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Investigation of Dry Tribo-Behavior of Aluminum Alloy AA6061/Al_2O_3/Graphite Composites Synthesized by Stir Casting Technique

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ABSTRACT

In order to meet the requirements of lightweight, high strength, and wear resistance, metal matrix composites are being manufactured with increasing interest, according to recent advancements in material science. Alumina (Al_2O_3) and Graphite (Gr) were added to the aluminum alloy matrix (AA6061) to increase the dry sliding wear resistance and to explore the impact of normal applied load and sliding speed on the coefficient of friction as well as its wear behavior. The composites were made by the stir casting technique. Hardness and tensile strength were two examples of mechanical qualities that have been assessed. Compared to the unreinforced aluminum alloy, the tensile strength of the metal matrix composites was improved by 17.7%, and the hardness increased by 44.1% at a loading of AA6061 (90wt%)/ Al_2O_3 (5wt%)/Gr (5wt%). A pin-on-disc tribometer was utilized to analyze the dry sliding tribo-behaviors of AA 6061 alloy reinforced with Al_2O_3 and Gr by varying the applied load and the sliding distance. The wear resistance of aluminum alloy reinforced with Gr (5wt%)/Al_2O_3(5wt%) increased by 85.0% when the load was applied at 25N compared to unreinforced aluminum alloy, and the frictional coefficient decreased by 58.0%. Additionally, an optical microscope and scanning electronic microscope were used to assess the worn surfaces.

1. INTRODUCTION

Aluminum matrix composites AMCs have tremendous potential for a variety of vehicles, aircraft, and other applications due to their high specific strength, temperature strength and modulus/stiffness making them crucial materials for mass reduction in stiffness restricted or high-temperature designs [1, 2]. Aluminium matrix composites experience dry sliding wear when applied as automobile engine parts (cylinder frames, pistons, and piston insert rings) [3, 4]. The aluminum alloy AA6061, which is one of the most commonly used materials in the automotive industry but has the disadvantage of having poor tribological properties, was chosen as the base/substrate for surface treatment [5]. Several investigations have shown that the stir-casting process is extensively utilized and appropriate for producing aluminum alloy AA6061 composites with high hardness and young modulus reinforcements such as inorganic (Al_2O_3, SiC, TiC, B_4C, etc), organic, hybrid, and nanomaterials. Furthermore, hybrid composites have shown high performance as compared to single reinforcement composites in terms of material characteristics [6-9].

Dilkush et al. fabricated surface metal matrix composites (SMMCs) by coating AA6061 aluminium alloy substrates with boron, silicon and tungsten powders. The SMMCs exhibited higher wear resistance as compared to the AA6061 [5]. The employment of diverse reinforcements in hybrid metal matrix composite (MMC) increased mechanical properties, but at a certain reinforcement level, it begins to degrade. As a result, reinforcements should only be applied up to a certain weight fraction; otherwise, they are pointless. This can be attributed to the agglomeration and increasing porosity with higher reinforcement content, as well as the optimal weight fraction of reinforcement varying amongst composites [10, 11]. AA 6061 was mixed with (2.5 to 7.5wt%) of SiC-Al_2O_3 and (0.5 to 2.5wt%) of rare earth CeO_2 by Vipin et al. Following the inclusion of cerium oxide, the findings showed improved mechanical characteristics with decreased porosity (rare earth particles). The tensile strength was enhanced from 30 to 123 MPa with the successful addition of 2.5wt% cerium oxide. After incorporating 2.5wt% CeO_2, the microhardness and Rockwell hardness of the AA6061 base alloy increased by 17.02 and 33.80%, respectively [12]. Ahmadi and Siadati described the wear resistance of MMC consisting of aluminum powder reinforced by (2.5wt% of CuO and 2.5wt% TiO_2) nanoparticles, which were produced using planetary ball mill techniques. the findings showed a decrease in the wear coefficient of the hybrid nanocomposites was about half compared with the base alloy [13].

