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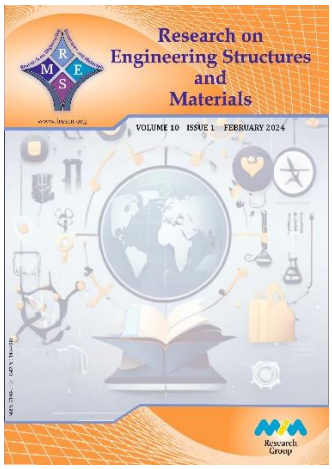

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Technical Note

Enhancing friction and wear performance in hybrid aluminum composites through grey relational analysis

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Abstract

Hybrid aluminum metal matrix composites (AMMCs) include qualities including being lightweight, very effective, and highly resistant to wear, and corrosion. The process used in this study to maximize friction and minimize wear of hybrid AMMCs involves applying grey relational analysis (GRA) to optimize the process features. Stir-casting was used to create hybrid AMMCs of the Al-6061 alloy reinforced with graphene (Gr) and silicon carbide (SiC). The experiment used Taguchi's L_{27} design, and three process parameters—normal load, sliding distance, and sliding speed—were combined with GRA to produce the maximum coefficient of friction and lowest wear rate. Al-6Gr-6SiC obtained the maximum hardness of 128 VHN and 253 MPa as tensile strength, further coefficient of friction, and wear were analyzed for the same composite., respectively. The ideal mixture of graphene (6 weight percent) and silicon carbide (6 weight percent) as reinforcement in Al-6061 alloy obtained the optimum value of frictional coefficient (0.29766) and wear (0.002588 mm^3/m), respectively.

1. Introduction

Aluminum alloys are extensively used as matrix materials in producing metal matrix composites (MMCs). These composites use the advantageous qualities of aluminum alloys while integrating reinforcing elements to attain improved mechanical, thermal, or other distinct performance characteristics. Due to their higher mechanical qualities compared to monolithic materials, aluminum alloys are deemed to be the most appropriate materials in the aerospace and automotive sectors. Aluminum alloys are popular among researchers for the creation of novel materials with improved properties because of their affordability and ease of supply [1]. A composite is a multi-stage construction that is created by combining reinforcements and a matrix. When metal is employed as the matrix material during the production process, the created composite is referred to as a Metal Matrix Composite (MMC) [2]. Aluminum alloys and two or more reinforcements are combined to create hybrid aluminum metal matrix composites (AMMCs), which have exceptional mechanical and tribological qualities [3]. Due to its high magnesium and silicon content, the aluminum alloy 6XXX series has already been utilized in the transportation and automotive industries. Due to its castability, the Al-6061 alloy is discovered to be the most popular alloy in the 6XXX family. Al-6061 alloy is used to make lightweight automobile components as well [4]. Al-6061 was used as the matrix in the current experiment, with Gr and SiC particles serving as reinforcement. Using Taguchi's L27 experimental design, the friction and wear of manufactured AMMCs were measured under ASTM standards [5]. The ideal set of process parameters at which the friction and wear values reach their optimum

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levels was found using the GRA approach [6]. A hybrid composite was formed by including graphene (Gr) and silicon carbide (SiC) as dual reinforcements in the aluminum matrix. The present literature has yet to extensively investigate the combination of graphene (Gr) and silicon carbide (SiC). Research publications often demonstrate the use of either SiC or graphene as a sole reinforcement or in combination with other reinforcements such as Al_2O_3, CNT, TiC, etc. [7]–[11]. The limited availability of literature on the particular combination of silicon carbide and graphene highlights our work's originality and unique character, enhancing the overall comprehension of hybrid composites with the capacity to reveal new synergies between these two reinforcing elements. The amount of reinforcement can be used up to 20% in metal matrix composites to avoid negative effects on the mechanical properties of the composite. Excessive amounts of reinforcement material can lead to poor bonding between the reinforcement and matrix, resulting in reduced ductility and toughness. The decision to restrict the experimentation to 12% for (6% graphene and 6% silicon carbide) despite the observed increase in hardness with higher percentages of these reinforcements may be attributed to several factors. While higher hardness is generally preferred for improved wear performance in certain applications, such as Parts like pistons, cylinder liners, and connecting rods will benefit from improved hardness and wear resistance. While higher percentages of reinforcement materials beyond 12% lead to agglomeration of the reinforcement particles.

