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Research Article

Tribological Behavior of Al/Nanomagnesium/Aluminum Nitride Composite Synthesized through Liquid Metallurgy Technique

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Despite its excellent qualities such as hardness, tensile, and yield strength, aluminum alloys are mostly used in aviation fins and car frames. However, wear resistance at maximum load is weak. This effort will now synthesize and investigate the tribological behavior of AA6063- (AlMg0.7Si-) AlN composites. The goal of this experiment is to determine the best wear rate and coefficient of friction for the AA6063-AlN with nanomagnesium composites developed. Weight percent, load (L), sliding velocity (SV), and sliding distance (SD) are the process factors studied, and the output responses are wear rate and friction coefficient. Bottom pouring type stir casting was used to create AA6063-AlN composites with various weight percentages. The various compositions are AA6063, AA6063-4 wt% AlN, AA6063-8 wt% AlN, and AA6063-12 wt% AlN. A pin-on-disc machine inspected the wear rate and friction coefficient of AA6063-AlN composites. Experimentation was done according to L_{16} orthogonal array (OA). Wear rate (WR) and coefficient of friction (COF) examinations were made to identify the optimum parameters to obtain minimum WR and COF for the AA6063-AlN composite via grey relational analysis (GRA). The contour plot analysis clear displays WR and COF with respect to wt% vs. L, wt% vs. SV and wt% vs. SD. The ANOVA outcomes revealed that wt% is the most vital parameter (85.55%) persuading WR and COF. The optimized parameters to achieve minor WR and COF was found as 12 wt% of AlN, L 20 N, SV 3 m/s, and SD 400 m. The worn surface was analyzed using scanning electron microscope and indicates that addition of AlN particles with matrix reduces the scratches. These articles offer a key for optimum parameters on wear rate and COF of AA6063-AlN composites via Taguchi grey relational analysis.

1. Introduction

The progressions in the production processes alongside the arrangement of adding a scope of reinforcement particles empower the metal matrix composites (MMCs) for enormous fabrication with various usages. MMCs include a metals or alloys strengthened with ceramic, metallic, or natural mixtures to upgrade the properties like strength, inflexibility, flexible modulus, wear and corrosion opposition, and warm conductivity [1]. Amid the accessible metals, Al has significant utilization in the fabrication of MMCs [2]. MMCs are used majorly in air craft, automobile, construction sec-

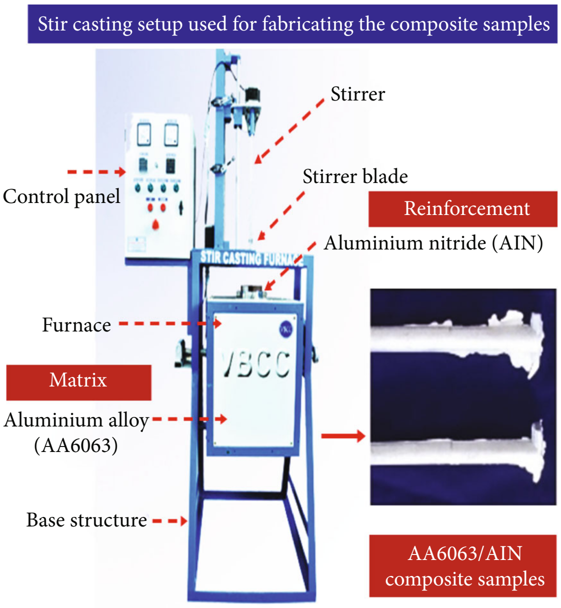


Figure 1: Stir casting setup used for the present work.

Figure 3: Pin-on-disc wear test apparatus.

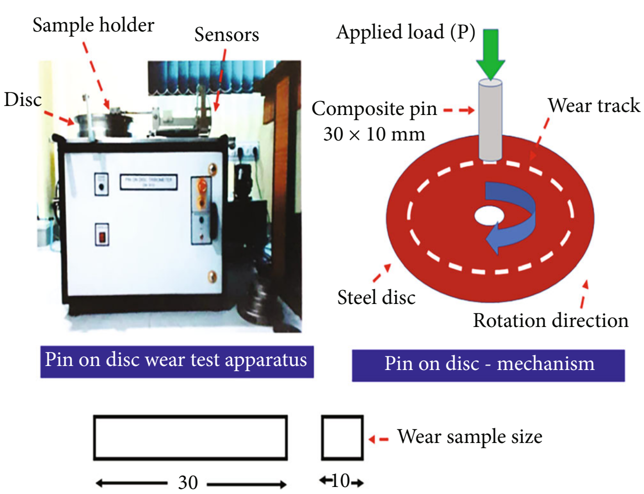


Figure 2: Schematic of pin-on-disc wear test apparatus.

tor, electronics stuffing, thermal controlling apparatus's despite of its better strength, superior elastic modulus, precise stiffness, and thermal and electrical conductivity [3]. MMCs strengthened with ceramics exhibit superior properties like wear and corrosion behavior than the customary alloys [4]. MMCs possess sustainable usages in various engineering sector. MMCs are utilized as another material for prevailing alloys in the field of automobile and aerospace sector [5, 6]. In the previous industry development period, aluminum and its alloys were ascertained to be foremost consistent less weight materials; additionally, it was utilized considerably on manufacturing automobile and space vehicle parts [7]. The expanding requests for less weight, excellent strength, superior high-temperature execution, outstanding corrosion opposition, and synthetically latent and energy-convertible materials in the transport, farming, infrastructure, and production companies have invigorated a consistently developing action to produce explicit composite materials named as aluminum matrix composites (AMCs).