It has been discovered that hybridizing graphite particles (Gr) in various combinations reduces the wear rate of AMCs. Numerous researchers have claimed that a continuous layer of solid lubricant formed on the tribo-surface during the dry sliding of metal/Gr composites [14]. This lubricating layer is created as a consequence of the shearing of graphite particles that are positioned right beneath the composite's sliding part. This lubricant film, which is rich in graphite, inhibits a metal-to-metal touch, alleviates plastic distortion in the subsurface zone and serves as a solid lubricant between the worn surfaces [15]. It also helps to lessen the amount of shear stress that is transferred to the material beneath the contact area. So it aids in lowering wear and friction and enhances the composite's seizure resistance. The character of the worn contact surface, the test conditions, the conditions, and the amount of graphite within the composites all affect the structure and keeping of this tribo film on the worn surfaces in addition to its morphology, stiffness, area fraction and thickness, which are significant causes in influential the behavior of materials. According to research, adding more graphite to aluminum alloy composites causes a thicker, more lubricating graphite film to grow on the oiling surface, which reduces the wear rate. But according to certain sources, when the graphite concentration rises, the hardness and fracture strength of composites decrease, rising the wear rate. As a result, it is clear that for any certain Al/Gr composites [16].

Raaft et al. [17] discussed the wear behavior, mechanical properties and microstructural characteristics of A390/Al_2O_3 and A390/graphite. The composites are produced using friction stir processing. The A390/Al_2O_3 composites exhibited lower wear rates than the A390-graphite composites. Rajkumar et al. investigated the wear of an AA6061-B_4C-Nanographite hybrid composite made using a two-step stir casting process. The study found that a mixture of 10% nano graphite and boron carbide particles had a wear rate of around $11*10^{-6}mm^3/Nm$ at a load of 25N [18].

Al_2O_3 has gained popularity in recent years as a potential replacement for ceramic reinforcement [19]. Due to the fact that Al_2O_3 does not interact with the matrix at high temperatures and does not form unwanted phases, it is one of the most widely used ceramic reinforcements [20-22]. With the inclusion of Alumina particles, these composites become harder and more durable. But because of the resulting increase in hardness, these composites are difficult to machine and wear out surfaces more quickly. In order to prevent surface wear in practice, it is necessary to maintain the benefits of Al_2O_3 particles while also solving the challenges associated with the machining of Al_2O_3 strengthened aluminum matrix and the lubrication concerns [23].

Veeresh et al. created an aluminum alloy 6061 reinforced with varying percentages of Al_2O_3 particles (5, 10, 15, and 20wt%). Al_2O_3 particles were found to refine the grains and to be dispersed uniformly in the aluminum matrix. AMMC's ultimate tensile strength and microhardness were increased by the supplement of Al_2O_3 particles [8].

Baradeswaran and Perumal, statement that the wear behavior and mechanical properties of AA7075/Al_2O_3/graphite hybrid composites are improved. The composites were fabricated using the liquid metallurgy route. The study resulted in a combination of 2wt% of Al_2O_3 and 5wt% of graphite exhibiting a wear rate of about $5*10^{-4}mm^3/m$ at 1m/s sliding speed and 20N applied load. Moreover, an investigation of the morphologies of the sliding surfaces demonstrates the appearance of delamination and abrasion wear mechanisms in the AA7075/Al_2O_3/graphite hybrid composites. Simsek et al., prepared aluminium composites reinforced with different amounts of (3-12%) Al_2O_3 and 2% (vol.) graphite, which were mechanically alloyed in a planetary mill. The study recorded that the wear rate of 9% Al_2O_3 and 2% (vol.) was about $8.5*10^{-4}$ mm^3/Nm at 20N applied load and 900m sliding distance.

This paper aimed to analyze the mechanical properties, microstructure, coefficient of friction, phase analysis, and wear behavior of AA6061 strengthened with graphite and alumina powders, which were prepared using a one-step stir casting method. To estimate component lifespan and wear damage, estimation of wear behavior in machine parts under dry sliding conditions is essential. The coefficient of friction and wear behavior of the manufactured composite under various weights and slid distances was studied using a pin-on-disc tribometer. Moreover, the tensile strength, elongation, hardness, microstructure and surface analysis were promoted. Experimental calculated values and results are compared using ASTM international standards B-308, G-99, E-407-99, E-8, and E-10. In this study, the results showed the tensile strength increased from 135.6 to 59.7 Mpa and the hardness enhanced from 31.5 to 45.5 HB. The coefficient of faction was decreased by about 58% and wear resistance was enhanced by about 85%. However, there was a research gap and not enough findings for improving wear and mechanical qualities by adding a combination of micro graphite and alumina particles as hybrid refinements on the aluminum alloy AA6061 produced by a one-step stir casting process have previously been published. Table 1 summarizes the research investigations in the stir casting method of (AA 6061/ reinforcements) hybrid composites.

