



Wear and dry tribological behavior of AA6061/Al₂O₃/graphite hybrid nanocomposites fabricated by stir casting

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This study is aimed at optimizing the wear and dry tribological behavior of aluminum oxide (Al₂O₃) and graphite (Gr) nanoparticles-reinforced aluminum matrix hybrid nanocomposites (AMHNCs). The cost-effective stir casting method is employed to fabricate the AA6061 alloy composites with varying Al₂O₃-to-Gr weight percentage (wt.%) ratios (1:1, 1:3, 1:5, 3:1, 3:3, 3:5, 5:1, 5:3, and 5:5), while the Taguchi approach is applied during designing the experimental procedures. The effects of reinforcement content, pouring temperature, and stirring time on wear performance are then assessed. Different loads (10, 20, and 30 N) are utilized during the wear evaluations conducted, which involved a pin-on-disk apparatus set to varying speeds (200, 400, and 600 rpm). A significant reduction in wear rate and friction in the obtained AMHNCs is observed, with the lowest wear rate ($5.9 \times 10^{-3} \text{ mm}^3/\text{Nm}$) recorded by the composite with 5 wt.% Al₂O₃ and 5 wt.% Gr processed at 700°C with 1-min stirring. The most substantial influence is exerted by Al₂O₃ content (79.56%), followed by Gr content (14.47%), pouring temperature (1.09%), and stirring time (4.88%). Microstructural analyses through field emission electron microscopy (FESEM) and energy-dispersive X-ray (EDX) confirmed uniform reinforcement dispersion, which contributed to the superior wear resistance of the AMHNCs over unreinforced alloys.

Keywords: AA6061; Al₂O₃; Graphite; Nanoparticles; Stir casting.

1. INTRODUCTION

Aluminum matrix composites (AMCs) are exceptionally strong, stiff, and wear-resistant, gaining attention from the aerospace, automotive, and structural industries [1], while their sliding wear capacities are excellent for critical automobile engine components, such as pistons, cylinder liners, and piston rings, arising from [2]. Among aluminum alloys, the AA6061 offers excellent weldability and corrosion resistance, but its relatively subpar tribological performance restricts its widespread application [3]. The diminished mechanical strength of conventional Al alloys under low temperatures can be addressed with metal matrix composites (MMCs), while hybrid nanocomposites have been engineered to elevate their performance through multiple reinforcing phases [4].

Research has been attempting to tailor the ideal reinforcement content for optimal performance of aluminum alloy 6061. Trade-offs between strength and wear resistance in AMCs can be addressed through the incorporation of combinations of hard ceramics and solid lubricants, yielding hybrid composites and reinforcement with materials, including aluminum oxide (Al_2O_3), Silicon Carbide (SiC), Titanium Carbide (TiC), Boron Carbide (B_4C), Titanium dioxide (TiO_2), Molybdenum disulfide (MoS_2), and zirconium dioxide (ZrO_2), following stir casting AA6061, which is a cost-effective and scalable approach [3].

Reinforced alloys are ideal for structural components in transport, architectural, and aerospace applications [5], where silicon and magnesium enable age hardening through precipitate strengthening [6]. A composite with uniform dispersion, refined microstructure, and improved mechanical performance is obtained from reinforcing AA6061 with Al_2O_3 through stir casting [7]. Reinforcing AA6061 Al_2O_3 and graphite (Gr) nanoparticles has also generated the exceptional strength-to-weight ratio, corrosion resistance, and formability of the 6XXX series aluminum (Al) alloys, especially AA6061 [8].

Direct metal-to-metal contact, plastic deformation, and shear stress transfer on sliding surfaces can be minimized with a continuous lubricating layer of Gr [9], a solid lubricant frequently added to reduce friction and improve wear resistance; however careful optimization is necessary as excessive Gr can compromise hardness and fracture strength [10]. Reinforcing AA6061 with Al_2O_3 has also resulted in refined grains and elevated the hardness and tensile strength [11, 12], while the incorporation of B_4C and nanographite has significantly reduced wear at moderate loads of the composites [13].

The AA6061 incorporated with TiO_2 and SiO_2 nanoparticles had enhanced wear and corrosion resistance. Scanning electron microscope (SEM) and X-ray diffraction (XRD) analyses of the hybrid system also exhibited uniform dispersion and minimal agglomeration [14]. Significantly reduced wear through abrasion and delamination wear mechanisms are also observed in AA7075 added with 2 weight percentage (wt.%) Al_2O_3 and 5 wt.% Gr [15], while the integration of 9% Al_2O_3 and 2 volume percentage (vol%) Gr yielded mechanically alloyed Al composites with a favorable wear rate of $8.5 \times 10^{-4} \text{ mm}^3/\text{Nm}$ under moderate load conditions.

Synthesizing metal matrix nanocomposites (MMNCs) is challenging, particularly when striving for uniformly dispersed nanoscale particles. Agglomeration and porosity also persistently hinder optimal MMNC [16], necessitating process optimization and advanced dispersion methods. Knowledge gaps and insufficient findings present further obstacles for improving wear and mechanical qualities by integrating combinations of micro Gr and alumina particles to refine hybrid AA6061 Al alloys produced through one-step stir casting [17]. Therefore, this study analyzed the mechanical attributes, microstructure, coefficient of friction, phase analysis, and wear behavior of Gr and alumina powder-

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 strengthened AA6061 prepared with one-step stir casting [18]. Table 1 includes a review of the studies conducted on hybrid composites using the stir casting method and AA 6061/reinforcements.

Table 1 Presents a summary of research investigations conducted on the stir casting method of (AA 6061/reinforcements) hybrid composites.

No	Reinforcements	Reference
1	Alumina - Silicon carbide – Cerium oxide	[19]
2	Silicon, zinc, graphite, chromium	[20]
3	Boron carbide -Nanographite	[21]
4	Zirconium dioxide -graphite	[22]
5	Alumina - Graphene Oxide	[23]
6	Silicon Carbide-Zirconium Dioxide	[23]
7	Nano TiC-graphite	[24]
8	Alumina-Graphite nanoparticles	Our work

2. RAW MATERIALS

Locally-sourced (Liandemetal.com) commercial AA6061 alloy plates are the base metal alloy in this study. Table 2 the standard chemical composition and chemical composition analysis of the AA6061 alloy, while the XRD patterns of the base alloy are demonstrated in Figure 1. According to international standards ASTM B209.

Table 2 Standard chemical composition and chemical composition data of the AA6061.

Elements (wt.%)	Si	Cu	Mg	Zn	Mn	Cr	Ti	Fe	Al
Standard	0.4-0.8	0.15-0.40	0.8-1.3	0.0-0.25	0.0-0.15	0.04-0.35	0.0-0.25	0.0-0.7	95.85-98.56
Measured	0.80	0.40	1.3	0.25	0.15	0.21	0.08	0.52	96.29

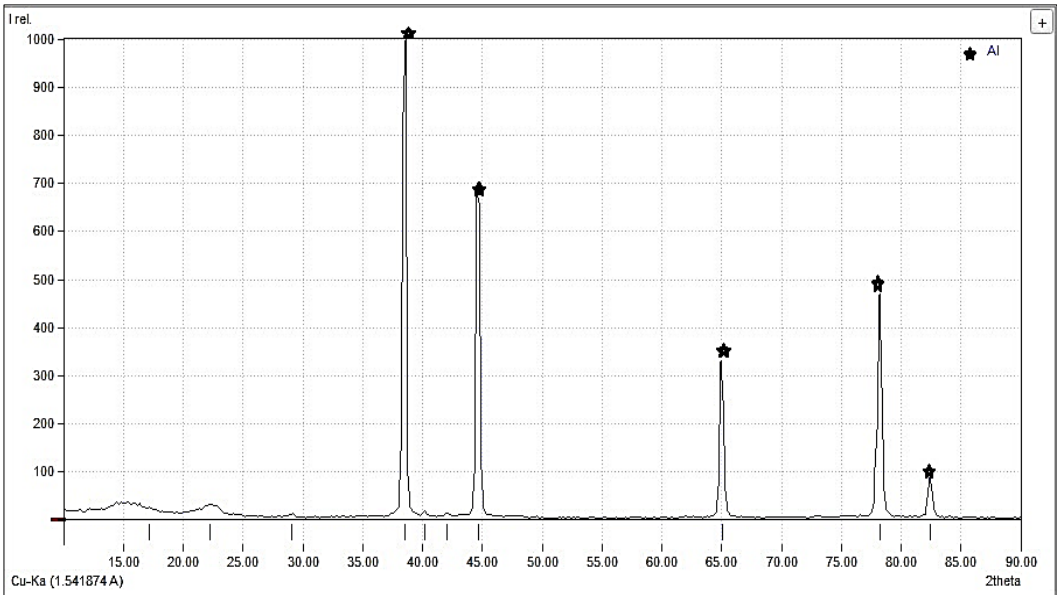


Figure 1 XRD patterns of the AA6061.

Hybrid reinforcements for AA6061 consist of hard ceramic (Al_2O_3) and self-lubricating Gr nanoparticles. In this study, the effects of different amounts of 99.9% purity Al_2O_3 nanoparticles between 40 nm and 50 nm and 99.8% purity Gr nanoparticles 50 nm to 70 nm on the AA6061 alloy are established. Both materials are supplied by Skyspring Nanomaterials, Inc., which sourced locally.

3. METHODOLOGY AND EXPERIMENT

This study simultaneously assessed the influence of multiple variables, analyzed data, and modeled the effects of various factors in the stir casting process with the Taguchi method. In this study, the inputs are defined as factors, while the outputs are response variables. During stir-casting to fabricate the AA6061 alloy composites reinforced with nanoparticles, various wt.% ratios of Al_2O_3 to Gr (1:1, 1:3, 1:5, 3:1, 3:3, 3:5, 5:1, 5:3, 5:5) are applied, with pouring temperatures of 680°C, 700°C, and 720°C, and stirring times of 1, 3, and 5 mins. Optimal experimental conditions are established with the Taguchi approach, specifically an orthogonal array. The three levels for process parameters are distributed across nine experiments utilizing the L9 array, and the design setup is presented in Table 3. The results obtained are also analyzed according to the Taguchi technique to identify the ideal conditions.