AMCs are less weight and better enactment materials that possess the possibility to substitute traditional materials in numerous progressive usages [8]. AMCs are notable for their better strength to weight proportion, unrivaled tribological behavior, and corrosion opposition properties; because of these reasons, monolithic alloys have been replaced in various fields like automotive, maritime, and aviation sector. Since the most recent thirty years, scientists have given their attention to these materials and are attempting to enhance the property to create them appropriate for usage in difficult territories [9]. Owing to the superior properties, AMCs are used in the manufacturing of aero frame structure, space shuttle component, landing gear, brake disc, knuckle housing, suspension arm, etc. [10]. AMCs have enhanced wear opposition, less weight, and better rigidity, with obvious superiority usages. AMCs can replace traditional materials in automotive and aeronautics sectors [11]. AMCs can be utilized in energy-related application areas like nuclear, renewable, and bioenergy sectors. By using AMCs in energy sectors as well as in oil refining industries, the life time of the component can be enhanced significantly [12, 13]. AlN is a normally necessary strengthening material for AMCs as it gets the compelling mixing of physical, tribological, and mechanical attributes like better hardness, less density, good versatile modulus, and remarkable wear obstruction. Particularly, usage of AlN particles as fortification has consistently upgraded the AMC mechanical properties [14]. AlN reinforced with aluminum is nonreactive; AlN possesses better hardness, better thermal conductivity, and least coefficient of thermal expansion [15].

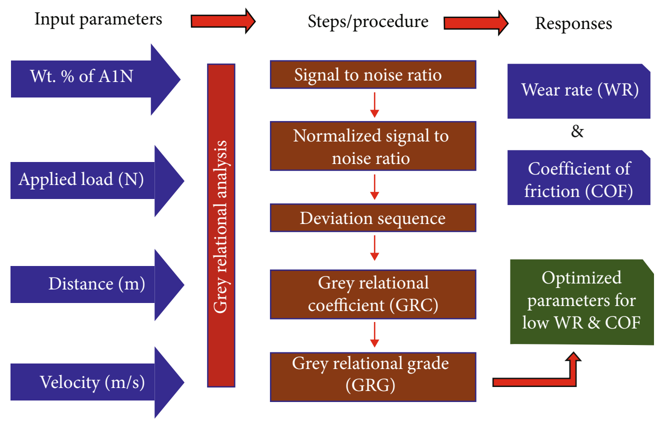


Figure 4: Steps followed for the TGRA method.

Table 1: Experimental results.

Exp. no.	wt% AlN (A)	L (N) (B)	SV (m/s) (C)	SD (m) (D)	WR (mm^3/m)	COF
1	0	10	1	400	0.00821	0.374
2	0	20	2	800	0.00884	0.419
3	0	30	3	1200	0.01112	0.392
4	0	40	4	1600	0.00948	0.445
5	4	10	2	1200	0.00556	0.496
6	4	20	1	1600	0.00582	0.501
7	4	30	4	400	0.00565	0.573
8	4	40	3	800	0.00605	0.498
9	8	10	3	1600	0.00469	0.662
10	8	20	4	1200	0.00482	0.598
11	8	30	1	800	0.00503	0.653
12	8	40	2	400	0.00517	0.688
13	12	10	4	800	0.00412	0.462
14	12	20	3	400	0.00407	0.380
15	12	30	2	1600	0.00402	0.411
16	12	40	1	1200	0.00396	0.449

AlN is a hard refractory ceramic and potentially attractive reinforcement. AlN possesses superior mechanical properties, least dielectric constant, enhanced electrical resistivity, good thermal steadiness, and better compatibility with aluminum alloy [16]. Because of the above-mentioned excellent properties, AlN is extensively utilized in electronic pocketing and structural industry uses [17]. Owing to the unique features of stir casting (SC) process, this is a foremost familiar method utilized commercially. Easiness and litheness of this method make this as inexpensive process and also suit for extensive production. By using SC method, complicated components can be manufactured via SC route. Nowadays, maximum consideration is given to SC route because homogenous dispersal of reinforcement particles with metal matrix can be attained [18]. SC route that produced MMCs exhibits superior properties despite of its least porosity and least crack creation. Aluminum combination developed MMCs manufactured utilizing SC process possessing enhanced properties [19]. The major issues experienced in MMC preparing are the dispersal of the reinforcement particles with the matrix amid SC. The above-stated problem can be overcome by selecting proper stirring speed, time, and temperature [20].

They [21] manufactured AlN-Al composite via squeeze casting route and studied the influence of various range cycling treatments on mechanical properties and concluded that broad range cycling treatment was the major valuable in enhancing tensile strength, and modest-range cycling treatment was preferable to improve yield strength and elastic limit. They [22] synthesized A359-AlN composites via stir and squeeze casting methods, and their mechanical properties were studied. It was concluded that adding of AlN particles from 5 to 15 wt% with A359 matrix enhances the hardness, ultimate compressive strength, and yield strength. This work [23] produced AA6061-AlN composites with various weight percentages through stir casting route and investigated the mechanical properties and stated that inclusion of AlN with AA6061 matrix enhances the macro- and microhardness, ultimate tensile strength, and yield strength. Authors [24] produced Al-AlN composites and described that elastic modulus and hardness improved drastically because of grain refinement and interface strengthening mechanism. They [25] manufactured TiB_2-AlN ceramic by hot pressing method and observed their mechanical properties. This work [26] synthesized Al-AlN composites through squeeze casting route, and their tensile strength was investigated. It has been observed that inclusion of AlN particles with Al matrix increases the tensile strength. This work [27] produced Al-AlN composite through in situ fabrication technique, and the results revealed that increasing the AlN particles increases the tensile strength. This work [28] explored the tribological properties of hybrid composites and stated that load was one of the utmost impelling parameters on the wear behavior. They [29] optimized the wear characteristics of aluminum hybrid composites and reported that load is the important parameter to attain least wear rate (WR).