2. Materials and Methods

2.1. Materials Used

In this investigation, Al-6061 alloy is used as the matrix or base alloy and its composition is shown in Table 1. Figure 1 shows the EDAX analysis of Al-6061 alloy that gives the elemental composition of the material. The graphene and silicon carbides are used as reinforcements and their properties are mentioned in Table 2.

Table 1. Matrix material composition

Elements	Aluminum	Magnesium	Silicon	Copper	Iron
Wt.%	97.2	1.00	0.6	0.25	0.40
Elements	Chromium	Zinc	Titanium	Manganese	
Wt.%	0.195	0.125	0.125	0.080	

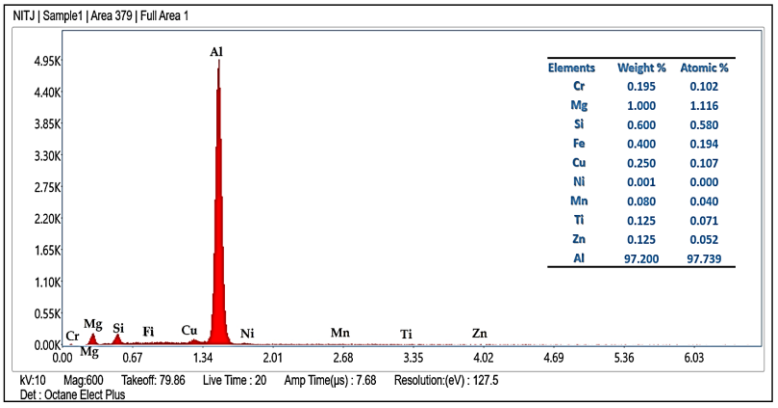

Fig. 1. EDAX analysis of Al-6061 alloy

Table 2. Reinforcement particle specifications

Reinforcement	Melting Point (°C)	Particle size	Density (g/cm3)
Gr- Powder	3650	5 nm	2.30
SiC- Powder	2700	220 µm	3.20

2.2. Methodology

2.2.1 Fabrication of Hybrid Composite

The manufacture of MMCs may be done using several different methods, most of which can be divided into liquid-state and solid-state methods [6]. In this study, Gr and SiC particles were used as reinforcements while Al-6061 was used as the matrix to create the hybrid AMMCs. With the use of a high-frequency induction heater, solid metal is first heated to 750°C in a graphite crucible until it melts or becomes semi-solid [12]. The reinforcements (graphene and silicon carbide) were then applied to the molten metal matrix after preheating. Figure 2 (a) shows the experimental setup of the stir-casting process and Figure 2 (b) shows the fabricated samples.

Fig. 2. Experimental setup and fabricated smaples

To achieve the homogeneous mixing of reinforcements into the molten matrix material, a graphite stirrer was employed. Mg and Zr are utilized in quantities of 2wt% for improved reinforcement wettability in the matrix [13]. Tetrachloroethane degasser is used to take carbon dioxide, nitrogen, and hydrogen out of the aluminum melt. To avoid melt oxidation, the entire procedure is carried out under an environment of inert gas, namely Argon. The melt is poured into the die, let to harden, and then removed to be processed further. The nomenclature of fabricated samples is mentioned in Table 3.

Table 3. Nomenclature of fabricated hybrid composites

S. No	Material	Composition
1	Al-6Gr-4SiC	90% Al + 6% Gr + 4% SiC
2	Al-4Gr-6SiC	90% Al + 4% Gr + 6% SiC
3	Al-6Gr-6SiC	88% Al + 6% Gr + 6 % SiC

2.2.2 Dry Sliding Wear

According to the ASTM G99 standard, the samples' wear behavior was examined using pin-on-disc wear test equipment [14]. The counter plate was constructed using EN31 steel,

which has a hardness of 62 HRC. The revolving steel counter circle is held against the wear test pins, which are made of composite materials and have dimensions of 10 mm in width and 30 mm in length. Between testing, the counter disc and the samples are meticulously cleaned to remove any worn material that may have adhered to the disc or sample. To make sure the level surface connected with the steel circle before testing, the surfaces of the pin tests were scrubbed against emery paper. The weight of the example is calculated using a computerized weighing offset with a high accuracy of 0.0001g after washing with the C_3H_6O solution. The weight loss is used to calculate the wear rate, which is expressed as wear volume loss per unit sliding distance [15].

