rate.

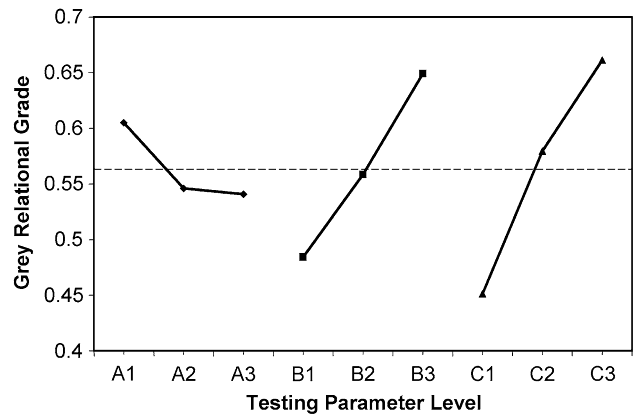

Fig. 7 Effects of dry sliding parameter levels on both specific wear rate and coefficient of friction

Table 11 ANOVA for specific wear rate

Factors	Sum of squares	Degrees of freedom	Mean sum of squares	TEST-F	*F*	Percentage of contribution
A	0.1678	2	0.0839	78.7011	4.46	21.0608
B	0.2420	2	0.1210	113.5029	4.46	30.4939
C	0.3176	2	0.1588	148.9215	4.46	40.0941
A × B	0.0068	4	0.0017	1.5836	3.84	0.3164
B × C	0.0192	4	0.0048	4.5132	3.84	1.9045
A × C	0.0248	4	0.0062	5.8084	3.84	2.6067
Errors	0.0085	8	0.0011	1.0000	…	3.5236
Total	0.7868	26	0.0303	…	…	100.0000

Table 12 ANOVA for coefficient of friction

Factors	Sum of squares	Degrees of freedom	Mean sum of squares	TEST-F	*F*	Percentage of contribution
A	0.5070	2	0.2535	64.4730	4.46	63.4293
B	0.0502	2	0.0251	6.3876	4.46	5.3839
C	0.1150	2	0.0575	14.6217	4.46	13.6123
A × B	0.0288	4	0.0072	1.8298	3.84	1.6584
B × C	0.0325	4	0.0081	2.0689	3.84	2.1364
A × C	0.0219	4	0.0055	1.3946	3.84	0.7886
Errors	0.0315	8	0.0039	1.0000	…	12.9911
Total	0.7869	26	0.0303	…	…	100.0000

Table 13 ANOVA for both specific wear rate and coefficient of friction

Factors	Sum of squares	Degrees of freedom	Mean sum of squares	TEST-F	*F*	Percentage of contribution
A	0.0229	2	0.0115	9.0833	4.46	5.1965
B	0.1225	2	0.0613	48.5023	4.46	30.5377
C	0.2016	2	0.1008	79.8005	4.46	50.6583
A × B	0.0138	4	0.0035	2.7364	3.84	2.2325
B × C	0.0038	4	0.0010	0.7532	3.84	0.3173
A × C	0.0182	4	0.0045	3.5939	3.84	3.3351
Errors	0.0101	8	0.0013	1.0000	…	7.7223
Total	0.3930	26	0.0151	…	…	100.0000

Table 14 Results of confirmation test for specific rate

		Optimal	
	Initial	Predicted value	Experimental value
Combination of testing parameters	A2B2C2	A2B3C3	A2B3C3
Specific wear rate	5.0288	…	3.1328
Gray relational coefficient	0.6270	0.9043	1.00

Improved specific wear rate: 1.896. Improved gray relational grade: 0.373

Table 15 Results of confirmation test for coefficient of friction

		Optimal	
	Initial	Predicted value	Experimental value
Combination of testing parameters	A2B2C2	A1B3C3	A1B3C3
Coefficient of friction	0.564	…	0.380
Gray relational coefficient	0.444	0.8388	1.00

Improved coefficient of friction: 0.184. Improved gray relational grade: 0.556

Table 16 Results of confirmation test for both specific wear rate and coefficient of friction