Table 3 L9 orthogonal array of composites of the AA6061 alloy reinforced with Al_2O_3 and Graphite nanoparticles.

Sample №	Al_2O_3 %	Graphite %	Pour time, °C	Stirring time, Min.
L1	1	1	680	1
L2	1	3	700	3
L3	1	5	720	5
L4	3	1	700	5
L5	3	3	720	1
L6	3	5	680	3
L7	5	1	720	3
L8	5	3	680	5
L9	5	5	700	1

First, this study melted the AA6061 Al alloy on a Gr crucible in an electric furnace equipped with a mechanical stirrer, with the casting process conducted according to the parameters listed in Table 2. Before their incorporation, the Al_2O_3 and Gr nanoparticles are preheated to 300°C for 1 hr after being wrapped in Al foil. The step is performed to improve wettability and solubility and reduce the moisture content of the materials. Premature solidification of the molten metal is prevented, and complete filling of the mold is ensured by preheating the casting mold to 350°C $\pm$ 10°C. Subsequently, magnesium (1 wt.%) is added to the molten alloy to further elevate wettability. The reinforcing particles (Al_2O_3 and Gr) are then gradually introduced into the molten metal.

A probe thermometer (infrared type) is employed to monitor the temperature of the molten metal throughout the casting process, which is continuously stirred at 450 rpm. The stir-casting process involved pouring molten Al_2O_3 and Gr nanoparticles into a permanent metal mold to form cylindrical blocks 20 mm in diameter and 150 mm long, as shown in Figure 2. Finally, the molten composites are allowed to solidify and cool to room temperature (air-cooled), producing Al matrix hybrid nanocomposites (AMHNCs). The matrix alloy (AA6061) is also cast under the same conditions for comparison with AMHNCs.



Figure 2 Casting mold.

3.1. Metallurgical and mechanical sample preparation

This study prepared samples of manufactured AA6061 (AMHNCs) using the pin-on-disc test principle. The test pin samples employed in this study are created in the CAD-CAM lab of Engineering Technical College-Baghdad based on the Boxford CNC lathe. The pin-shaped samples are 5 mm in diameter and 15 mm tall, and an initial spherical end of 5 mm radius. Hardened steel EN-32 with a surface roughness of 1Ra is utilized as the rotating disc, while the disc-shaped samples had an outer diameter of 54 mm, an inner diameter of 38 mm, and a 10 mm thickness with a hardness of 583 HV. The discs are manufactured by Micro Precision (Universal Friction and Wear Test Machine, Model-MMW-1A, BEIJING United Test CO., LTD.).

Metallography allowed the evaluation of material structure, flaws, cracks, and other indications of the AA6061 alloy and composite materials in this study, utilizing different SiC papers (1000, 2000, 3000, and 4000), while ALUMINA N.2 and water are employed to polish and prepare them for wear. Optical microstructure is also assessed with field emission electron microscopy (FESEM). Preparing metallographic samples includes sectioning, mounting, grinding, polishing, and etching. Keller's reagent, consisting of Hydrofluoric Acid 2 mL HF (48%), 3 mL hydrochloric acid (HCl) (37%), and 5 mL nitric acid (HNO₃) (65%) in 190 mL of distilled water, is employed to immerse the specimens at room temperature according to the methodology reported by [25].

4. RESULTS AND DISCUSSION

4.1. Wear test results

Dry wear tests are performed on the base alloy and hybrid composites. The wear rate, coefficient of friction, and frictional force exhibited an inverse relationship with the content of Al_2O_3 and graphite. The wear rate is directly proportional to the sliding speed, meaning that an increase in sliding speed increased the wear rate, as shown in Figures 3, 4, and 5. The optimum conditions for minimizing the wear rate of Aluminium Matrix Hybrid Nanocomposites (AMHNCs) after stir casting are identified through experimental trials, as shown in the table. The reduction in wear rate is attributed to the effective homogenization of the Al_2O_3 and graphite nanoparticles within the AA6061 matrix, governed by the selected process parameters.

The best result is achieved in Experiment L9, which used 5% Al_2O_3 , 5% graphite, a pouring temperature of 700 °C, and a stirring time of 1 minute, yielding the lowest wear rate value of $(5.9 \times 10^{-3} \text{ mm}^3/\text{Nm})$. The next best result is observed in Experiment L8, with 5% Al_2O_3 , 3% graphite, a pouring temperature of 680 °C, and a stirring time of 5 minutes, giving a wear rate of $(6 \times 10^{-3} \text{ mm}^3/\text{Nm})$. Among all the variables studied, the Al_2O_3 content had the greatest influence on wear rate (79.56%), followed by graphite content (14.47%), pouring temperature (1.09%), and stirring time (4.88%). These factors collectively contributed to 100% of the observed variation.

The ranking of influential parameters on the wear rate of AA6061/(Al_2O_3 + Gr) composites after stir casting is as follows: Al_2O_3 content had the most significant effect, followed by graphite content, stirring time, and finally pouring temperature. In addition to wear performance, the hardness of the composite increased significantly under optimal stir casting conditions. Overall, the results confirmed that applying the appropriate parameters reduced the wear rate, coefficient of friction, and frictional force of the AMHNCs, indicating improved tribological performance.

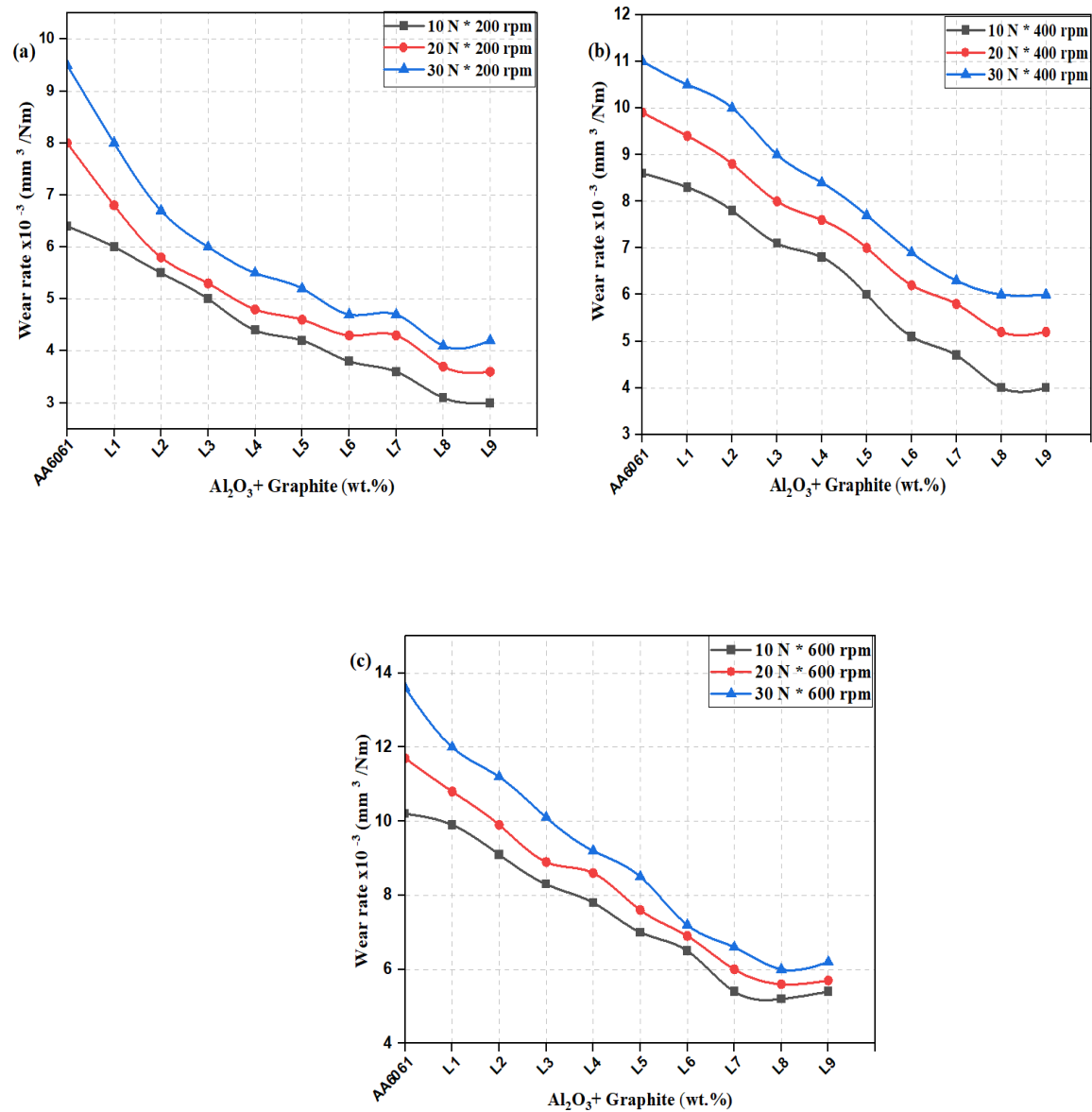


Figure 3 Wear rate of AA6061 alloy-based AMHNCs as a function of wt.% Al_2O_3 +Graphite:(a) variant load with 200 rpm, (b) variant load with 400 rpm, (c) variant load with 600 rpm.