2.2.3 Taguchi-Grey Relational Analysis

Using Taguchi's L27 experimental design, the friction and wear of manufactured AMMCs were measured following ASTM G-99 [16]. The ideal set of process parameters at which the friction and wear values become optimal was determined using the GRA approach with three process parameters; Load (N), distance (m), and speed (m/s). The levels of the process parameters are shown in Table 4.

Table 4. Selection of process parameters

S. No	Material	Load	Distance	Speed
1	Al-6Gr-4SiC	20	1000	1.5
2	Al-4Gr-6SiC	40	2000	3
3	Al-6Gr-6SiC	60	3000	4.5

3. Results and Discussion

3.1. Morphology of Fabricated Samples

The morphology of the manufactured samples, namely the aluminum stir-cast hybrid composites reinforced with silicon carbide and graphite particles, has a significant impact on their structural features and subsequent performance in different applications. SEM study of the base alloy (Al-6061) is shown in Figure 3(a), revealing the microstructure of the unaltered aluminum matrix. Figure 3(b) specifically examines the scanning electron microscopy (SEM) examination of Al-6Gr-4SiC samples, which shows a clear concentration of the reinforcing particles. The clustering seen may be ascribed to causes such as uneven distribution during the stirring process or inadequate dispersion of the graphite (Gr) and silicon carbide (SiC) particles inside the aluminum matrix. The observed clustering has the potential to affect the mechanical and tribological characteristics of the composite, hence impacting parameters like hardness and wear resistance.

The SEM examination of Al-4Gr-6SiC samples in Figure 3(c) reveals a surface that is much smoother in comparison to Figure 3(b). The enhanced smoothness of the Al-4Gr-6SiC samples may be ascribed to the enhanced dispersion and uniform distribution of the graphite and silicon carbide particles inside the aluminum matrix. The enhanced dispersion is probably due to the optimized processing settings used during the stir-casting process, resulting in a more homogeneous integration of the reinforcement phases. The SEM examination of Al-6Gr-6SiC samples, as shown in Figure 3(d), reveals a surface where reinforcement particles are evenly distributed throughout the aluminum matrix. The uniform dispersion seen in this picture is likely due to many variables that enhance the efficiency of processing and mixing during the stir-casting process.