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

No.	Reinforcements	Ref.
1	Alumina - Silicon carbide – Cerium oxide	[12]
2	Silicon, zinc, graphite, chromium	[24]
3	Boron carbide -Nanographite	[18]
4	Zirconium dioxide -graphite	[25]
5	Alumina - Graphene Oxide	[26]
6	Silicon Carbide-Zirconium Dioxide	[27]
7	Nano TiC-graphite	[28]
8	Alumina-Graphite	Our work

2. EXPERIMENTAL

2.1 Materials

Aluminium alloy type AA6061 was provided by Shandong Xintong Aluminum Technology Co., Ltd, Shandong, China. The chemical compositions of the AA6061 are given in Table 2. The graphite powder was acquired from Luoyang Tongrun Nano Technology Co., Ltd., Gaoxin District, China. Alumina Powder was produced by Renfert GmbH, Germany.

Table 2. The base aluminum alloy (AA6061) chemical compositions

Elements wt%	Nominal ASTM B308	Used
Mg	0.8-1.2	1.08
Fe	0-0.7	0.17
Si	0.4-0.8	0.63
Cu	0.15-0.4	0.32
Mn	0-0.15	0.12
Cr	0.04-0.35	0.06
Zn	0-0.25	0
Ti	0-0.15	Balance
Al	0.02	Balance

2.2 Stir casting composite preparation

The stir-casting technique is the most significant and widely utilized approach in the development of Metal Matrix Composites (MMC) and the metallurgical process. The schematic diagram of the stir-casting process is shown in Figure 1. The AA6061/graphite/alumina composites were prepared by placing chopped aluminium alloy with 1% of Mg in a graphite crucible [29]. Mg was used to improve the graphite and alumina wettability with the aluminium matrix. The chopped AA6061 alloy was melted at 700°C. Before adding the particles of Gr and Al_2O_3 to the molten aluminium, the particles were preheated to 300℃ to remove any moisture, and then the mixture was vigorously stirred for 15 minutes at 650rpm [30]. Finally, the melted slurry was poured into preheated stainless-steel mold at 400℃, which has 20mm length and 40mm diameter, and then the mold was subjected to air cooling. This procedure was repeated to produce Different composition samples. After the solidification, specimens were prepared according to the requirements of the mechanical tests. The compositions of the three samples prepared are given in Table 3.

Table 3. The metal matrix composition

Samples	AA6061 (wt%)	Graphite (wt%)	Al_2O_3 (wt%)
S1	100	0	0
S2	95	5	0
S3	90	5	5

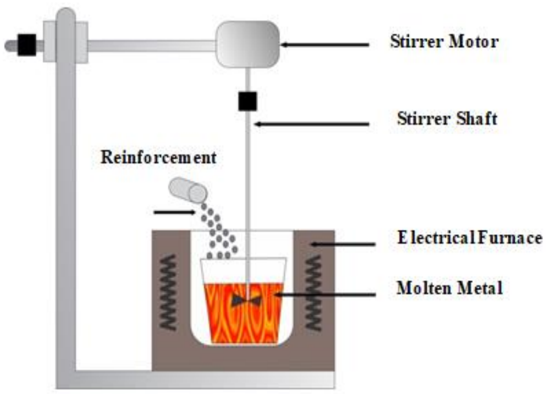

Figure 1. The stir casting technique

2.3 Characterization and testing

Microstructure examinations of metal matrix composites of AA6061\Gr\Al_2O_3 were performed using “Thermo scientific Axia” scanning electron microscopy and “MEIJI” optical microscopy. For the microstructure evaluations, the samples were prepared using standard grinding and polishing methods then the samples were etched for 20sec in a mixture of (2ml HF, 3ml HCl, 5ml HNO_3, and 190ml water) according to ASTM E407-99. The tensile test was carried out using the “GUNT” universal tensile test machine at 0.2mm/min strain rate at room temperature. The tensile specimens were prepared according to the ASTM E8 standard. Brinell hardness test was carried out using a ball of 2.5mm in diameter and a load of 31.25 Kgf. Friction and wear performance was examined using a computerized Pin-on-Disc tribometer connected to ASTM G99 as shown in Figure 2 [31].