From the in depth literature exploration, it is implicit that scarce research work has been done via AlN as strengthening particle through Al matrix. Therefore, the goal of the paper has been to investigate the tribological properties of AA6063-AlN composites produced via SC process. By

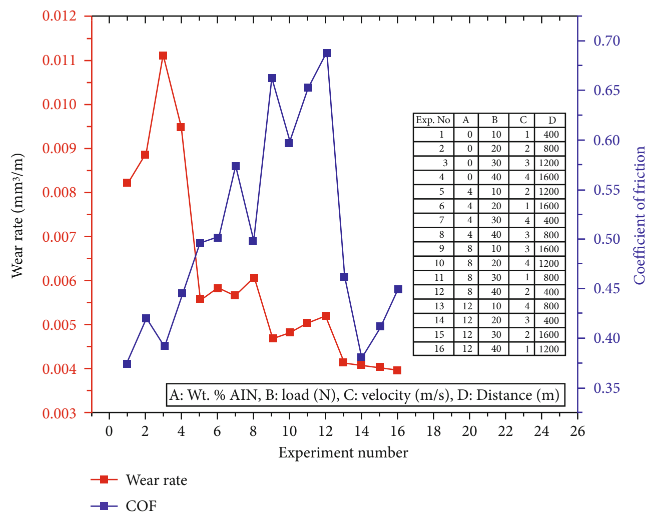


Figure 5: Rank plot for WR and COF.

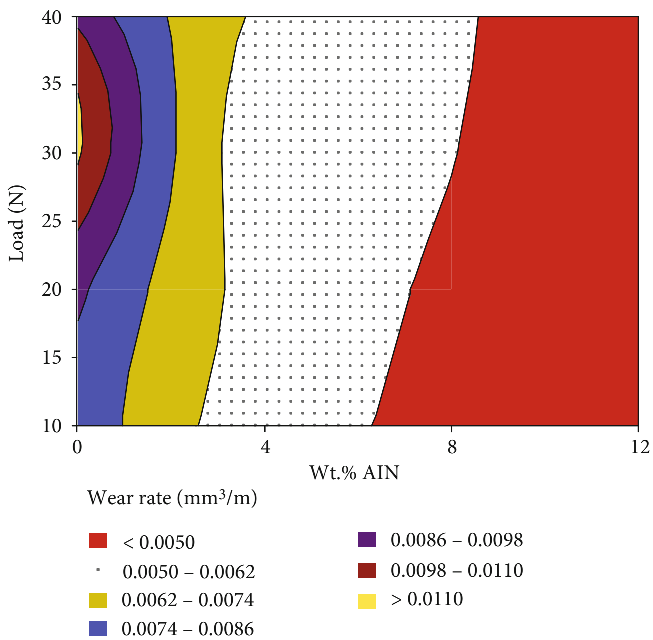


Figure 6: Contour plots wt% vs. load.

varying the reinforcing component weight percentage in the matrix composite analyzed and by using Taguchi grey relational analysis, the suitable tribological parameters obtaining optimum wear rate (WR) and coefficient of friction (COF) were identified. Such parameters included load (N), sliding velocity (m/s), and sliding distance (m) which existed in the contact zone analyzed. In this study, four-level four factors were utilized to compose the L_{16} array with prominent techniques of Taguchi.

2. Materials and Methods

2.1. Sample Preparation. AA6063 was employed as base material and AlN as reinforcement. The Chemical composition of AA6063 alloy, Si-0.44 wt%, Mg-0.56 wt%, Cu-0.02 wt%, Mn-0.03 wt%, Fe-0.46 wt%, Cr-0.03 wt%, Zn-0.66 wt%, Ti-0.02 wt%, Al remaining wt%. The essential quantity of AA6063 and AlN powder was quantified via digital weight instrument. Increasing the wettability, 2 wt% of nanomagnesium particles (45 nm) is included with AlN. Magnesium particles play a vital role in enhancing the bonding with matrix and reinforcement. AA6063 was liquefied using crucible furnace at 825°C temperature. AlN powder was heated at a 400°C temperature. Later, to attain the liquefied range, various wt% of AlN reinforcement particles were included to synthesize numerous combinations AA6063, AA6063-4 wt% AlN, AA6063-8 wt% AlN, and AA6063-12 wt% AlN. The stirring was done at a speed of 500 rpm for 5 min. The stir casting setup utilized for the present study is displayed in Figure 1.