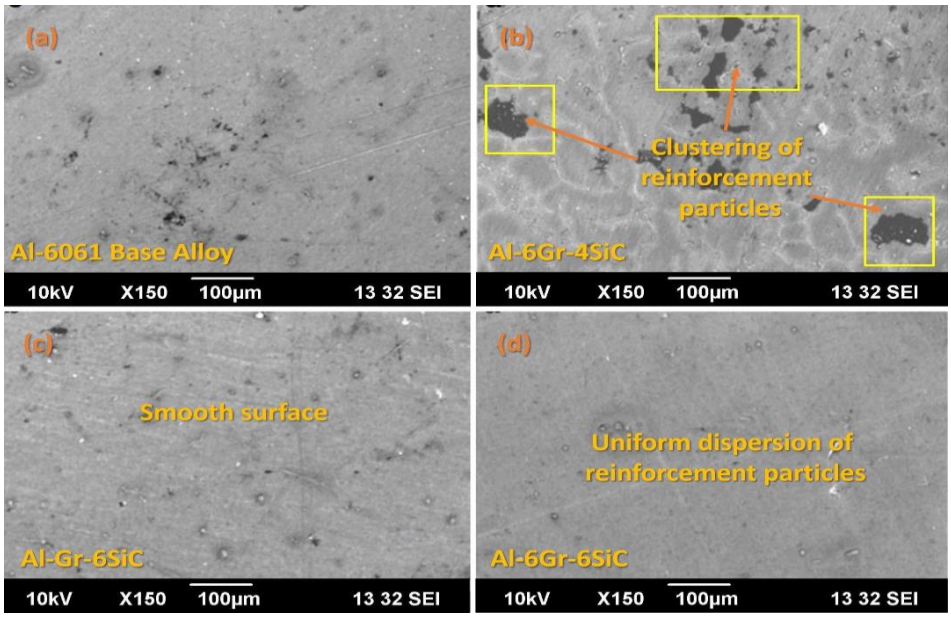

Fig. 3. Morphology of fabricated samples

3.2. Hardness and Tensile Strength

Hardness is a material property that measures its resistance to deformation, particularly when subjected to an indentation or applied load. The Vickers hardness test is a popular method that uses a diamond-shaped indenter. The hardness value is determined by measuring the diagonals of the resulting indentation. The Vickers Hardness Number (VHN) is calculated based on the applied force (200 gf) and the surface area of the indentation. Based on the hardness measurements the hardness value of the sample (Al-6Gr-4SiC) is measured to be 102 VHN. The hardness value of the sample (Al-4Gr-6SiC) is recorded as 116 VHN. The sample composed of aluminum, graphite, and silicon carbide (Al-6Gr-6SiC) has the maximum recorded hardness, with a value of 128 Vickers Hardness Number (VHN). As Table 5 indicates it is evident that the sample (Al-6Gr-6SiC) exhibits the highest level of hardness among the three samples. This finding indicates that, within the scope of this particular comparison, the composite denoted as "Al-6Gr-6SiC," which has a greater concentration of silicon carbide (SiC), exhibits the highest level of hardness among the materials subjected to testing. The heightened level of hardness may prove to be beneficial in scenarios where the ability to withstand wear and maintain hardness is of utmost importance, particularly in components that are exposed to abrasive environments.

Table 5. Mechanical properties of hybrid composites

S. No	Samples	Hardness (VHN)				Tensile Strength (MPa)			
		VHN1	VHN2	VHN3	Mean	TS1	TS2	TS3	Mean
1	Al-6Gr-4SiC	103	101	102	102	212	216	214	214
2	Al-4Gr-6SiC	114	116	115	116	235	239	237	237
3	Al-6Gr-6SiC	126	130	128	128	251	253	255	253

In a similar vein, it can be seen that the sample (Al-6Gr-6SiC) exhibits the highest value of tensile strength when compared to the other two samples as shown in Figure 4 (a). This

finding indicates that, within the context of this particular comparison, the composite denoted as "Al-6Gr-6SiC," which has a greater concentration of silicon carbide (SiC), demonstrates the greatest level of tensile strength. The heightened tensile strength is beneficial in scenarios where materials must endure substantial stretching or pulling pressures without experiencing considerable deformation or fracture. This observation suggests that the composite material being referred to exhibits the highest level of strength when compared to the other materials that were evaluated within the given context. Figure 4 (a and b) shows the tensile test samples before and after testings.

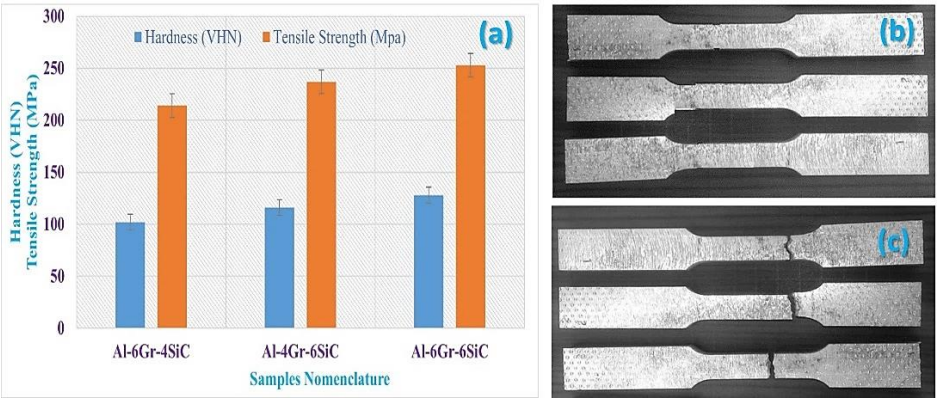

Fig. 4 Graphical representation of hardness and tensile strength

3.3. Wear and Friction Measurement

Sample No. 3 (Al-6Gr-6SiC) is selected for conducting the dry wear and friction tests due to its superior hardness and tensile strength compared to the other two samples. An increase in hardness generally signifies enhanced resistance to wear, whereas a higher tensile strength implies increased strength and endurance under applied stresses. The performance of Sample 3 is assessed in settings where friction and wear are significant variables by the implementation of dry wear and friction tests. This testing methodology has the potential to provide significant insights into the material's performance in practical scenarios, particularly when subjected to abrasive or sliding contact with various surfaces. The measured values of wear and friction are represented in Figure 5.