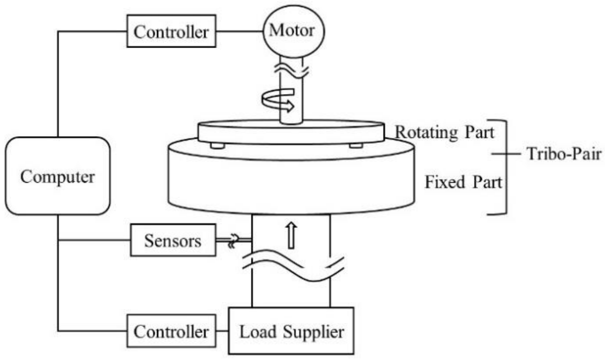

Figure 2. Schematic of the pin on disc tribometer

3. RESULTS AND DISCUSSION

3.1 Mechanical properties

The impact of Al_2O_3 and graphite on the tensile strength and hardness of aluminum composites was examined in order to acquire a deeper understanding of the toughening and strengthening mechanisms of alumina and graphite. Table 4 shows the tensile strength and hardness of AA6061 alloy and its composites. It is found that the supplement of Gr and Al_2O_3 increases the hardness and tensile strength of composites, compared to aluminium alloy when the content of Gr and Al_2O_3 is 5wt%, the tensile strength reaches a maximum of 159.7MPa and increases by 17% compared to the AA6061 matrix [32, 33]. The improvement can be attributed to the distribution of Gr and Al_2O_3 particles in the matrix. Improving tensile strength of MMC can be attributed to the interaction of dislocations and Gr\Al_2O_3 particles during applied load. Moreover, these reinforcement particles act as barriers hindering the dislocation movement under the effect of load [34]. The hardness results show the effect of adding Gr and Al_2O_3. The hardness of S2 and S3 increased by about 17 and 44% respectively as compared to S1. The S3 has a higher hardness value as compared to the S1 and S2 due to the presence of a high amount of Al_2O_3. It is apparent from Table 3 that a reduction in elongation occurred. The elongation of S1 (AA6061 without additives) is higher than the elongation of the other samples, which is due to S1 containing a higher percentage of aluminium as compared with S2 and S3 [35].

Table 4. Mechanical properties of AMC produced by satire casting method

Samples	Mechanical properties of AA6061 composite		
	Tensile strength (MPa)	Elongation %	Hardness (HB) (Kgf\mm^2)
S1	135.6	8.1	31.5
S2	141.2	7.2	36.8
S3	159.7	6.3	45.4

3.2 Microstructural investigations

Two magnifications of the optical microstructure of the AAl6061\Gr\$Al_2O_3$ are shown in Figure 3. The uniform dispersion of the powder is acquired at the specimens scale. The segregation is observed, at a microscale level, which is attributed to the solidification process pushing out the particles to the preferentially located eutectic regions. The examination of microstructures also appeared that the Gr\$Al_2O_3$ particles lead to refine the grains, by obstructing the growth of the dendritic structure during the solidification proses. It can be seen, that Gr and Al_2O_3 presented mostly at the grain boundaries, although some are mentioned inside grains of the metal matrix.