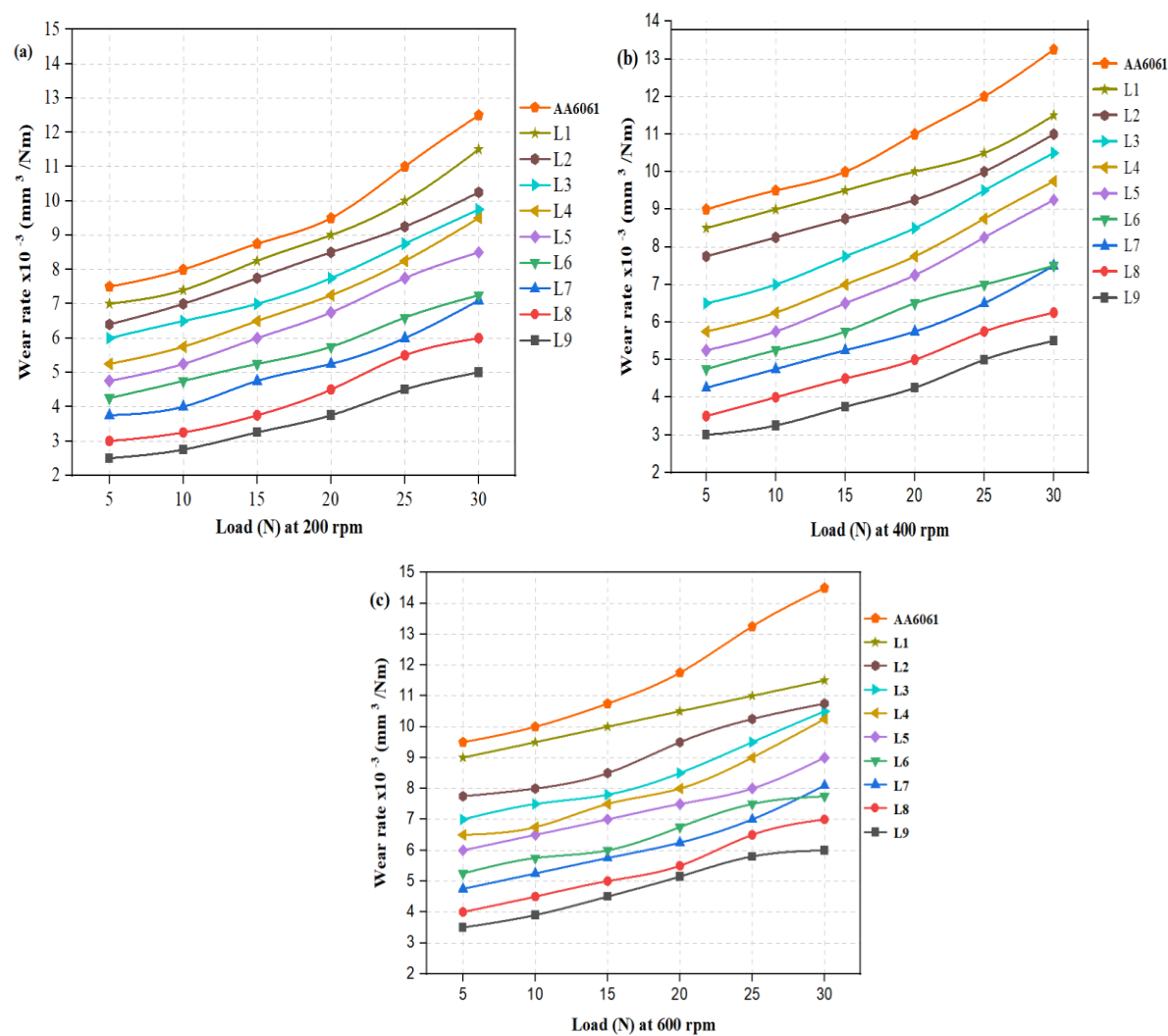


Figure 4 Wear rate of AA6061 alloy-based AMHNCs as a function of applied load: a) variant Al₂O₃+Graphite content with 200 rpm, (b) variant Al₂O₃+Graphite content with 400 rpm, (c) variant Al₂O₃+Graphite content with 600 rpm.

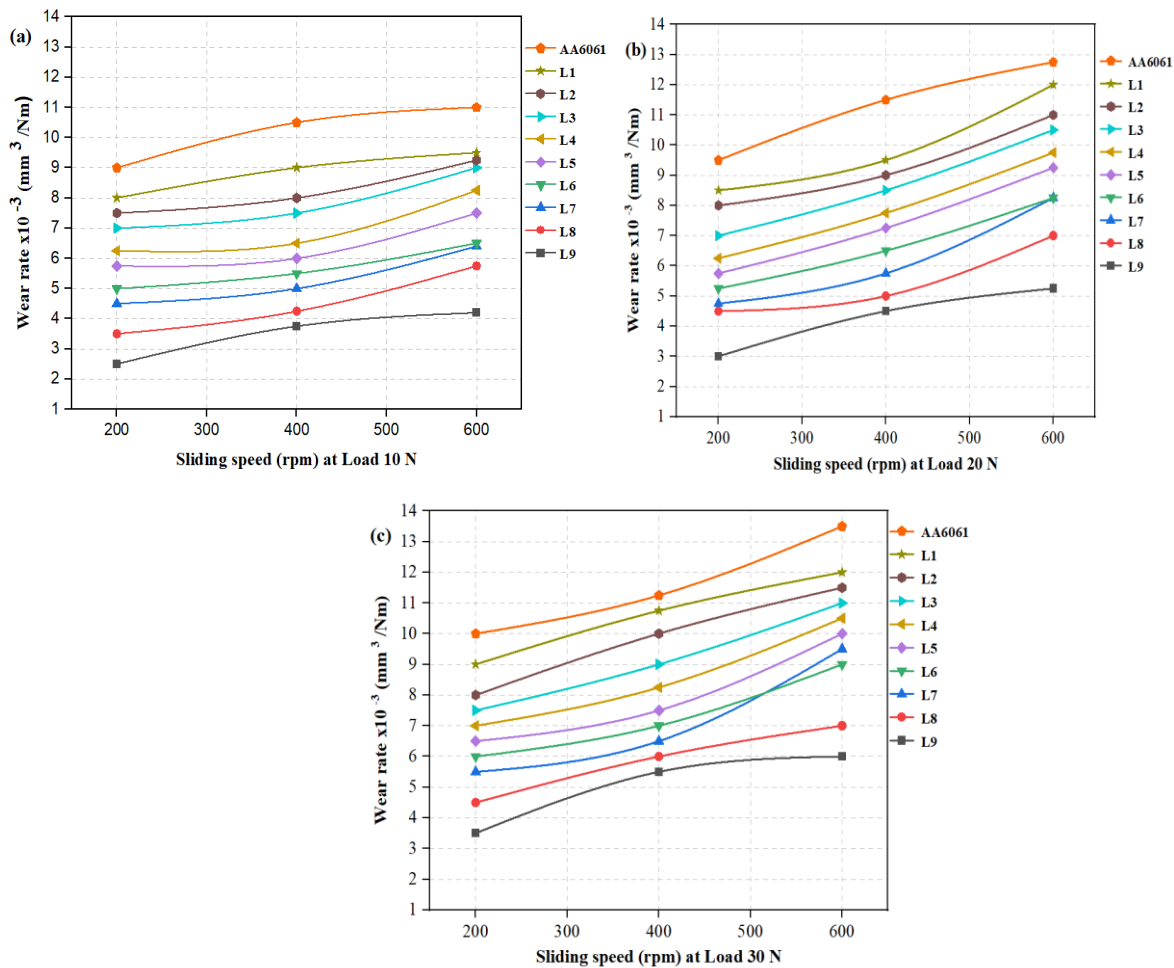


Figure 5 Wear rate of AA6061 alloy-based AMNCs as a function of sliding Speed: a) variant Al_2O_3 +Graphite content with 10 N, (b) variant Al_2O_3 +Graphite content with 20 N, (c) variant Al_2O_3 +Graphite content with 30 N.

4.2. Friction and wear performance

The friction coefficient and wear performances of AA6061 reinforced by Gr and Al_2O_3 are shown in Figures 6, and 8 and Figure 9. The surfaces of the samples are also investigated by scanning electron microscopy in order to comprehend the coefficient of friction and wear performances of unreinforced aluminum alloy and its composites. The frictional coefficient behaviors of AA6061 strengthened with Gr and Al_2O_3 powders have been tested at a spindle speed of 600 RPM and 30N of normal load. Figure 6 shows a high difference between the coefficient of friction (COF) behaviors of the four samples. For sample AA 6061 (Al (100 wt%)/Gr (0 wt%)/ Al_2O_3 (0 wt%)), unstable coefficient friction behaviors are observed due to direct contact with no tribo-film formation between worn surfaces. This behavior produced a rough surface with clear grooves and cracks (Figure 7 a). For In sample L6 (Al (92 wt%)/Gr (3 wt%)/ Al_2O_3 (5 wt%)), the tribobehavior is enhanced by lowering the COF by about 35% compared to AA 6061. The curve shows COF stable behavior until it reaches 100s, after which its value increases with time. This different behavior is due to the formation of an un-uniform and/or discontinuous tribo-film between contact surfaces, which led to producing surfaces with shallow grooves and pits (Figure 7 b).

For sample L8 (Al (92 wt%)/Gr (5 wt%)/Al₂O₃ (3 wt%)) and L9 (Al (92 wt%)/Gr (5 wt%)/ Al₂O₃ (5 wt%)), stable COF behavior is observed throughout the test time and produced a smooth contact surface (Figure7 c). This resulted in COF being decreased by about 58% as compared to AA 6061, which is attributed to the development of a stable tribo-layer between the worn surfaces. The COF as a function of Al₂O₃/Gr content and applied loads is shown in Figure 8. The COF variation with applied load is determined at 600 rpm spindle speed and 600 sec test time. All cases show an inverse proportionality relation between the measured COF and the applied load. This behavior is expected for sliding metal contact surfaces because applied load results in increased oxidation of the worn surfaces[26].