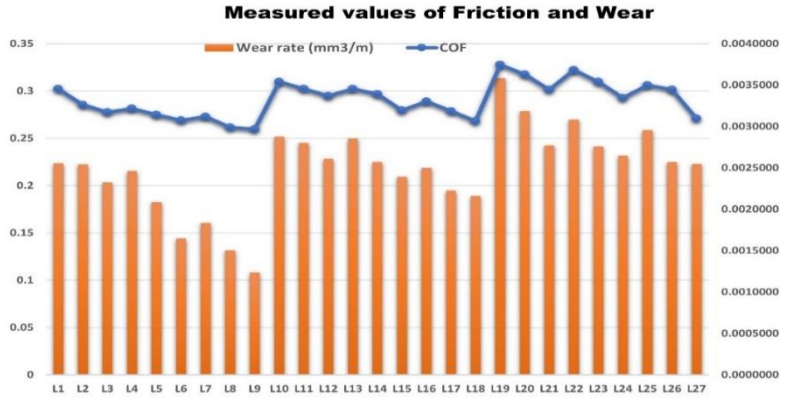

Fig. 5. Measured values for wear and friction

3.5. Optimization using the GRA Approach

Table 6 shows the orthogonal array with experimental observation after the wear test on the Pin-on-disc apparatus. In the grey relational analysis, the real several outputs were reduced to a single output. In this method, the final stage of grading was given to the output values as shown in Table 7. Getting the normalized values from the response data is the first stage in the procedure. The second stage involves calculating the departure from the sequence, and the third involves determining the grey relationship coefficient. The grey relational grades (GRG) are created in the next step by calculating the mean of the GR coefficient, and the highest rank is then used to determine the best combination of answer values [17]–[19].

Table 6. Orthogonal Array with experimental observation

S. No	Orthogonal Array	Load (N)	Speed (m/s)	Distance (m)	COF	Wear rate (mm^3/m)
1	L_1	20	1.5	1000	0.3023	0.0026
2	L_2	20	1.5	2000	0.2852	0.0025
3	L_3	20	1.5	3000	0.2776	0.0023
4	L_4	20	3	1000	0.2814	0.0025
5	L_5	20	3	2000	0.2748	0.0021
6	L_6	20	3	3000	0.2691	0.0016
7	L_7	20	4.5	1000	0.2729	0.0018
8	L_8	20	4.5	2000	0.2615	0.0015
9	L_9	20	4.5	3000	0.2596	0.0012
10	L_{10}	40	1.5	1000	0.3098	0.0029
11	L_{11}	40	1.5	2000	0.3023	0.0028
12	L_{12}	40	1.5	3000	0.2947	0.0026
13	L_{13}	40	3	1000	0.3023	0.0029
14	L_{14}	40	3	2000	0.2966	0.0026
15	L_{15}	40	3	3000	0.2795	0.0024
16	L_{16}	40	4.5	1000	0.2890	0.0025
17	L_{17}	40	4.5	2000	0.2786	0.0022
18	L_{18}	40	4.5	3000	0.2681	0.0022
19	L_{19}	60	1.5	1000	0.3278	0.0036
20	L_{20}	60	1.5	2000	0.3174	0.0032
21	L_{21}	60	1.5	3000	0.3013	0.0028
22	L_{22}	60	3	1000	0.3222	0.0031
23	L_{23}	60	3	2000	0.3098	0.0028
24	L_{24}	60	3	3000	0.2928	0.0026
25	L_{25}	60	4.5	1000	0.3060	0.0030
26	L_{26}	60	4.5	2000	0.3013	0.0026
27	L_{27}	60	4.5	3000	0.2710	0.0025