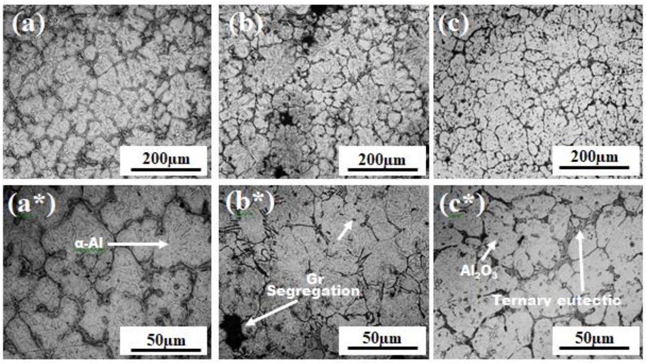

Figure 3. The optical microstructure of the AMC: (a,a*) AA6061, (b,b*) AA6061with 5wt% Gr, (c,c*) AA6061with 5wt% Gr and 5 wt% Al_2O_3

3.3 Friction and wear performance

The friction coefficient and wear performances of AA6061 reinforced by Gr and Al_2O_3 are shown in Figure 4, Figure 6 and Figure 7. The surfaces of the samples also were 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 spindle speed 800RPM and 20N of normal load. Figure 4 shows a high difference between the coefficient of friction (COF) behaviors of the three samples. For sample S1 (Al (100 wt%)/Gr (0wt%)/Al_2O_3 (0wt%), unstable coefficient friction behaviors were observed due to direct contact with no tribo-film formation between worn surfaces. This behavior produced a rough surface with clear groves and cracks (Figure 5a). For sample S2 (Al (95wt%)/Gr (5wt%)/ Al_2O_3 (0wt%), the tribo-behavior was enhanced by lowering COF by about 39% as compared to S1. 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 groves and pits (Figure 5b) [36, 37]. For sample S3 (Al (90wt%)/Gr (5wt%)/ Al_2O_3 (5wt%), stable COF behavior was observed throughout the test time and produced a smooth contact surface (Figure 5c). This resulted in COF being decreased by about 58% as compared to S1, which was attributed to the development of a stable tribo-layer between the worn surfaces [38].

The COF as a function of Al_2O_3\Gr content and applied loads are shown in Figure 6. The COF variation with applied load was determined at 800rpm spindle speed and 180sec 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 [39].

The wear rates of AA6061\Gr\AL_2O_3 composites were also investigated. To achieve the study stat, the wear tests were performed in similar environmental conditions at 800rpm spindle speed for 10 minutes. The wear rates have been measured as a function of normal applied load (5-25N), and reinforcement type. The effect of reinforcement on the wear rate of AA6061 is shown in Figure 7. The S1 curve represents the wear rate of AA6061 under multi-normal load. The wear rate increased as the applied load increased.

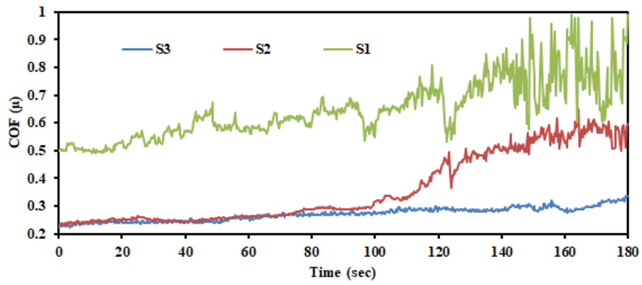

Figure 4. Coefficient of friction behaviors of AA6061\Gr\Al_2O_3 composites

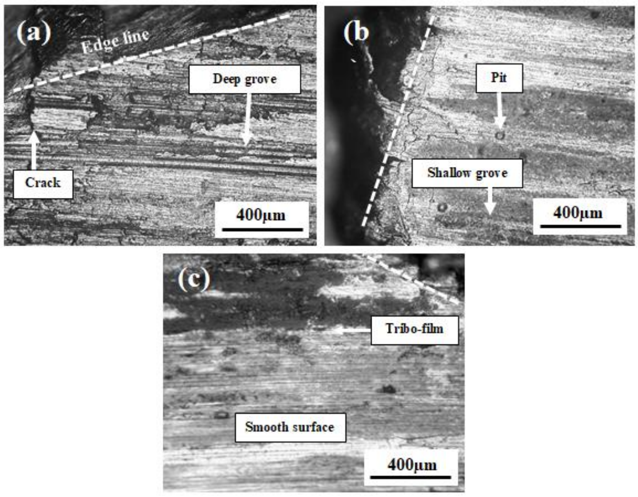

Figure 5. Frictional AMC surfaces at 20N normal applied load; (a) S1, (b) S2, (c) S3