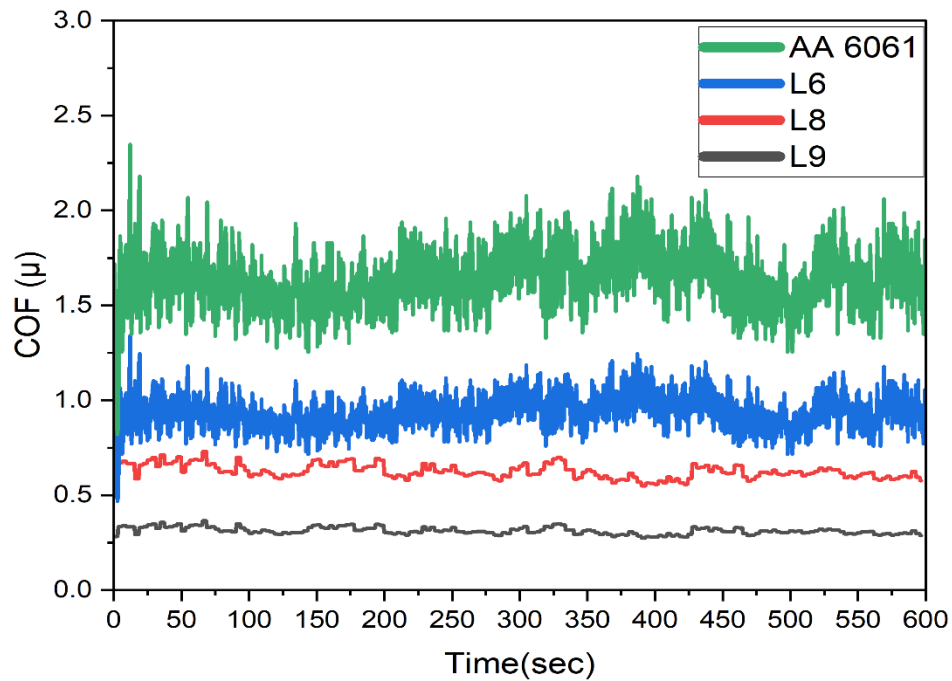


Figure 6 Coefficient of friction behaviors of AA6061\ Al₂O₃\ Graphite nanocomposites.

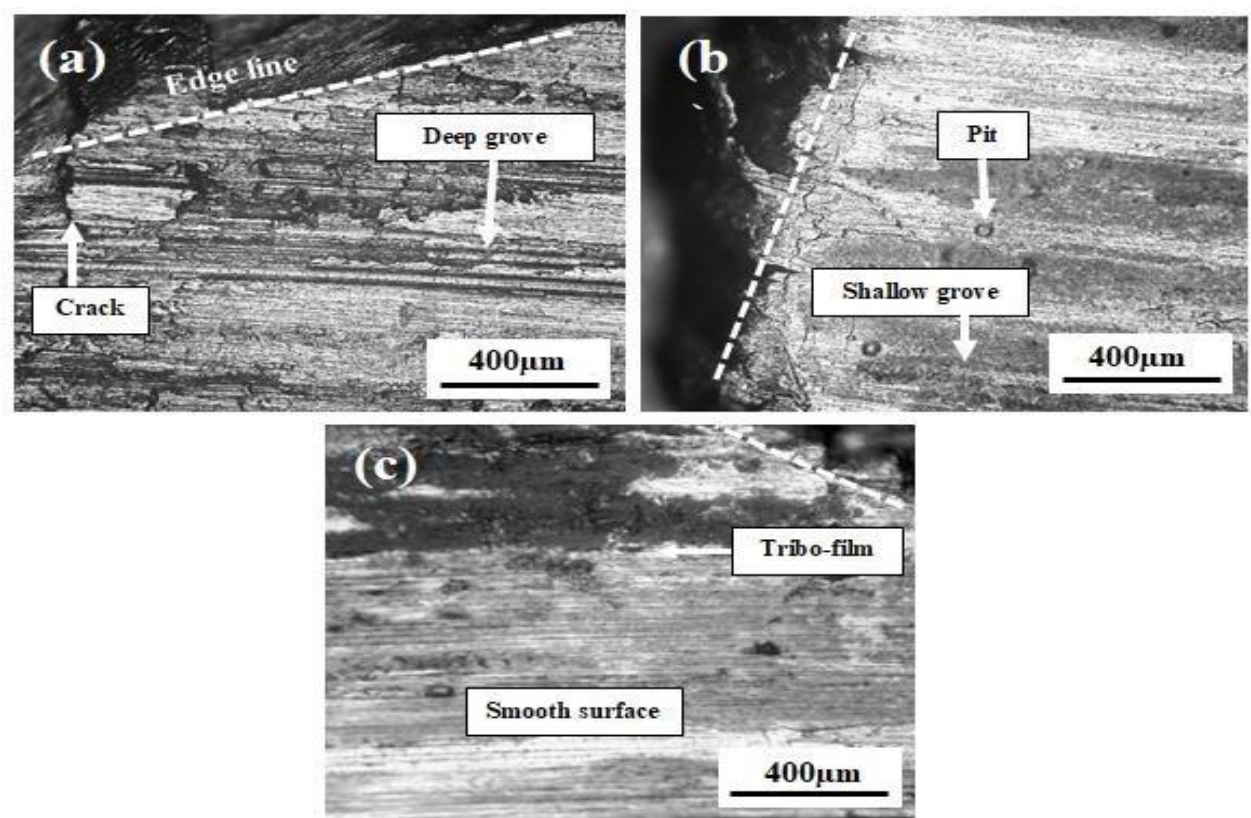


Figure 7 Frictional AMHNCs surfaces at 30N applied load; (a) AA6061, (b) L6, (c) L8 & L9.

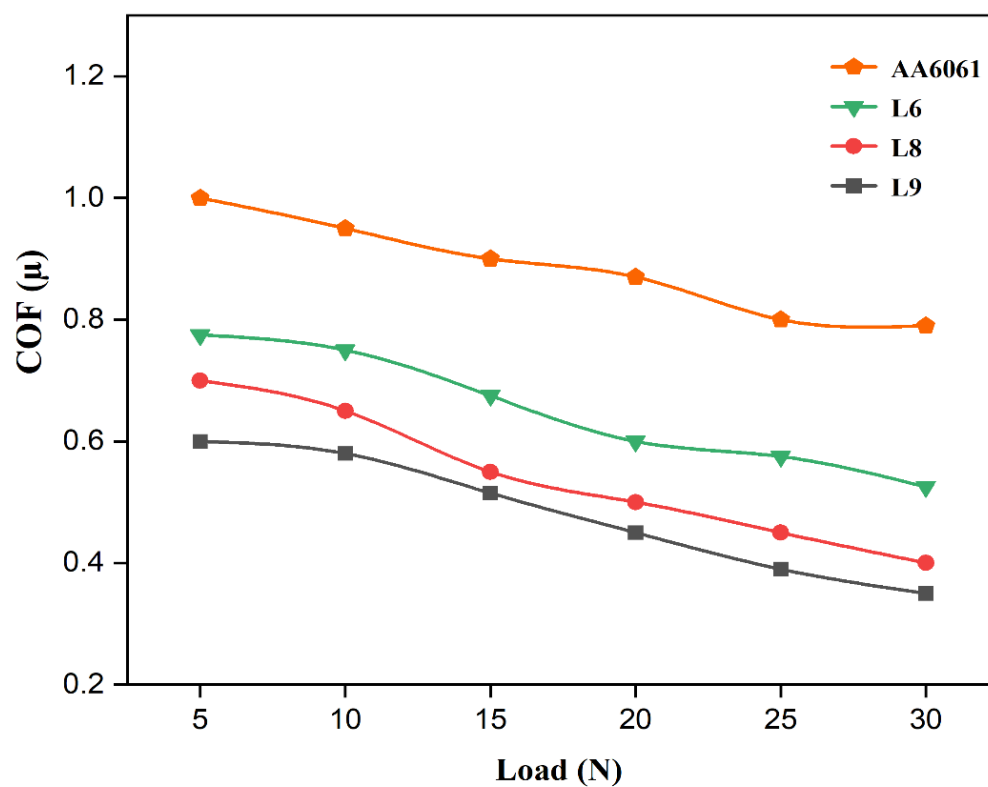


Figure 8 Effect of Al_2O_3 /Graphite content on the coefficient of friction of AMHNCs under multi-applied loads.