Table 7. Grey relational analysis

S. No	Normalized value		Deviation Sequence		GR Coefficient		GRG	RANK
1	0.625	0.560	0.375	0.440	0.571	0.532	0.552	10
2	0.375	0.554	0.625	0.446	0.444	0.529	0.487	16
3	0.264	0.462	0.736	0.538	0.404	0.482	0.443	20
4	0.319	0.519	0.681	0.481	0.424	0.510	0.467	17
5	0.222	0.361	0.778	0.639	0.391	0.439	0.415	22
6	0.139	0.174	0.861	0.826	0.367	0.377	0.372	25
7	0.194	0.254	0.806	0.746	0.383	0.401	0.392	24
8	0.028	0.114	0.972	0.886	0.340	0.361	0.350	26
9	0.000	0.000	1.000	1.000	0.333	0.333	0.333	27
10	0.736	0.695	0.264	0.305	0.655	0.621	0.638	4
11	0.625	0.664	0.375	0.336	0.571	0.598	0.585	8
12	0.514	0.583	0.486	0.417	0.507	0.545	0.526	13
13	0.625	0.687	0.375	0.313	0.571	0.615	0.593	7
14	0.542	0.566	0.458	0.434	0.522	0.535	0.529	12
15	0.292	0.490	0.708	0.510	0.414	0.495	0.454	18
16	0.431	0.535	0.569	0.465	0.468	0.518	0.493	15
17	0.278	0.421	0.722	0.579	0.409	0.463	0.436	21
18	0.125	0.392	0.875	0.608	0.364	0.451	0.407	23
19	1.000	0.997	0.000	0.003	1.000	0.993	0.997	1
20	0.847	0.828	0.153	0.172	0.766	0.744	0.755	3
21	0.611	0.651	0.389	0.349	0.562	0.589	0.576	9
22	0.917	0.784	0.083	0.216	0.857	0.698	0.778	2
23	0.736	0.646	0.264	0.354	0.655	0.586	0.620	6
24	0.486	0.599	0.514	0.401	0.493	0.555	0.524	14
25	0.681	0.729	0.319	0.271	0.610	0.649	0.629	5
26	0.611	0.566	0.389	0.434	0.563	0.535	0.549	11
27	0.167	0.556	0.833	0.444	0.375	0.530	0.452	19

3.5.1. ANOVA for GRG's

ANOVA was used to examine each process parameter's percentage contribution and its significance at a 95% confidence level [20]. The acquired findings of the GRGs' ANOVA are displayed in Table 6.

Table 8. Analysis of variance for GRG's

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Load (N)	2	0.240204	0.120102	13.90	0.000
Speed (m/s)	2	0.127637	0.063818	7.38	0.004
Distance (m)	2	0.006978	0.003489	0.40	0.673
Error	20	0.172867	0.008643		
Total	26	0.547685			
		R^2 = 68.44%		R^2(adj) = 58.97 %	

The findings indicated that load, distance, and sliding speed percentages contributed 61.505%, 25.124%, and 13.371%, respectively, to the ideal values of friction and wear [21]–[23]. According to Table 8, all of the criteria were found to be relevant. Figure 6 shows the residual plots for Grey Relational Grades.

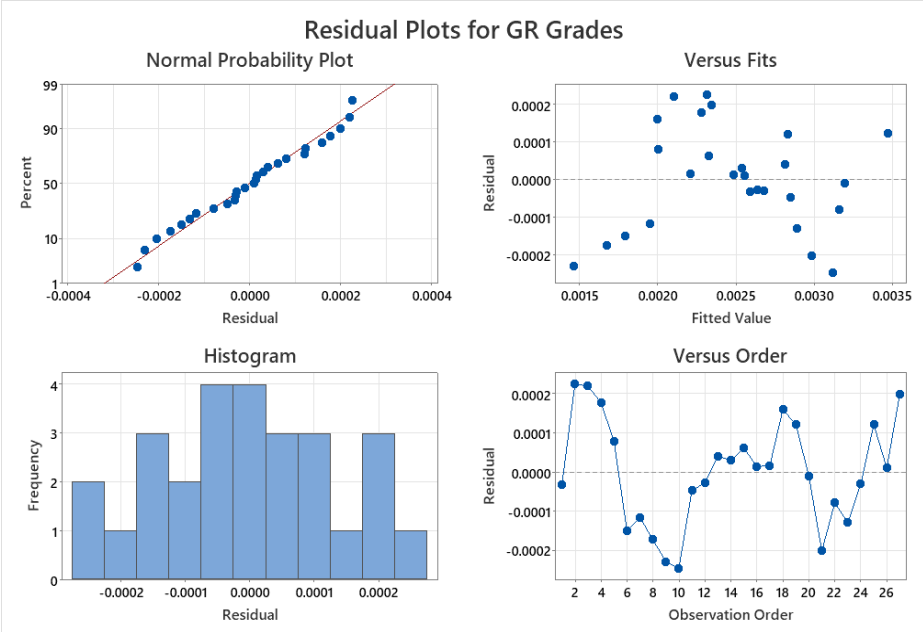

Fig. 6 Residual plots for Grey Relational Grades

3.5.2. Regression Equations

3.5.2.1 Coefficient of Friction

0.290917 - 0.01488 Load (N)_20 + 0.00028 Load (N)_40 + 0.01460 Load (N)_60 + 0.01112 Speed (m/s) 1.5 + 0.00112 Speed (m/s)_3.0 - 0.01225 Speed (m/s)_4.5 + 0.01060 Distance (m)_1000 + 0.00102 Distance (m)_2000 - 0.01162 Distance (m)_3000= 0.29776

