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RESEARCH

Role of Solid Lubricant and Bauxite Residue on the Tribological Behaviour of Aluminium Hybrid Composites

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A B S T R A C T

Aluminium Matrix Composites (AMCs) have acquired popularity due to their advantageous qualities, such as high strength, stiffness, and lightweight nature when compared to other metals. These materials are particularly essential in a range of industries, including automotive and aerospace, due to their remarkable features. Wear, a frequent outcome of two rubbing surfaces in motion, has been scientifically examined. The wear behavior of AMCs reinforced with graphite (Gr) and red mud (RM) particles is the subject of this study. A thin layer of graphite particles protects against direct metal-to-metal contact and decreases wear rates. The study also looks into the impact of several factors on wear rates, such as load, speed, and time. Load has a substantial influence on wear, with larger loads resulting in more wear due to increased frictional pressure and material debonding. The hardness of the mechanically mixed layer (MML) that forms on worn surfaces has been improved, resulting in lower wear rates. Furthermore, oxidation and the addition of graphite particles influence wear rates at higher speeds. The effects of time on wear rates are also investigated, and ceramic particles are added to increase wear resistance. The findings contribute to a better understanding of wear processes and the creation of wear-resistant materials. According to the study, AMCs reinforced with graphite and red mud particles have better wear resistance, making them suitable for a wide range of technical applications. This study provides insight into the intricate aspects of preparation of Al – Gr-RMp composites and its wear behaviors subjected to various parameters such as load, speed and time.

1. INTRODUCTION

Aluminium matrix composites (AMCs) are gaining popularity due to their superior strength, stiffness, and weight over Aluminum alloys. Aluminium and its alloys are widely utilized in automobiles and airplanes. These materials have a high specific strength and corrosion resistance, a low density, and a high specific stiffness [1]. High modulus continuous fibers, whiskers, chopped fibers, and nanoparticles are used in the reinforcing phase. Wear is a common effect of two moving surfaces in contact. Wear is a characteristic of a framework that is affected by changes in load, speed, or operating conditions. The presence of oxides on contact can minimize wear rates by limiting or eliminating direct metal contact. At higher temperatures, a smoothly-burnished top layer with a glaze over the surface of the compressed particles is formed, resulting in less friction between the contact surfaces and a very low rate of wear [2]. AMCs reinforced with Gr particles have better wear characteristics because of the reduced wear produced by the formation of a thin layer of Gr particles, which prevents sliding surface metal to metal contact. Wear was greatly influenced by the creation of a thin lubricating coating of Gr particles, and the breakdown of this film resulted in the removal of worn material. The results show that the wear rate of Al-Gr composites with 0-6 wt% Gr reduces as particle concentration increases. The quick formation of a lubricating covering of graphite particles has been connected to wear reduction by preventing sliding surface contact and reducing plowing action of Al chips [3]. The inclusion of red mud (RM) a byproduct of the bauxite ore is used as a reinforcement in many composites for wear-resistant applications. The addition of red mud to some materials may improve abrasion resistance and minimize wear. The phrase "abrasive wear" refers to the surface being cut or plowed by harder particles or asperities, causing metal displacement and the formation of chips and scratches. Two processes dominate material loss in abrasive wear: plowing and micro cutting [4]. The wear properties of AMCs can be further optimized by controlling the size and distribution of the reinforcement particles, as well as the bonding between the reinforcement and the aluminum matrix. Due to these properties, AMCs are finding increasing use in a variety of applications, including aerospace, automotive, and military industries. In light of the above, this study investigates the wear behavior characteristics of aluminum reinforced with red mud (RM) and graphite (Gr) hybrid composites developed through stir casting. The research examines the impact of adding varying percentages of red mud and graphite to the aluminum metal matrix composites, which are subjected to various test parameters to evaluate their wear properties in comparison to the base alloy Al-8011.