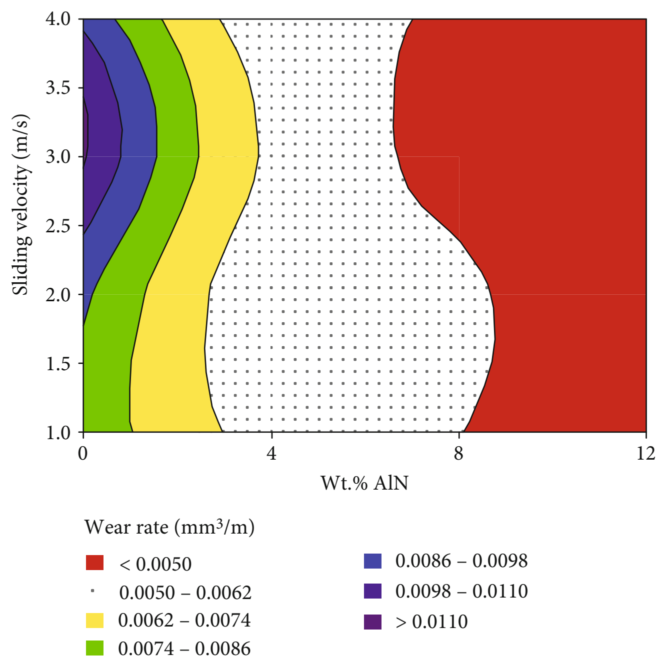


Figure 7: Contour plots wt% vs. sliding velocity.

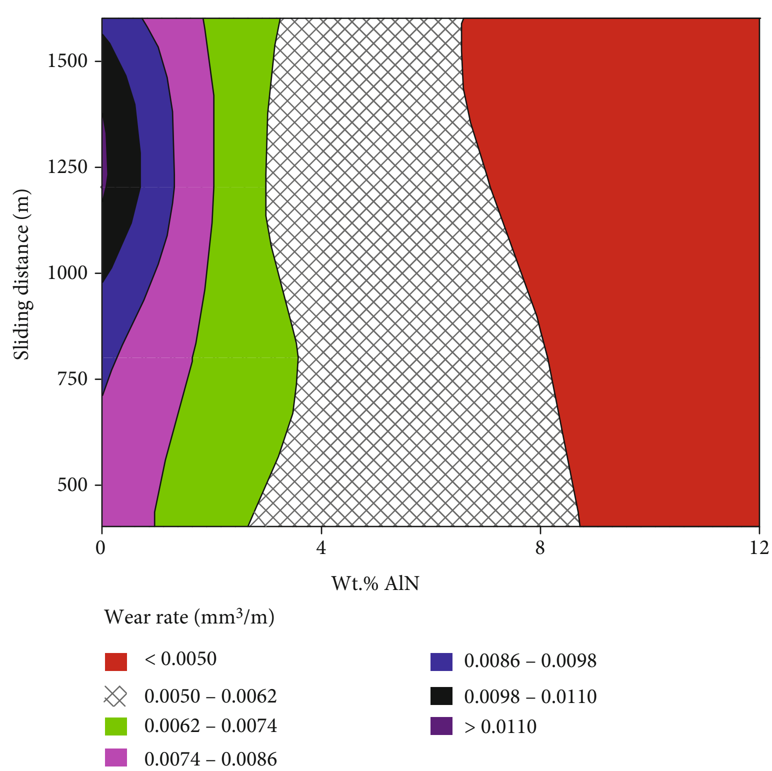


Figure 8: Contour plots wt% vs. sliding distance.

2.2. Tribotester. Figures 2 and 3 display schematic and actual pin-on-disc apparatus used for tribological analysis.

2.3. TGRA Method. Figure 4 displays the steps followed for Taguchi grey relational analysis (TGRA) process. To increase the wettability, magnesium is added in least quantity amid stirring [30]. Immediately, melted metal was distributed into a die to get needed sizes. Scanning electron microscope (SEM) inspection was carried out in the produced specimens. The tribology examination was done via pin-on-disc device DUCOM TR20-LEASTM. The dimension of the pin used was 30 mm length and 10 mm diameter

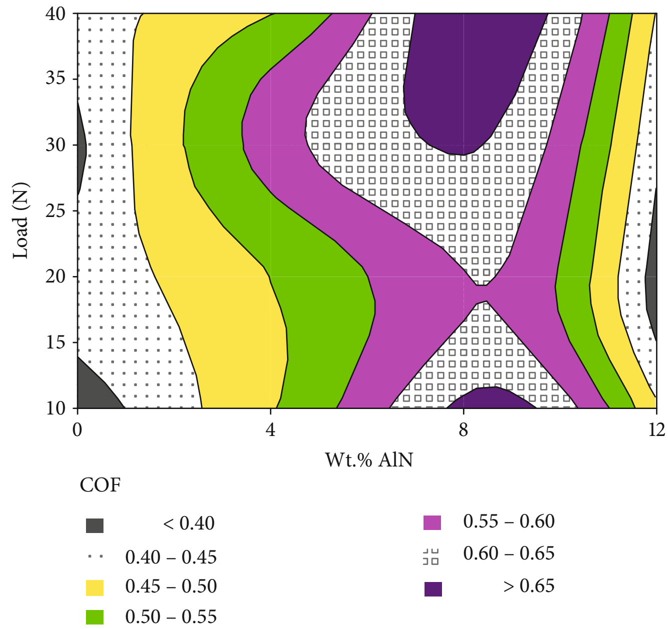


Figure 9: Contour plots wt% vs. load.