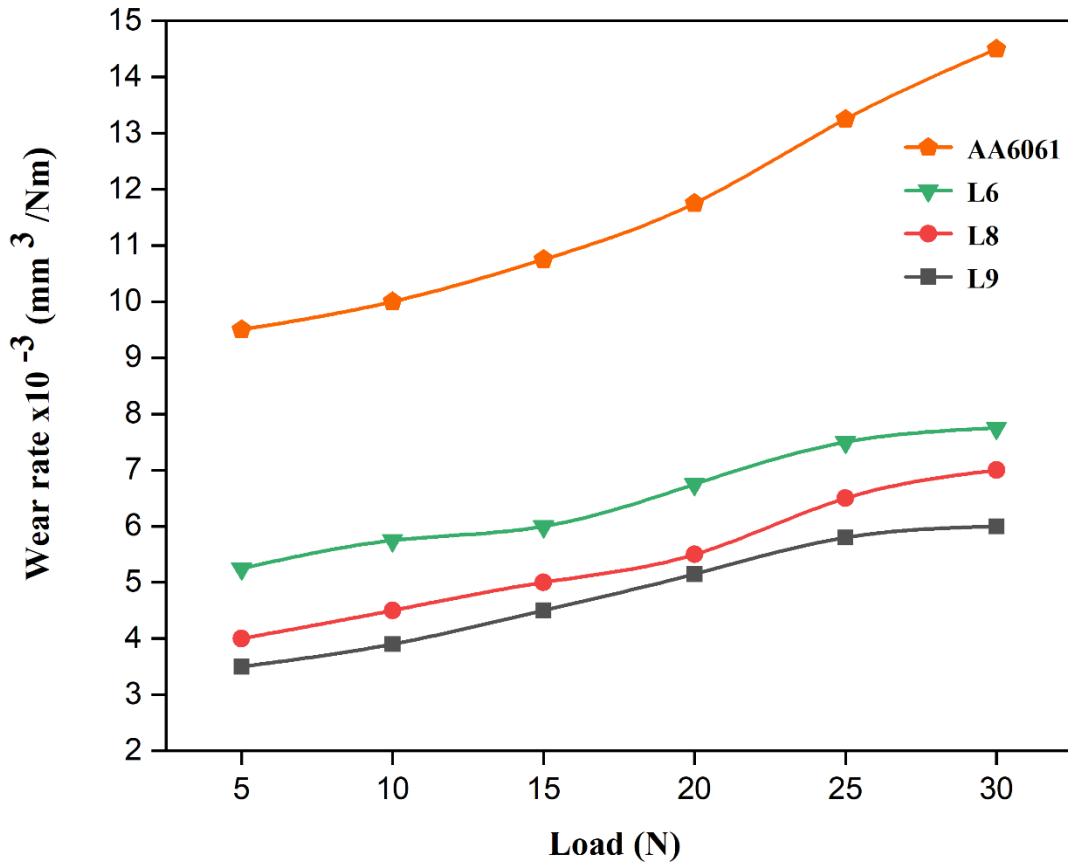


Figure 9 Effect of Al₂O₃/Graphite content on the wear rate of AMHNCs under multi-applied loads.

4.3. Optimal wear measurement parameters

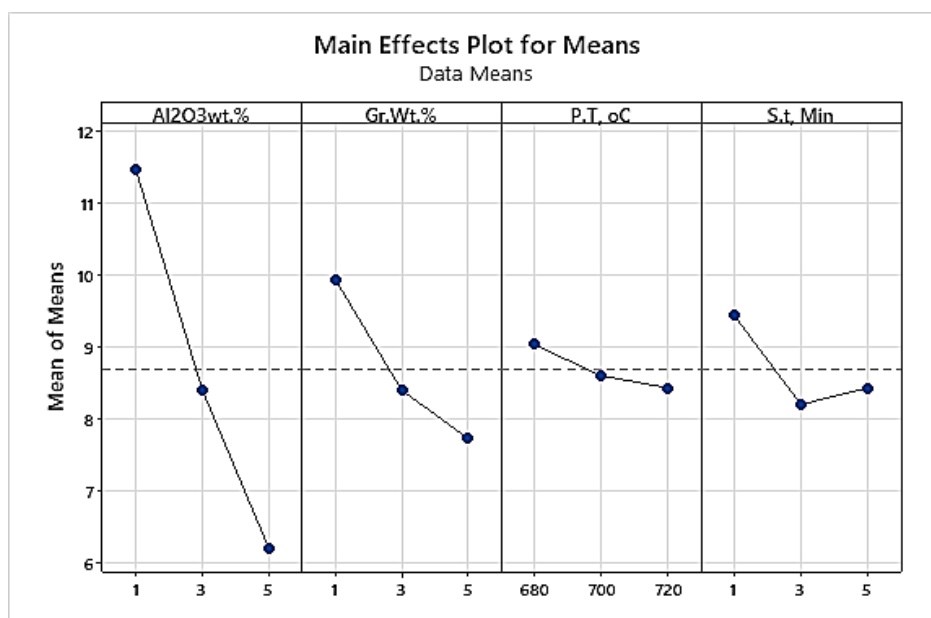
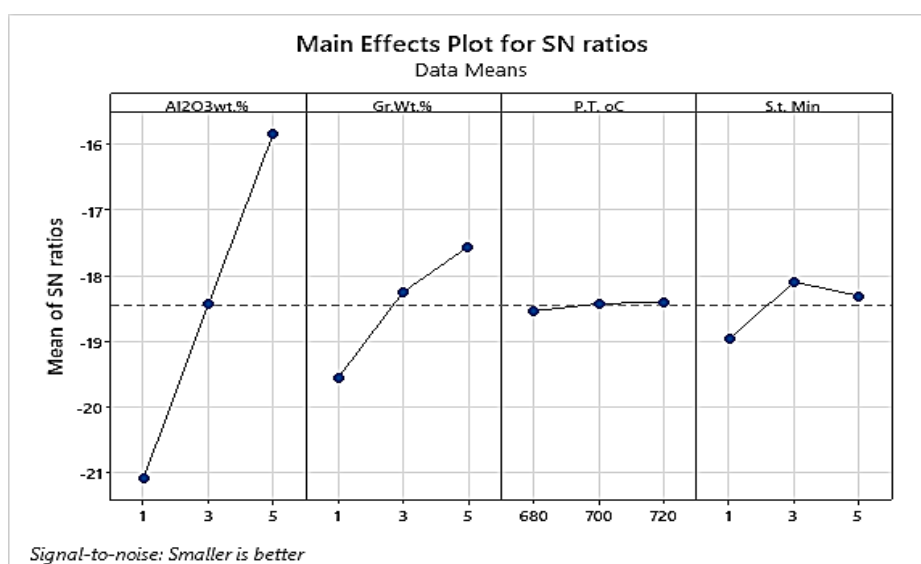
This study applied the Taguchi method to design the conditions and parameters for assessing the lowest wear rate and highest wear resistance of the AMHNCs. The highest load of 30 N and the fastest sliding speed of 600 rpm at a constant 10 minutes are set to determine the wear rate mechanism of the evaluated samples under substantial load and time. A wide range of wear rates is documented by the various levels, variables, and parameters. Equation (1) represents the regression equation for the wear rate test utilized in this study.

$$\text{Wear rate} = 8.689 + 2.778 \text{ Al}_2\text{O}_3\text{wt.\%}_1 - 0.2889 \text{ Al}_2\text{O}_3\text{wt.\%}_3 - 2.489 \text{ Al}_2\text{O}_3\text{wt.\%}_5 + 1.244 \text{ Gr.wt.\%}_1 - 0.2889 \text{ Gr.wt.\%}_3 - 0.9556 \text{ Gr.wt.\%}_5 + 0.3444 \text{ P.T, } ^\circ\text{C}_680 - 0.08889 \text{ P.T, } ^\circ\text{C}_700 - 0.2556 \text{ P.T, } ^\circ\text{C}_720 + 0.7444 \text{ S.t, Min}_1 - 0.4889 \text{ S.t, Min}_3 - 0.2556 \text{ S.t, Min}_5 \quad (1)$$

Based on the data listed in Table 4, the lowest wear rate values are obtained by the 5% Al₂O₃ and 5% Gr AA6601 sample that is subjected to 720°C pouring temperature and 3 mins stirring. The mean and SNs ratio in Figures 10 and 11 also supported the findings.

Table 4 Wear rates based on the Taguchi (L9) experiments.

Exp.	Al ₂ O ₃ %	Gr%	P.T, °C	S.t, Min	Wear Raet*10 ⁻³ (mm ³ /Nm)	SNRA1	MEAN1
L1	1	1	680	1	13.8	-22.7976	13.8
L2	1	3	700	3	10.6	-20.5061	10.6
L3	1	5	720	5	10.0	-20.0000	10.0
L4	3	1	700	5	9.3	-19.3697	9.3
L5	3	3	720	1	8.6	-18.6900	8.6
L6	3	5	680	3	7.3	-17.2665	7.3
L7	5	1	720	3	6.7	-16.5215	6.7
L8	5	3	680	5	6.0	-15.5630	6.0
L9	5	5	700	1	5.9	-15.4170	5.9

**Figure 10** Mean response for wear rate of AMHNCs for different variables and levels.**Figure 11** SNs ratio response for wear rate of AMHNCs for different variables and levels.

The results obtained revealed the optimal conditions for minimizing the wear rate of AMHNCs after stir casting, including improved homogenization, 720°C pouring temperature, and 3 min stirring period. An ideal wear rate of 5.9×10^{-3} is achieved by the AMHNC sample incorporated with 5% Al₂O₃ and 5% Gr. Meanwhile, the AMHNC reinforced with 5% Al₂O₃ and 3% Gr, fabricated with a pouring temperature of 680°C and stirred for 5 mins, documented 6×10^{-3} .

Based on the data in Tables 5 and 6, the wear rate of the AMHNC samples produced in this study is primarily influenced by the Al₂O₃% content (79.56%), followed by the Gr% content (14.47%), stirring time (4.88%), and pouring temperature (1.09%). The hardness values of the composite samples also rose significantly after applying the optimal stir casting conditions. Consequently, the properties of the AMHNCs are enhanced.

Table 5 Wear rate analysis of variance (ANOVA) results.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution%
Al ₂ O ₃ %	2	41.9822	20.9911	*	*	79.56
Gr%	2	7.6356	3.8178	*	*	14.47
P.T	2	0.5756	0.2878	*	*	1.09
S.t	2	2.5756	1.2878	*	*	4.88
Error	0	*	*	*	*	0
Total	8	52.7689	*	*	*	100

Table 6 Rank of the factors that influence wear rate.

Level	Al ₂ O ₃ wt.%	Gr.Wt.%	P.T, °C	S.t, Min
1	-21.10	-19.56	-18.54	-18.97
2	-18.44	-18.25	-18.43	-18.10
3	-15.83	-17.56	-18.40	-18.31
Delta	5.27	2.00	0.14	0.87
Rank	1	2	4	3

4.4. Microstructure evaluation (FESEM)

Essential aspects facilitating the procurement of homogenous discontinuous reinforced nanocomposite materials are the microstructure, phase, and distribution of reinforcing nanoparticles. Figures 12 to 15 illustrate the FESEM images of the Al₂O₃ and Gr distribution in the matrix of the AA6061/Gr/Al₂O₃ composites fabricated in this study at various magnifications. Comparisons between the alumina and Gr in the hybrid composite and the Al base alloy (AA6061) provided clarity. Based on the microstructures and phase images, the hybrid nanocomposite samples made from AMHNCs exhibited superior reinforcing material proportions.