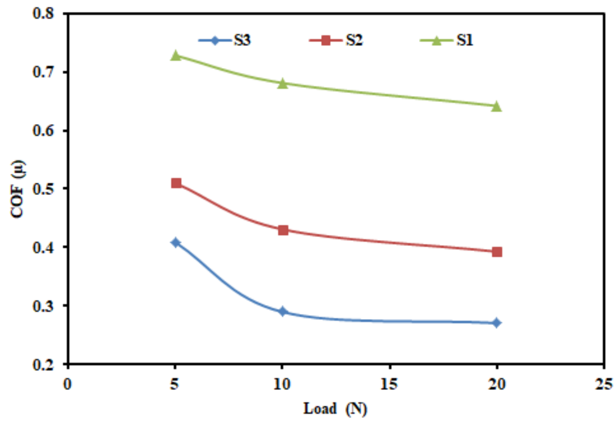

Figure 6. The effect of Al_2O_3\Gr content on the coefficient of friction of AMC under multi-applied loads

Moreover, the sliding contact surfaces become filled with imperfections such as cracks, deep grooves, and cavities, as shown in Figure 8. Surface defects are formed because of the combination of adhesive and abrasive sliding wear at the worked surfaces [40]. The defects are attributed to no formation of tribo-film within contact surfaces. In the case of

S2, the observed wear rate increased after being subjected to a 15N applied load. The adhesive sliding wear has occurred as shown in Figure 8. The adhesive wear occurred due to the failure of tribo-film versus normal applied load. The S3 curve shows high wear resistance with stable wear behavior due to the presence of hard Al_2O_3 particles in the formation of tribo-film. The Al_2O_3 particles enhance the ability of the tribo-film to withstand normal load [41]. The improvement in wear resistance at 25N applied load was about 85% as compared to S1. The modified sliding surface of S3 is shown in Figure 8.

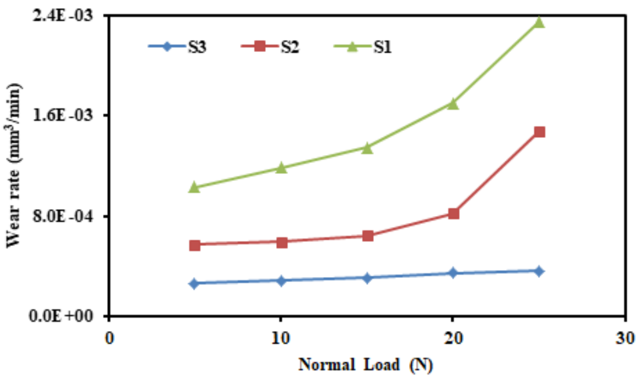

Figure 7. The effect of reinforcement and loads on the wear rate of AA6061

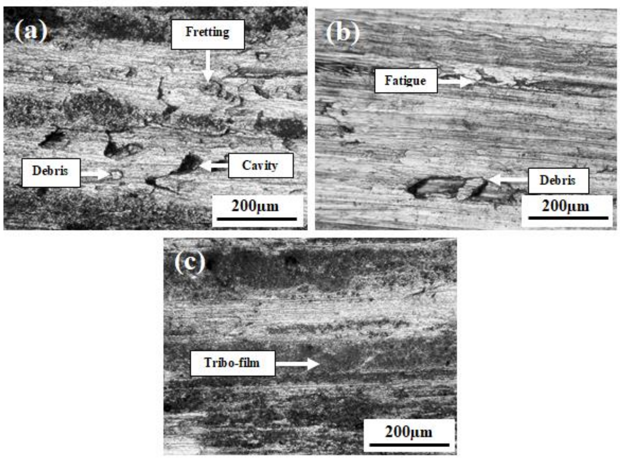

Figure 8. The AMC worn surfaces at 25N normal applied load; (a) S1, (b) S2, and (c) S3