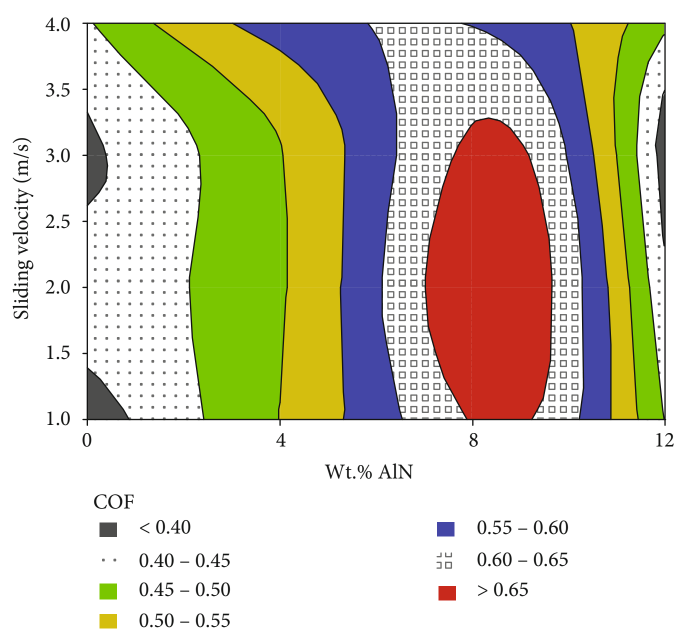


Figure 10: Contour plots wt% vs. sliding velocity.

as per ASTM G99-04 standard [31]. EN31 steel was used as disc. The tribological analysis was done at different process parameters load 10, 20, 30, and 40 N; sliding velocity 1, 2, 3, and 4 m/s; and sliding distance 400, 800, 1200, and 1600 m. The initial parameter of the surface roughness of the tested sample is 0.61 μm.

2.3.1. Multiobjective Valuation. Taguchi process merged with grey is a principal process. By grey approach, the multiobjective valuation can be transformed fair too; just response optimization and obligatory process parameter can be attained [32]. In this study, GRA was used to identify the optimal level of tribological parameters on the multiobjectives of the responses. The below formulas are used to find the optimum results shown in

$$y_i^*(x) = \frac{\max z_i(y) - z_i(y)}{\max z_i(y) - \text{mix} z_i(y)}, \quad (1)$$

$$\xi_i(k) = \frac{\Delta\min + p\Delta\max}{\Delta x_i(k) + p\Delta\max}, \quad (2)$$

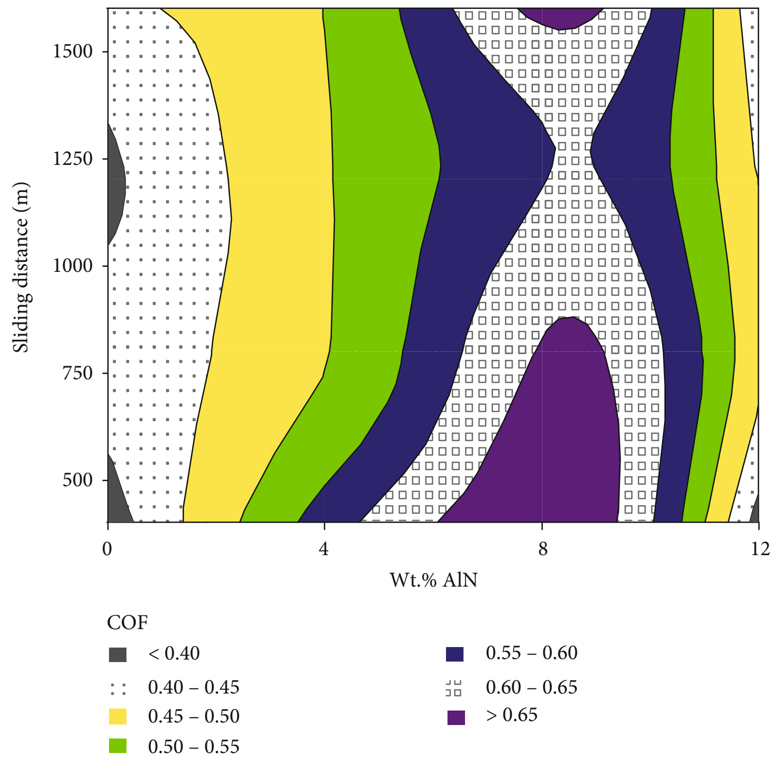


FIGURE 11: Contour plots wt% vs. sliding distance.

TABLE 2: Calculated S/N ratio and normalized S/N ratio values.

Ex. no	S/N ratio		Normalized S/N ratio	
	WR (dB)	COF (dB)	WR (dB)	COF (dB)
1	41.71314	8.54257	0.40642	1.00000
2	41.07095	7.55572	0.31844	0.85669
3	39.0779	8.13428	0.00000	0.94268
4	40.46383	7.03280	0.22905	0.77389
5	45.0985	6.09037	0.77654	0.61146
6	44.70154	6.00325	0.74022	0.59554
7	44.95903	4.83691	0.76397	0.36624
8	44.36489	6.05541	0.70810	0.60510
9	46.57654	3.58284	0.89804	0.08280
10	46.33906	4.46598	0.87989	0.28662
11	45.96864	3.70174	0.85056	0.11146
12	45.73019	3.24823	0.83101	0.00000
13	47.70206	6.70716	0.97765	0.71975
14	47.80811	8.40433	0.98464	0.98089
15	47.91548	7.72316	0.99162	0.88217
16	48.0461	6.95507	1.00000	0.76115

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

3. Results and Discussions

3.1. Wear Behavior of AA6063-AlN Composites. Wear rate (WR) and coefficient of friction examinations were made to identify the optimum parameters to obtain minimum WR and COF for the produced composite via GRA. Experiments were done according to L_{16} OA, and the results were comprehensive in Table 1. Figure 5 displays the rank plot for WR and COF. The rank plot clearly displays the experimental trials with respect to WR and COF. It is clear from the graph COF is less than the WR while increasing the trials.