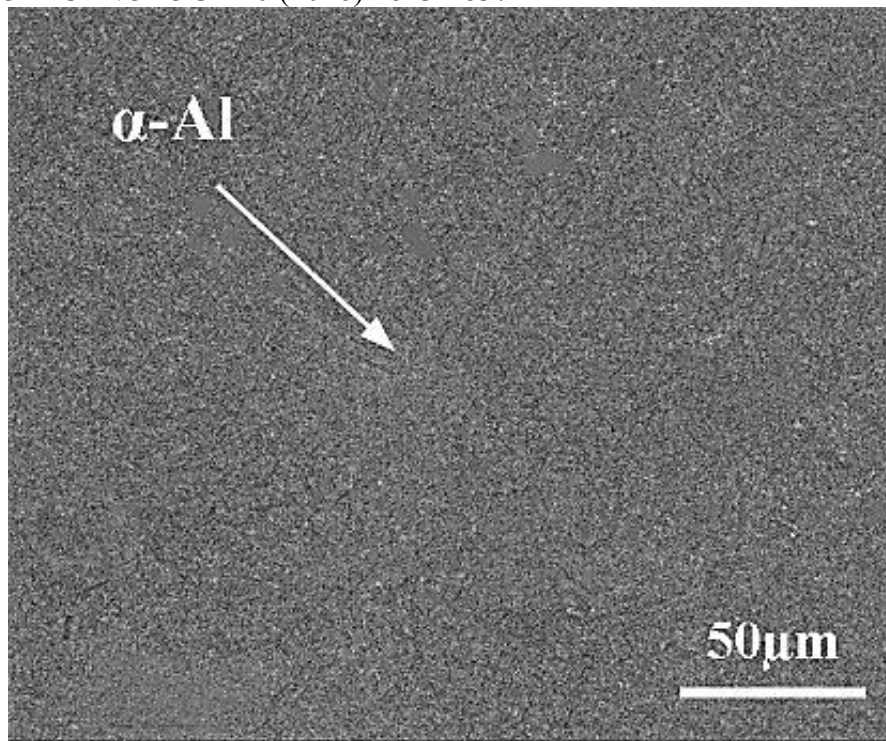


Figure 12 FESEM micrograph of the AA6061 alloy grains.

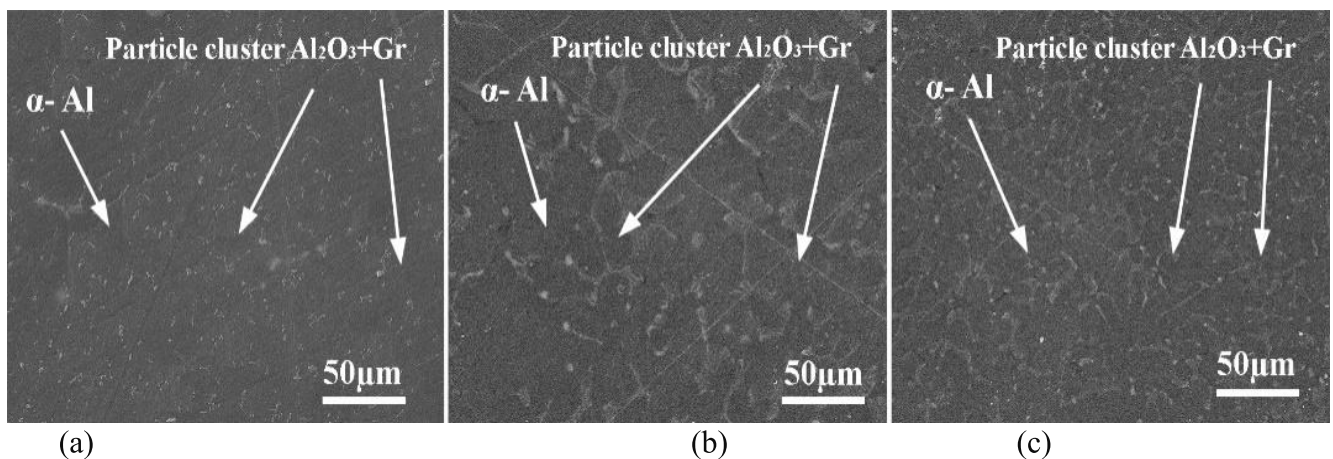


Figure 13 FESEM of the hybrid composites (a) AA6061 + 1% Al_2O_3 + 1% Gr, (b) AA6061 + 1% Al_2O_3 + 3% Gr, and (c) AA6061 + 1% Al_2O_3 + 5% Gr.

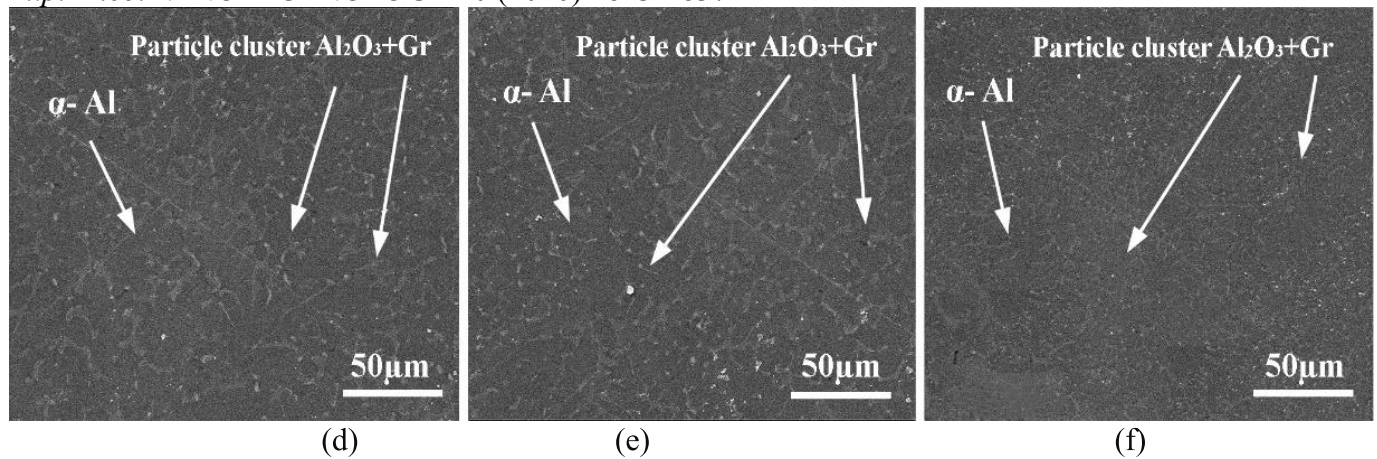


Figure 14 FESEM for the hybrid composites (a) AA6061 + 3% Al₂O₃ + 1% Gr, (b) AA6061 + 3% Al₂O₃ + 3% Gr, (c) AA6061 + 3% Al₂O₃ + 5% Gr.

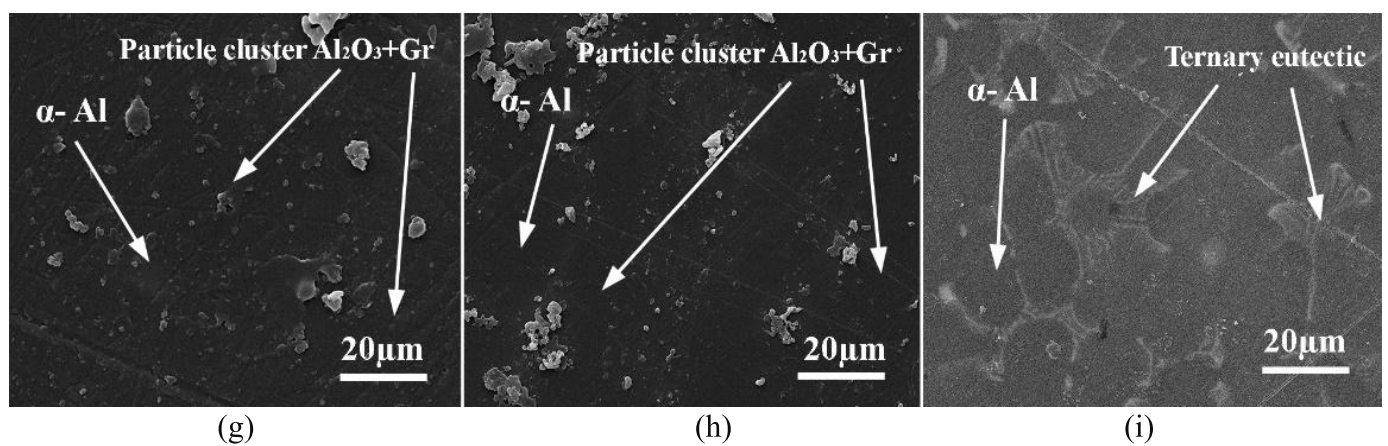


Figure 15 FESEM for the hybrid composites (a) AA6061 + 5% Al₂O₃ + 1% Gr, (b) AA6061 + 5% Al₂O₃ + 3% Gr, (c) AA6061 + 5% Al₂O₃ + 5% Gr.

Segregation in composites can arise from particles being expelled from the solution and concentrated in preferred eutectic regions. The powders in this study are uniformly dispersed, which is observed at the microscopic scale. The Gr and Al₂O₃ particles might also have contributed to grain refinement by obstructing dendritic structures from forming during the solidification process, as observed in the microstructure analysis of the AMHNCs [27]. Nonetheless, minor clustering is observed in the grain and grain boundaries of the composite samples despite no voids in the microstructure.