3.5.2.2 Wear Rate (mm^3/m)

0.002492 - 0.000470 Load (N)_20 + 0.000062 Load (N)_40 + 0.000408 Load (N)_60 + 0.000314 Speed (m/s)_1.5 + 0.000008 Speed (m/s)_3.0 - 0.000322 Speed (m/s)_4.5 + 0.000253 Distance (m)_1000 - 0.000020 Distance (m)_2000 - 0.000233 Distance (m)_3000 = 0.002588 mm3/m

Figure 7 represents the effect of wear testing parameters on wear rate. The function of load is major, accounting for a substantial portion (61.505%) of the observed variation in GRG. The high F-value (13.90) and low p-value (0.000) suggest that the load has a substantial impact on the friction and wear performance of the hybrid composites, making it a highly relevant factor. Variations in load levels have a significant influence on the results. Velocity is an additional crucial factor, making a substantial contribution (25.124%) to the total variation in GRG. The F-value of 7.38 and the p-value of 0.004 indicate the statistical importance of speed. Changes in the speed at which objects slide against one another have an impact on their frictional behavior, highlighting the significance of speed in attaining the best possible performance. Distance, while it contributes to the variation (13.371%), has a lesser influence in comparison to load and speed. The F-value of 0.40 and the p-value of 0.673 indicate that distance has a relatively weak statistical significance in impacting

GRG. Variations in the distance of sliding have a relatively lesser effect on the observed tribological results. The aggregate impact of load, speed, and distance explains a significant proportion (about 68.44%) of the observed variation in GRG. The small p-values for load and speed show a strong degree of confidence in their importance, confirming their essential roles in attaining ideal tribological features. Distance, while it has an impact, is statistically less important in the context of this research.

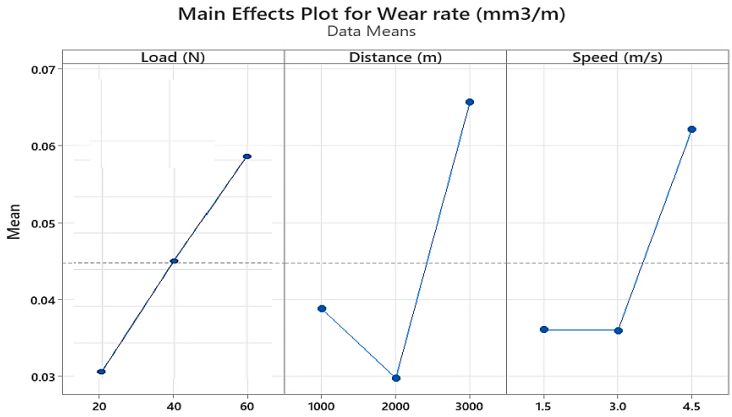

Fig. 7. Effect of process parameters on wear rate

3.6. Micrographs of Worn-Out Surfaces After Wear Test

The friction and wear of the synthesized hybrid AMMCs supplemented with graphene and silicon carbide particles are depicted in Figure 5 [24]–[26]. After the inclusion of hard reinforcement particles and their uniform dispersion in the matrix material, an increase in friction and a decrease in wear rate were noted [27]–[29]. The examination of sliding wear behavior included a comprehensive analysis under different situations, with specific attention given to worn surfaces using scanning electron microscope observations. Out of all the factors that were evaluated, the applied load was shown to be the most relevant influence on wear rate. As a result, worn-out surfaces were examined while being subjected to applied stresses of 20 N, 40 N, and 60 N.