Figure 9 shows the relationship of specific wear with sliding distance. It is apparent from Figure 9 that the specific wear of AMCs exhibited a decreasing trend as the sliding distance increased. This is explained by a considerable amount of asperities within both action surfaces' junctions at the initially sliding motion. To fully understand the results of specific wear rates, SEM was carried out on the worn surfaces of the three types of AMC. Different behaviors of worn surfaces were apparent in Figure 10. This is due to the difference in the mechanism of asperity deformation. The elastic stress on the sharp asperities might be lower than the effective stress that leads to plastically deforming of these sharp asperities at their contact points, except at the reinforcement points. The fracturing of a few asperities was possible on both plastically deformed surfaces during sliding action that led to producing fine debris [41]. The work hardening of the MMC may take place due to the sliding, in which the specimen's surface asperities become in contact with the disc surface under the applied load [42]. Consequently, the specific wear has decreased with the increase in the sliding distance [43].

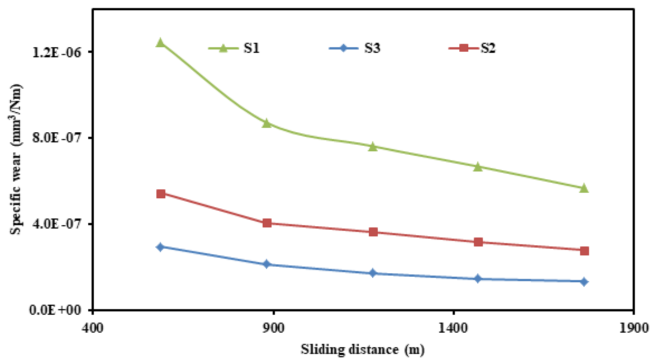

Figure 9. The relations of AMC specific wear with sliding distance

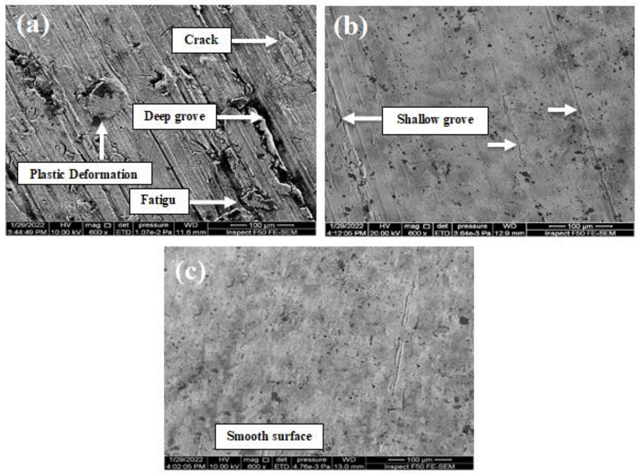

Figure 10. Scanning electronic microscope of AMC worn surfaces at 15N normal applied load and 1750m sliding distance; (a) S1, (b) S2, (c) S3

4. CONCLUSIONS

The mechanical properties and dry sliding wear performance of aluminum alloy AA6061 strengthened by alumina and graphite were investigated. By adjusting applied loads, sliding distance, and the weight percentage of the graphite and alumina, a pin-on-disc device is utilized to analyze the tribological behavior of aluminium matrix composite. The results showed:

1. The addition of graphite and alumina within aluminum alloy AA6061 leads to decreases in the coefficient of friction against normal applied load.
2. The decrease in friction coefficient that lead to decreases in frictional heat produced during dry sliding wear was attributed to the creation of a solid lubrication layer and the inclusion of the alumina-graphite as reinforced within AA6061.
3. Also, the adding alumina and graphite particles within aluminium alloy caused an increase in hardness and tensile strength due to the particles acting as barriers hindering the dislocation movement under the effect of load.
4. When a load of 25 N was applied, the wear resistance of aluminum alloy reinforced with graphite

(5wt%)/alumina (5wt%) increased by 85.0%, and the frictional coefficient decreased by 58.0% as compared to the AA 6061 base metal.

5. Additionally, When Gr and Al_2O_3 are present in an aluminum alloy at a 5 wt% concentration, the tensile strength can reach a maximum of 159.7 MPa and rises by 17% in comparison to the unreinforced matrix.
6. The worn surfaces become smooth and the tribo-film was modified due to the addition of graphite and alumina within aluminum alloy AA6061.

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