Matrix reinforcement is attained by adding reinforcement particles to the matrix alloy, initiating heterogeneous nucleation. Therefore, a higher wt.% of reinforcement particles in the samples increases the number of heterogeneous nucleation sites, which causes the matrix to shrink and produce a nearly uniform microstructure. The notable interfacial bonds between the matrix metal and the reinforcement particles also enable AMHNCs to effectively transfer loads from the matrix to the reinforcing materials [28]. Accordingly, this study subjected the AMHNC samples with a higher proportion of reinforcement nanoparticles to microstructural and phase analyses to better understand the distribution and interaction of the nanostructured reinforcements within the Al matrix. The presence of alumina and Gr in the hybrid composite offered in-depth information on the effects of the reinforcement particles on the properties of the resultant materials when compared to the base AA6061 Al alloy.

4.5. XRD Analysis

Figures 16 (a), (b), and (c) demonstrate the XRD patterns of the 1% Al_2O_3 incorporated with 5% Gr, 5% Al_2O_3 added with 1% Gr, and 5% Al_2O_3 integrated with 5% Gr samples, respectively. For the analysis to be meaningful, it is possible to choose samples based on the expectation that they will provide easy-to-understand and work with XRD patterns, such as Material Composition (Matrix and Reinforcements), Phase Identification, Structural Analysis, and Homogeneity. Based on the results, the relative intensities of the XRD peaks for the AA6061 composites containing Al_2O_3 and Gr nanoparticles indicate the presence of the α -Al phase as a major phase with minor phases of Al_2O_3 and Gr compounds.

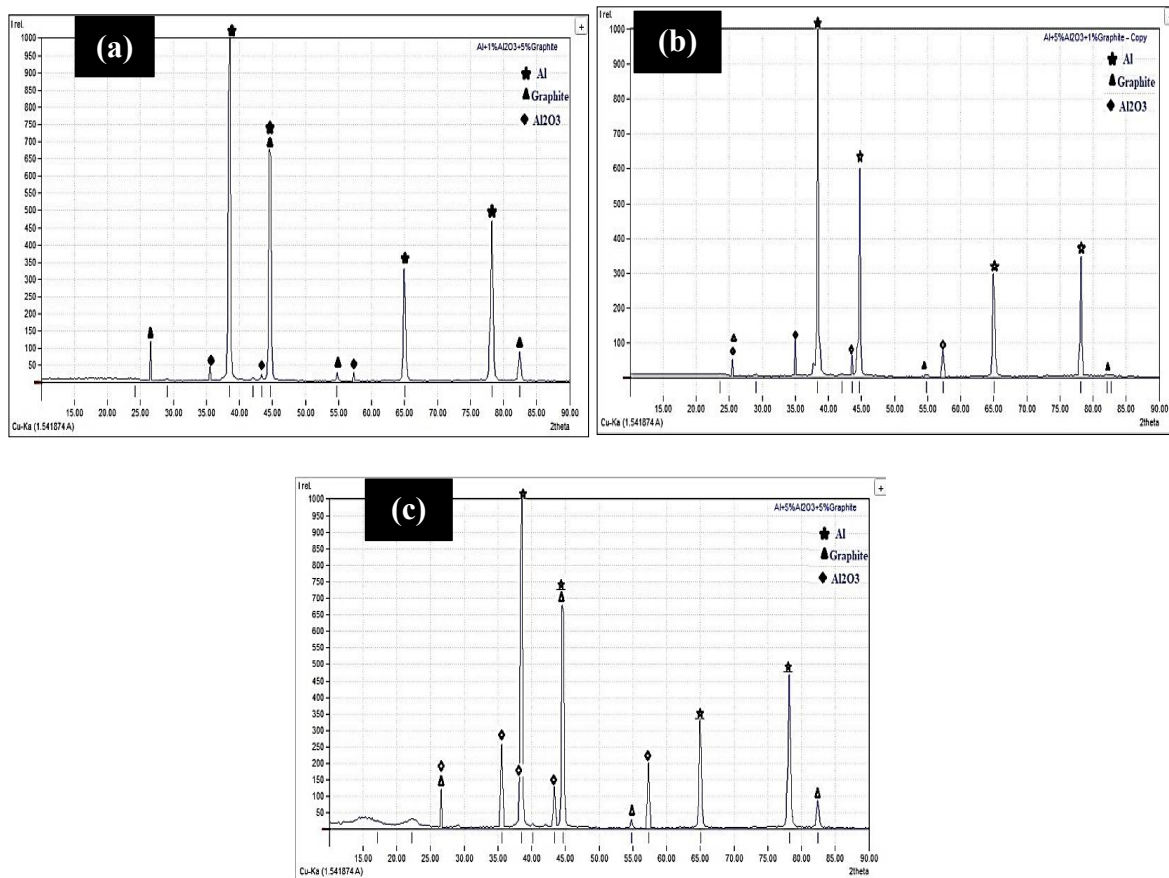


Figure 16 XRD patterns of (a) the AA6061-1% Al_2O_3 + 5% Gr, (b) AA6061-5% Al_2O_3 + 1% Gr, and (c) AA6061-5% Al_2O_3 + 5% Gr.

4.6. Analysis of microstructure

Figure 17 displays two magnifications of the optical microstructure of the AA6061/Gr./Al₂O₃. The uniform dispersion of the powder is acquired at the specimen scale. The segregation is observed at the microscale, attributed to the solidification process pushing particles into the preferentially located eutectic regions. The examination of microstructures also indicated that the Gr/Al₂O₃ particles refined the grains by obstructing the growth of the dendritic structure during solidification. It can be seen that Gr and Al₂O₃ are mostly at the grain boundaries, although some are mentioned inside the grains of the metal matrix.

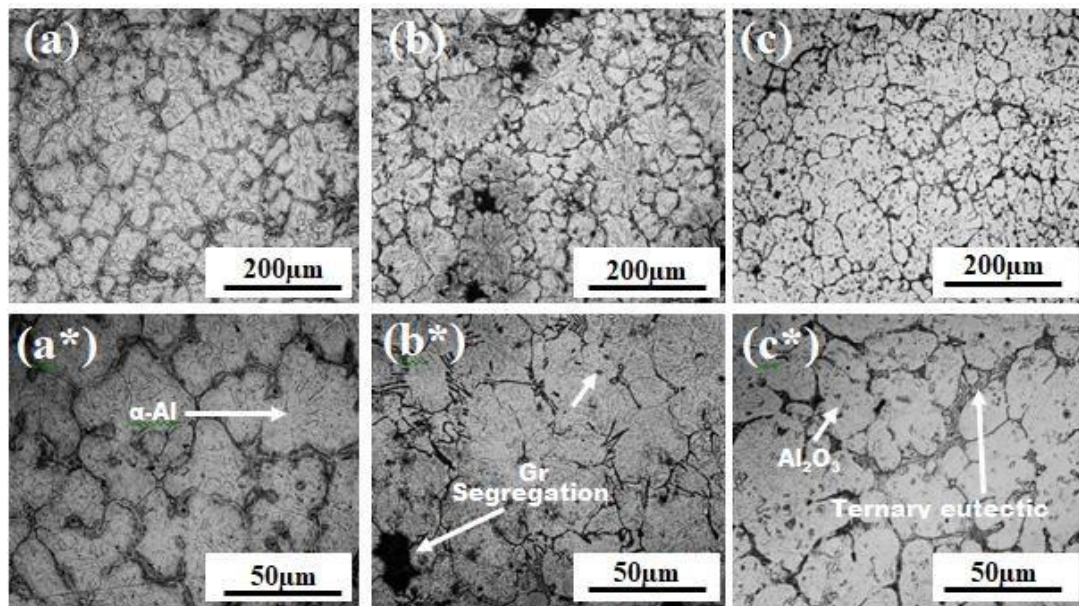


Figure 17 Optical microstructure of the AMCs: (a, a*) AA6061, (b,b*) AA6061 with 5 wt% Gr, (c,c*) AA6061 with 5 wt% Gr and 5 wt% Al₂O₃.

4.7. Analysis of worn surfaces

This study observed the surfaces that had undergone wear with FESEM. The wear and friction parameters are established through microstructural evaluations of the worn pin composite surfaces, providing a thorough understanding of the tribological characteristics of the samples assessed. Figure 18 illustrates the FE-SEM image of a worn AA6061 alloy surface captured at 30 N stress and 600 rpm sliding velocity, where deep grooves are created by sharp asperities slicing into the supplied AA6061 metal pin surface. Adhesion wear is also documented, as evidenced by deep ploughing scars, delamination, and significant plastic deformation.

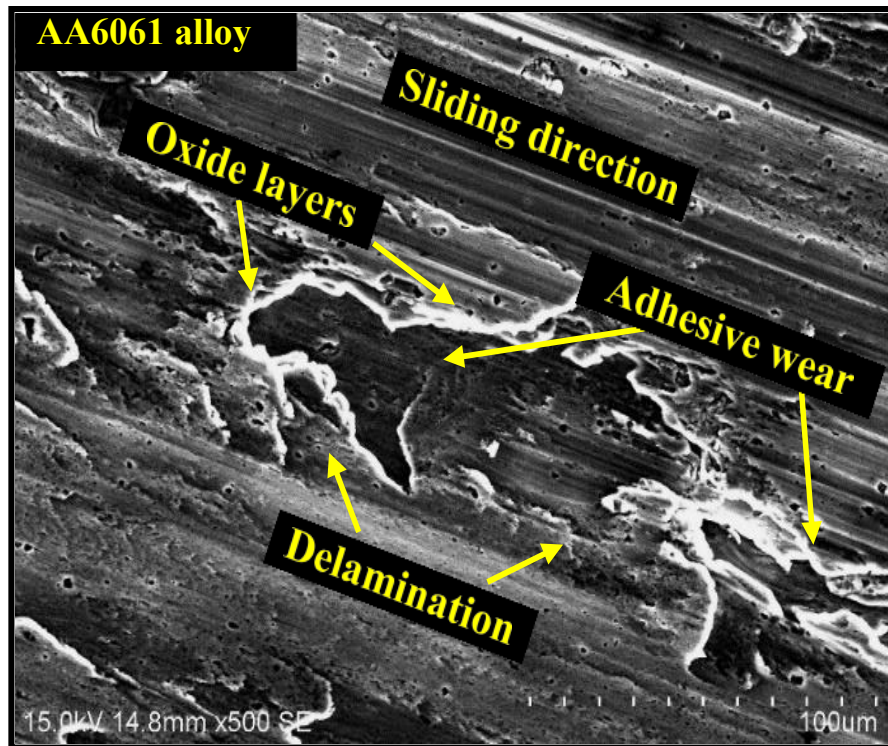


Figure 18 FESEM of the worn surface of the AA6061 alloy under the load of 30 N and a sliding speed of 600 rpm.