3.1.1. Effect of Process Parameter on WR. Figures 6–8 display the contour plot for WR (a) wt% vs. L, (b) wt% vs. SV, and (c) wt% vs. SD. It is clear that wear rate rises with the rise in P, V, and D and declines with rise in the wt% of AlN particles. It could be well understood from Figures 5–7 that wt% of AlN particles possesses extreme impact on wear rate as related to another process parameters. Least wear rate is obtained for 12 wt% AlN particles; the major reason is 12 wt% AlN particles tarnished away from the composites creating a tiny film on the counter face at the edge outcomes in enhanced wear resistance. Moreover, the occurrence of AlN particles performs as load behavior element. The wear rate is in the sequence of 12% >8% >4% >0% wt% of AlN. When the wt% of AlN particles increases as well as load and sliding distance rises and wear rate decreases, this could be despite of the reason that with greater loads, the creation of frictional heat lessens the composite hardness which eventually outcome in pull down of the wear resistance [33].

3.1.2. Effect of Process Parameter on COF. Figures 9–11 display the contour plot for COF (a) wt% vs. L, (b) wt% SV, and (c) wt% vs. SD. From Figures 8–10, it is observable that COF declines with the rise in wt% of AlN particles, P, V, and D.

Table 3: Calculated deviation sequences, grey relational coefficient, and grade.

Ex. no	Deviation sequence		Grey relational coefficient		Grey relational grade	Rank
	WR	COF	WR	COF		
1	0.59358	0.00000	0.45722	1.00000	0.728608	5
2	0.68156	0.14331	0.42317	0.77723	0.600198	10
3	1.00000	0.05732	0.33333	0.89714	0.615238	7
4	0.77095	0.22611	0.39341	0.68860	0.541002	15
5	0.22346	0.38854	0.69112	0.56272	0.626922	6
6	0.25978	0.40446	0.65809	0.55282	0.605453	9
7	0.23603	0.63376	0.67932	0.44101	0.560164	14
8	0.29190	0.39490	0.63139	0.55872	0.595056	11
9	0.10196	0.91720	0.83063	0.35281	0.591718	12
10	0.12011	0.71338	0.80631	0.41207	0.609190	8
11	0.14944	0.88854	0.76989	0.36009	0.564992	13
12	0.16899	1.00000	0.74739	0.33333	0.540362	16
13	0.02235	0.28025	0.95722	0.64082	0.799018	4
14	0.01536	0.01911	0.97019	0.96319	0.966690	1
15	0.00838	0.11783	0.98352	0.80928	0.896397	2
16	0.00000	0.23885	1.00000	0.67672	0.838362	3

Table 4: Response table for GRG.

Level	wt% AIN	L (N)	SV (m/s)	SD (m)
1	0.6213	0.6866	0.6844	0.6990
2	0.5969	0.6954	0.6660	0.6398
3	0.5766	0.6592	0.6922	0.6724
4	0.8751	0.6287	0.6273	0.6586
Delta	0.2986	0.0667	0.0648	0.0591
Rank	1	2	3	4

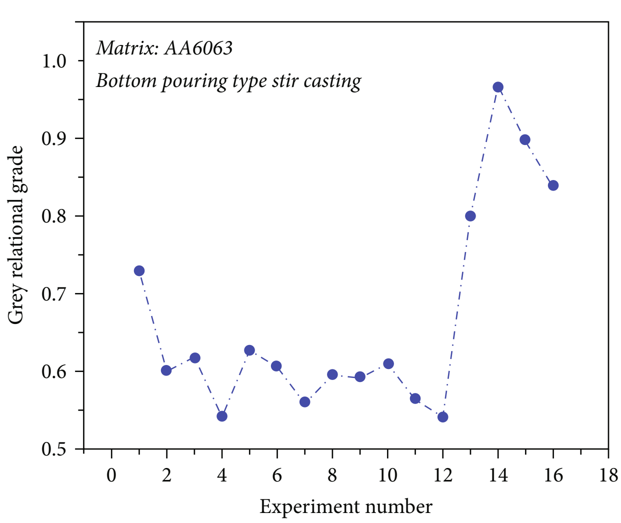


Figure 12: Grey relational grade.

The major reason for deceases in COF could be because at the time when the load rises, temperature of the worn surface enhances, which creates the composites to become soft; by this way, the COF declines [34]. As the wt% of AlN rises up to 12 wt%, the COF drops; despite of greater wt% of AlN particles, the distribution of particles is homogenous, which hints to a lesser value as linked to the another composite samples [35].