		Optimal	
	Initial	Predicted value	Experimental value
Combination of testing parameters	A2B2C2	A1B3C3	A1B3C3
Specific wear rate	5.0288	…	3.9342
Coefficient of friction	0.564	…	0.380
Gray relational grade	0.535	0.7874	0.889

Improved specific wear rate: 1.0946. Improved coefficient of friction: 0.184. Improved gray relational grade: 0.354

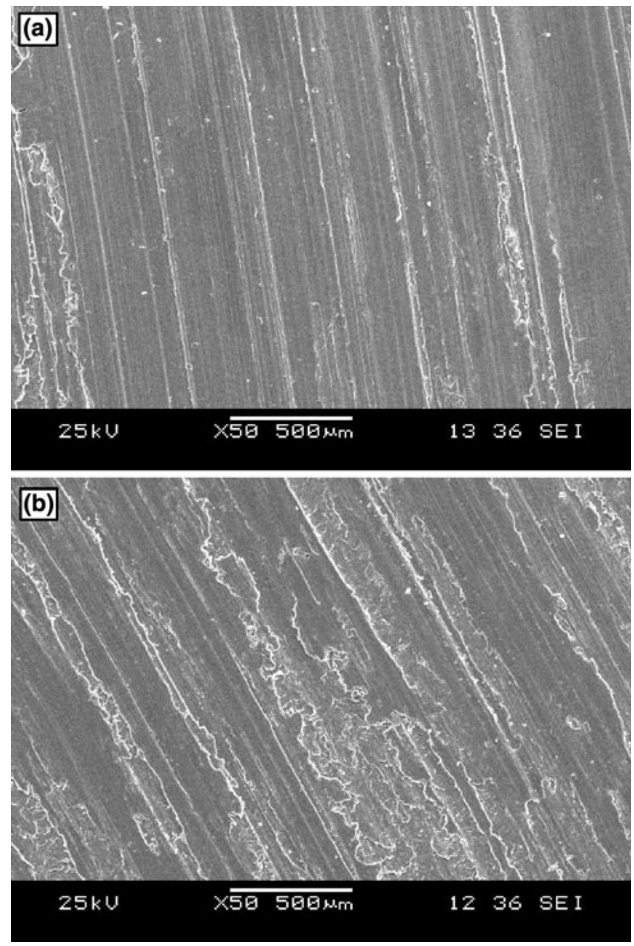

Fig. 8 SEM image of worn surface of aluminum-5 wt.% of alumina-4 wt.% of molybdenum disulfide at 4 m/s. (a) 10 N and (b) 50 N

5. Conclusions

This article presents investigations which are summarized as follows:

- Orthogonal array with gray relational analysis is used to optimize the multiple performance dry sliding characteristics of aluminum hybrid composites.
- For the lowest specific wear rate, 30 N applied load, 4 m/s sliding speed, and 4 wt.% molybdenum disulfide percentage are used as optimum combination.

- For the lowest coefficient of friction, 10 N applied load, 4 m/s sliding speed, and 4 wt.% molybdenum disulfide percentage are used as optimum combination.
- For both specific wear rate and coefficient of friction, lowest values given are 10 N applied load, 4 m/s sliding speed, and 4 wt.% molybdenum disulfide percentage.
- Based on the ANOVA, molybdenum disulfide percentage (40.0941%) followed by sliding velocity (30.4939%), and applied load (21.0608%) exert a significant influence on the specific wear rate of aluminum composites.
- In case of the coefficient of friction, applied load (63.4293%) followed by molybdenum disulfide percentage (13.6123%), and sliding velocity (5.3839%) exert a significant influence.
- Thus, for both specific wear rate and coefficient of friction, molybdenum disulfide percentage (50.6583%) followed by sliding velocity (30.5377%) and applied load (5.1965%) exert a significant influence.
- Interactions between applied load, sliding velocity, and molybdenum disulfide percentage on the dry sliding are of a small percentage; yet they are considered statistically insignificant.

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