On the surfaces of the AA6061 alloys, the oxide layer is removed at a notably higher rate than its production, suggesting an extremely low formation of oxide layers. The phenomenon might be due to the friction-induced rise in temperature, which weakens the not very hard and weak matrix alloy [29]. The debris that emerged from the worn surface and filled the spaces between the particles of the Al_2O_3 and Gr has deteriorated the adequate penetration depth demonstrated in Figure 19. Worn debris particles sliding at the interface between the specimen surface and the counter face disc also might have contributed to the reduced shearing force of the Al_2O_3 and Gr, and the frictional force [30]. Similarly, decreased adhesion and rising Al_2O_3 and Gr nanocomposite contents diminished the coefficient of friction, caused by the increased contact area between the counter face and the reinforcement particles. Conversely, the matrix exhibited a minimal decoherence rate during the sliding wear test at ambient temperature conditions, which could be from well-refined and bound Al_2O_3 and Gr particles [31].

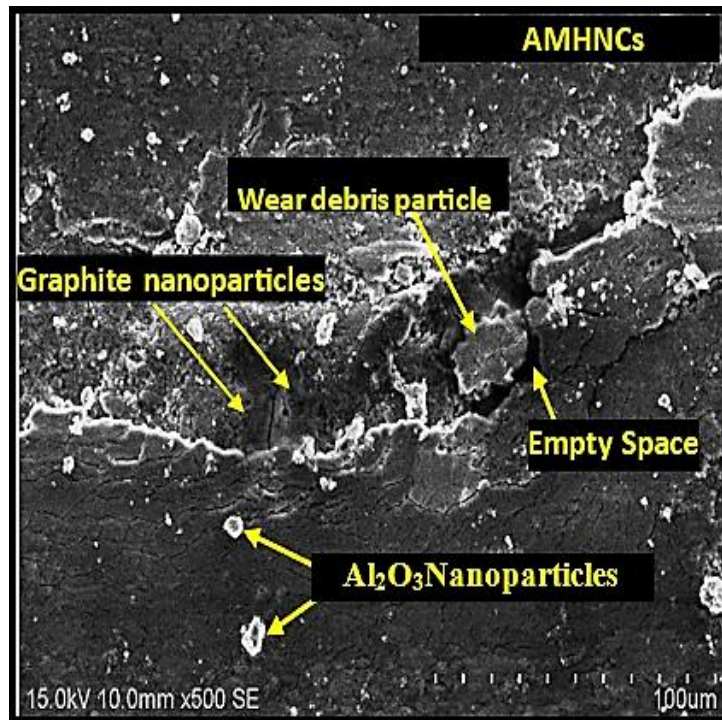


Figure 19 FESEM micrograph of the worn surface of the AA6061- Al_2O_3 + Gr nanocomposites incorporated with 5% Al_2O_3 and 5% Gr under a 30 N load and 600 rpm sliding speed.

4.8. Analysis of worn surfaces wear test

Based on the findings, the ideal hybrid nanocomposite sample, which is labelled L9A, consisted of 5 wt.% Al_2O_3 , and 5 wt.% Gr nanoparticles, and AA6061 as the base alloy. Following wear tests conducted under a 30 N load and 600 rpm sliding velocity for 10 mins, the worn surfaces of the base alloy and the L9 sample are observed under FESEM at different magnifications. The effects of the applied load on the wear behavior of the samples are illustrated in Figure 20.

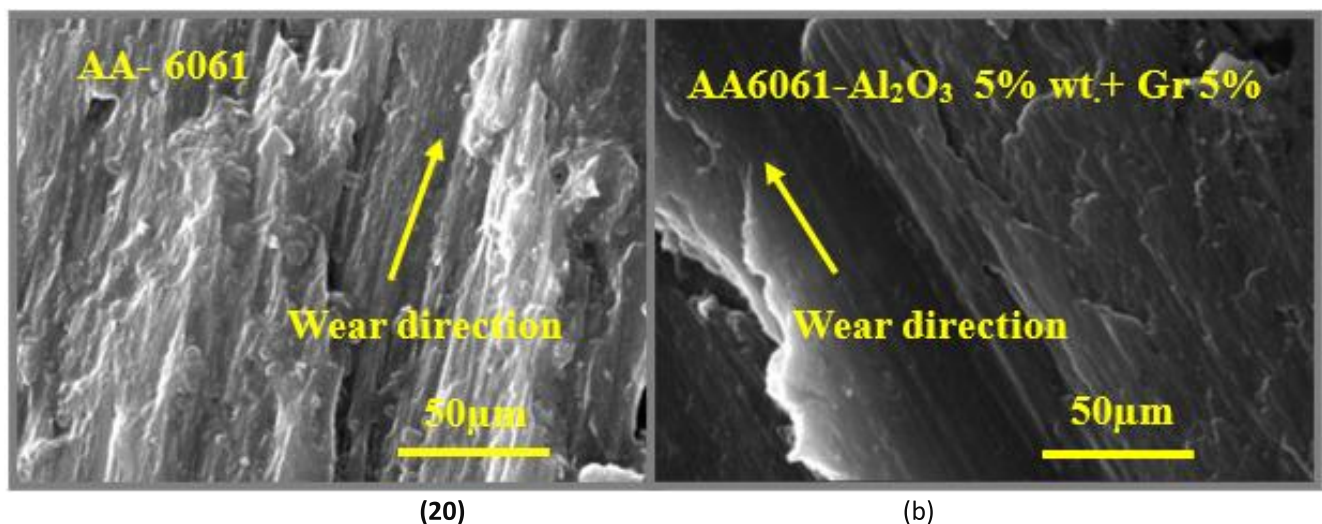


Figure 20 FESEM micrograph of the worn surface. (a) AA6061, (b) Al_2O_3 +Graphite Nanocomposites with percentage of Al_2O_3 5%wt.+Gr. 5%wt. under the load of 30 N and sliding speed of 600 rpm.

Typically, most abrasive materials exhibit signs of adhesive wear upon microstructural examination. Longitudinal grooves and irregularly shaped pits are the most prominent features observed on the worn surfaces across all samples in this study, revealing abrasive and adhesive wear mechanisms. The surface features also indicated the presence of micro-cutting actions by hard asperities or debris, which caused the grooves, while localized material removal or delamination due to adhesion or subsurface crack propagation formed the pits.

Upon examination of the worn surfaces, the wear tracks broaden and deepen to evolve into pronounced grooves with load increments. Numerous micro- and macro-cracks are also observed. The detachment and movement of fine hard particles, such as silicon oxide or titanium oxide, which act as third-body abrasives between the sample and the counter face, further increase the wear severity of the surfaces. The third-body interactions also contributed significantly to the overall material removal and surface degradation.

As the applied load increases, the base AA6061 alloy and the composite samples demonstrated a higher accumulation of wear debris on their surfaces. Meanwhile, the wear tracks appear shallow and closely spaced on surfaces that are subjected to lower loads. Localized oxide layers also formed, attributed to frictional heating, indicating oxidative wear or oxidative corrosion mechanisms.

The extent of surface deformation of the composite samples assessed in this study is directly proportional to the applied load. Localized plastic deformation and wear process might also be intensified by the presence of hard reinforcement particles embedded within a softer matrix, which could cause these particles to protrude or be dislodged to the surface [32]. The effects of the tribological mechanisms on the worn surfaces are demonstrated in Figure 20.

5. CONCLUSIONS

This study successfully generated AMHNCs with uniform particle distribution and grain refinement through the stir casting process. Increasing the wt.% of Al_2O_3 and Gr had also improved the hardness of the AMHNCs. Furthermore, this determined the lowest wear rate and optimal wear resistance of the AMHNCs at the highest load of 30 N and fastest sliding speed for 10 mins based on the wear test performed under different conditions and parameters according to Taguchi design. The outcomes indicated that the wear rate of the hybrid composite with 5% Al_2O_3 and 5% Gr nanoparticles was lower ($5.9 \times 10^{-3} \text{ mm}^3/\text{Nm}$) compared to other composites and the base alloy samples ($13.7 \times 10^{-3} \text{ mm}^3/\text{Nm}$). A reduced coefficient of friction was observed in the composite samples reinforced with 5% Al_2O_3 and 5% Gr nanoparticles. The sample documented a 0.18 coefficient of friction, while the base alloy (AA6061) had 0.34 when evaluated at different loads and speeds at constant time (10 mins). Similarly, the % Al_2O_3 and 5% Gr-reinforced Al composite had a diminished frictional force of 10.0, contrasting the 22.9 value recorded by the base alloy (AA6061). Conclusively, Al_2O_3 and Gr wt.%, sliding speed, applied load, stirring time, and pouring temperature exerted the most influence on the wear rate of the hybrid nanocomposites generated in this study. The nanocomposites reinforced with 5% Al_2O_3 and 5% Gr also demonstrated the highest hardness and wear resistance among the hybrid samples.

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