3.1.3. *Grey Relational Analysis*

(1) Multiresponse Examination. Taguchi technique combined through grey is a dominant technique. By means of grey, the multiresponse examination could be transformed simply to only retort optimization, and needed process parameter can be attained. The procedure intricate in GRA is provided below. The initial procedure is to regularize the restrained values. The fabric made famous by solitary CGF fibres could withstand a light load. As the weight percentage of CG fibres in the composite materials rises, so does the ability to support so much weight. The stress causes failure and has more excellent deformability as the percentage of CG fibre within the layered combination increases. Intended for this situation, Taguchi configuration combined through grey would be utilized for upgraded execution attributes. Table 2 shows the calculated S/N ratio and normalized S/N ratio values for the littler the better as far as WR and COF introduced. Table 3 displays the grey relational coefficient, grey relational grade (GRG), and rank for 16 experimentations. From Table 3, 1^{st} rank shows the upper GRG, which would have the improved multiexecution qualities. As of Table 3, 14^{th} trail has the optimum parameters for many execution attributes as far as WR and COF. Table 4 shows the response table for GRG. From Table 4, it is seen that 0.2986 is the limit of max-min esteem. Thus, it is presumed that wt% of AlN is most affected parameter for WR and COF trailed by L, SV, and SD. The sequence of prompting influences is in the order as enumerated wt% of AlN (0.2986), L (0.0667), SV (0.6648), and SD (0.0591). Figure 12 displays the grey relational grade. Figure 13 displays the main effects plot for GRG.

3.1.4. Analysis of Variance. The consequence of the process parameter impelling the numerous superiority features is examined via ANOVA. Table 5 displays the ANOVA for GRG for determining the utmost substantial factors. From Table 5, it can be perceived that the wt% of AlN is the supreme important factor (contributing 85.55%). The wt% of AlN has a foremost impact on the multiperformance characteristics for AA6063-AlN composites trailed by load (contributing 3.97%), sliding velocity (3.66%), and sliding distance (2.71%).

3.1.5. Confirmation Test. The optimum level of parameter was utilized to validate the output response qualities for WR of AA6063-AlN composite. The predicted and experimental values of GRG were attained via exploiting

$$\gamma_{\text{pre}} = \gamma_m + \sum_{k=1}^{n} (\gamma_i - \gamma_m). \tag{4}$$

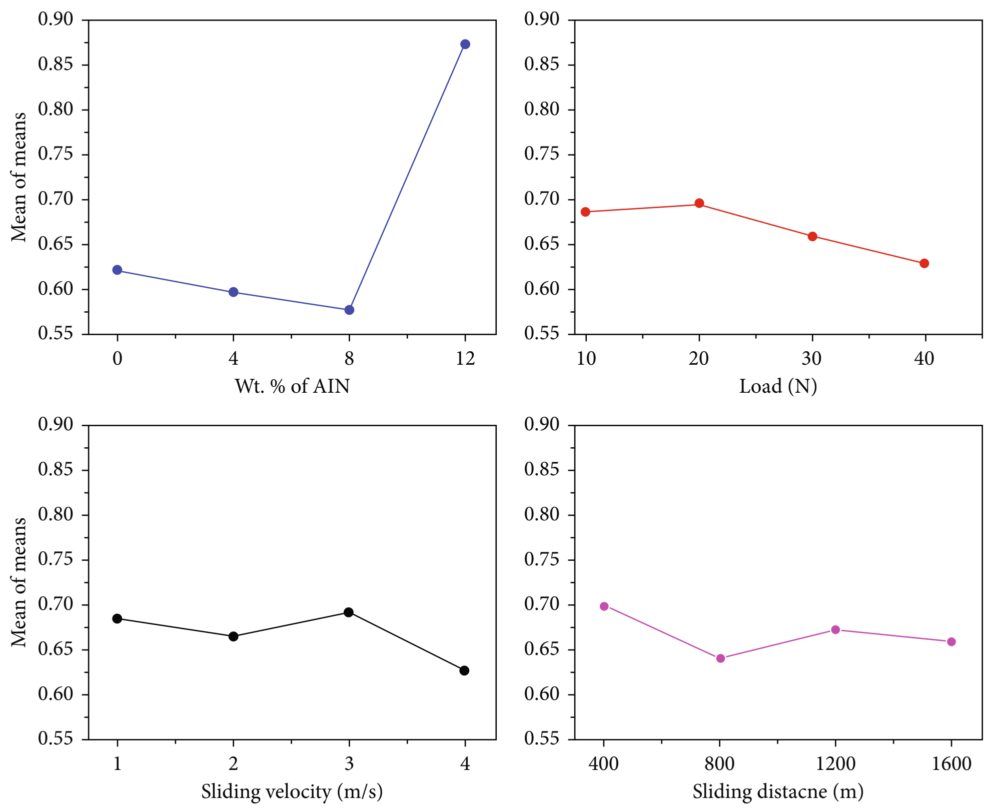


Figure 13: Main effect plot for GRG.

Table 5: ANOVA for GRG.

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*	Contribution (%)
wt% AlN - A	3	0.233985	0.233985	0.077995	20.96	0.016	85.55%
L (N) - B	3	0.010863	0.010863	0.003621	0.97	0.509	3.97%
SV (m/s) - C	3	0.010031	0.010031	0.003344	0.90	0.534	3.66%
SD (m) - D	3	0.007434	0.007434	0.002478	0.67	0.627	2.71%
Error	3	0.011163	0.011163	0.003721			4.11%
Total	15	0.273477					100%

$S = 0.0609994$; $R - \text{Sq} = 95.92\%$; $R - \text{Sq(adj)} = 79.59\%$.

Table 6: Confirmation experimental results.

Responses/level	Predicted value $A_4B_2C_3D_1$	Experimental value $A_4B_2C_3D_1$
WR (mm^3/m)	—	0.00407
COF	—	0.380
GRG	0.959317	0.799018

Table 6 displays the comparison of the predicted and experimental values of the GRG utilizing optimal level parameters, and these values are precise near to one another. The GRG percentage of predicted value is improved by 83.3%.