Distinct characteristics, including peeled-off particles, delamination, and abrasive wear, were seen at a load of 20 N (Figure 8a) [30]–[32]. The impact intensified when subjected to a 40 N force (Figure 8b), exposing features such as oxidation and adhesive wear. At 60 N load, there was clear evidence of delamination and the appearance of tiny particles (Figure 8c) [33]–[35]. The inclusion of cerium oxide particles significantly improved the hardness and wear resistance of the produced specimens. Nevertheless, an increase in the hardness of the surfaces in contact resulted in the deterioration and wearing away of the material. Sliding wear may lead to the formation of a heterogeneous dispersion layer, which in turn produces debris consisting of particles of aluminum, iron, carbon, and silicon oxide. The inclusion of planar surfaces and increased rigidity, caused by plastic deformation, led to a reduction in the wear rate of the composites. The observation shows that the lowest wear rate of 0.002588 mm^3/N-m when subjected to a 60 N load, sliding over a distance of 1000 m, and at a velocity of 1.5 m/s.

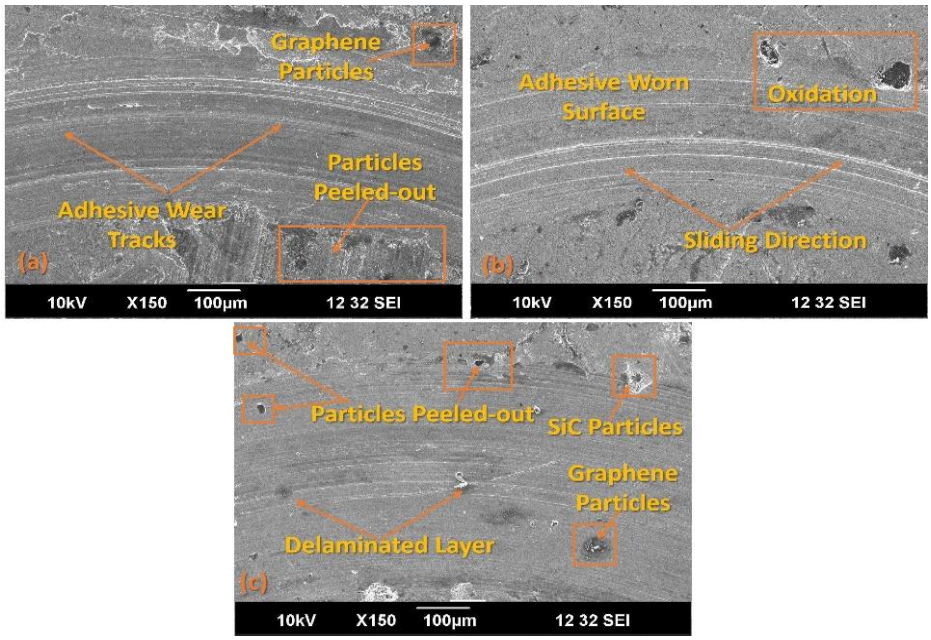

Fig. 8. (a, b, and c) SEM Morphology of Worn-out surfaces after Wear test

4. Conclusions

The main aim of the current study was to find the optimized set of stir-casting parameters using grey relational analysis, which simultaneously affects the friction and wear of the fabricated AMMCs. The conclusions of the study are mentioned below:

- The research effectively optimized the fabrication parameters for hybrid aluminum metal matrix composites (AMMCs) by using grey relational analysis (GRA) and Taguchi's L_{27} design.
- The Al-6Gr-6SiC composite proved to be the most favorable combination, demonstrating exceptional hardness (measured at 128 Vickers Hardness Number) and tensile strength (measured at 253 MPa).
- The use of both graphene (Gr) and silicon carbide (SiC) as reinforcements in the Al-6061 matrix resulted in enhanced tribological characteristics of the hybrid AMMCs.
- The chosen composite exhibited improved resistance to friction, with a coefficient of friction of 0.29766, and reduced wear rates, measuring 0.002588 mm^3/m.
- The tribological behavior of AMMCs is significantly influenced by the parameters of load, sliding speed, and sliding distance. The research highlighted the crucial roles they play in attaining ideal mechanical and frictional characteristics.
- The analysis of variance (ANOVA) findings highlighted the significant impacts of load (61.505%), speed (25.124%), and distance (13.371%) on achieving optimal friction and wear values.
- Analysis using scanning electron microscopy (SEM) of the manufactured samples showed clear microstructural traits that have an impact on the mechanical and tribological properties.
- The arrangement and spread of reinforcing particles were seen to influence hardness, resistance to wear, and the overall performance of the composite.
- The optimized composite (Al-6Gr-6SiC) shows promise for use in applications that need exceptional wear resistance and durability.

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