The normal probability plot of GRG is exposed in Figure 14. It displays that entirely, the errors are originated out to be generally dispersed alongside the straight line at 95% confidence level.

3.2. Worn Surface Analysis. Figures 15(a)–15(d) shows the shallow scratches, sliding direction, microcutting, smeared surfaces, microploughing, wear track, peelers, and delamination of AA6063-AlN composites examined via SEM. Figure 15(a) shows the shallow scratches and sliding direction. Figures 15(b)–15(d) show the worn surface of AA6063-4 wt% AlN, AA6063-8 wt% AlN, and AA6063-12 wt% AlN composites. From Figure 15(b), microcutting and smeared surfaces were observed. From Figure 15(c), microploughing, wear track, and smeared surfaces were witnessed. From Figure 15(d), peelers and delamination were witnessed. From the detailed observation, it could be clearly understood that increase in reinforcement weight percentage results in noticeable wear decline. Minimum scratches were found for composite samples, and presence of reinforcement particles prevents the scratch formation [36].

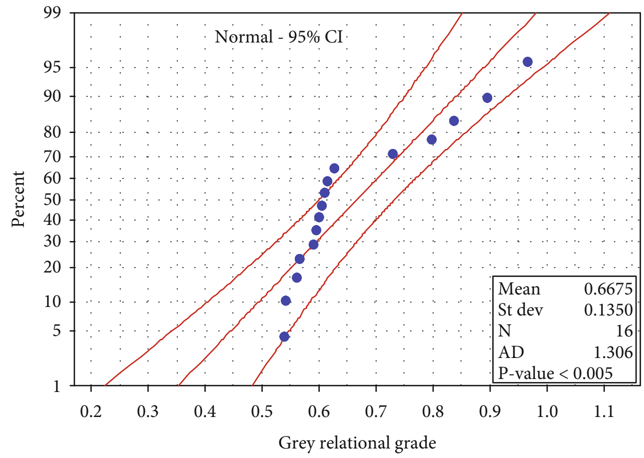
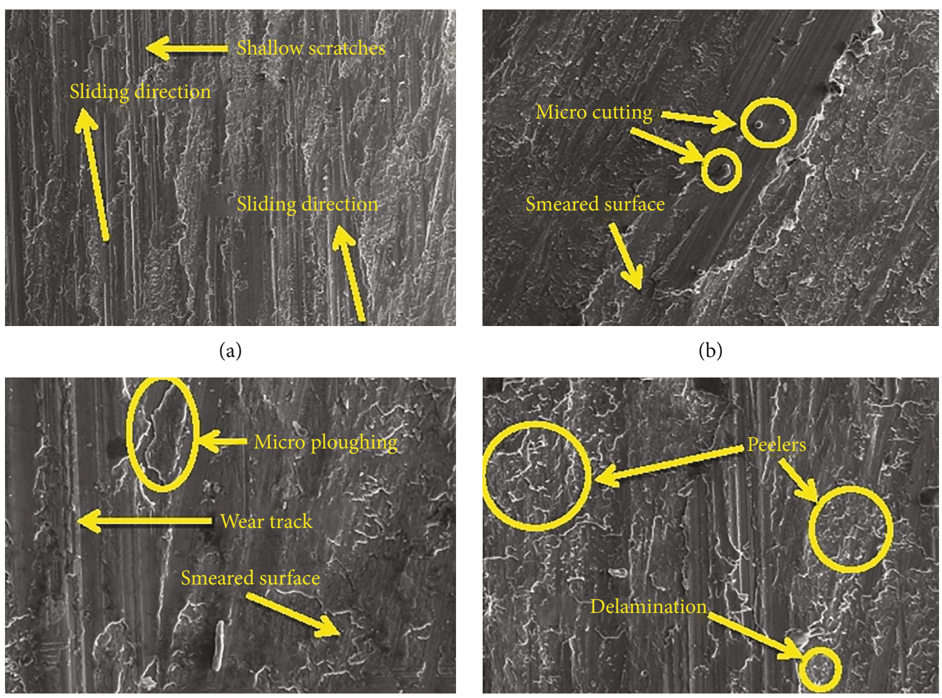


Figure 14: Normal probability plot.



(a) (b) (c) (d)

Figure 15: Worn surface morphology of (a) AA6063, (b) AA6063-4 wt% AlN, (c) AA6063-8 wt% AlN, and (d) AA6063-12 wt% AlN composites.

4. Conclusions

Stir casting is an appropriate method for producing AMCs with required characteristics for technical applications. Stir casting was used to successfully create AA6063-AlN composites. The influence of AlN on the wear behavior of the AA6063 was examined utilizing a pin-on-disc tribometer.

(i) GRA is an appropriate method for determining the best process parameters to achieve the lowest WR and COF for AA6063-AlN composites. The tribological characteristics of AA6063-AlN composites were examined by GRA, and the best parameters for achieving minimal WR and COF were discovered to be 12 wt% AlN, L 20 N, SV 3 m/s, and SD 400 m. ANOVA was used to determine the effect parameters on WR and COF responses. The GRG's estimated value percentage has increased by 83.3 percent

(ii) SEM was used to examine worn surfaces, and diverse wear mechanisms were observed for all composites

(iii) The achieved results with the same parameters and output replies were to be studied and compared in the future utilizing various optimization strategies such as neural network and fuzzy logic system

Data Availability

The data used to support the findings of this study are included within the article. Further data or information is available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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