2. EXPERIMENTAL DETAILS

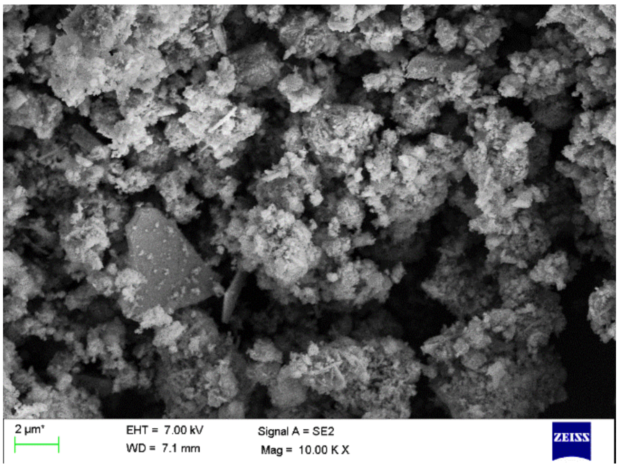
The matrix phase of aluminum alloy is the subject of the majority of MMC research. The combination of ductility, lightweight, corrosion resistance, environmental strength, and useful mechanical properties looks to be ideal. Aluminium has a density of 2.7 g/cm^3 and a melting point of 660.3 °C, making it a lightweight material. The melting temperature is high enough to suit the needs of a variety of applications while being low enough to allow for acceptable and diverse processing procedures. AMCs were chosen for the investigation owing to their broad availability, low production costs, and relatively isotropic properties [5]. Aluminium can endure a range of reinforcements, such as particles, fibers, and whiskers. Aluminium alloys widely utilized in the manufacturing of MMCs include LM-25, 1100, 2024, 3014, 6061, 6063, 7072, 7075, 8011, and others. In this investigation, an Al- 8011 alloy with the composition shown in table 1 was employed as the matrix, with bauxite residue/red mud of an average size of 90μm and graphite flakes of an average size of 150 μm were serving as reinforcement. The red mud came from Hindalco Belagavi in Karnataka. Table 2 lists the chemical makeup of the applied red mud. Figure 1 depicts SEM micrographs of matrix, red mud, and graphite flakes.

Table 1. The composition of Al-8011alloy [4].

Element	Content (%)
Al	97.3 - 98.9
Fe	0.60 - 1
Si	0.50 - 0.90
Mn	≤ 0.20
Zn	≤ 0.10
Cu	≤ 0.10
Ti	≤ 0.08
Cr	≤ 0.05
Mg	≤ 0.05

Table 2. The chemical composition of red mud used in present research.

Element	Content (%)
CaO	1.00
Na2O	3.42
TiO2	9.56
SiO2	7.23
Fe2O3	45.93
Al2O3	18.34
Etc.	6.52



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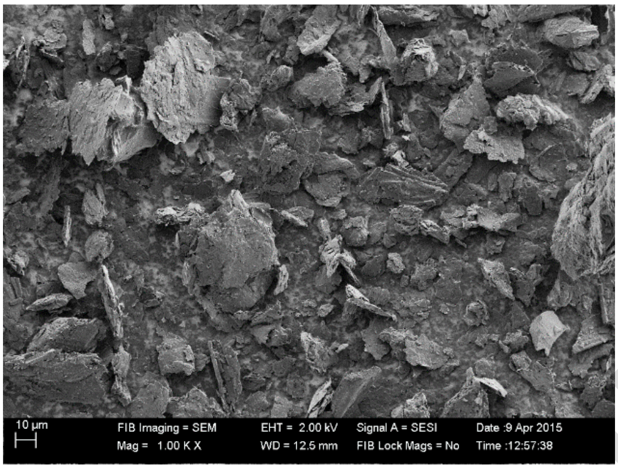

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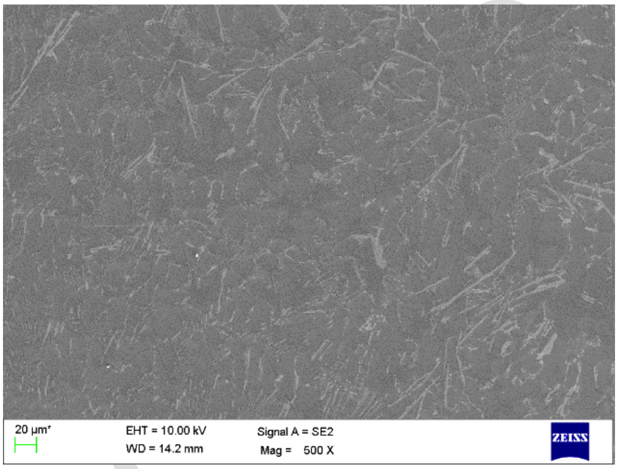

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Fig. 1. SEM micrographic image of (a) Red mud particles (b) Graphite flakes (c) Al-8011 alloy.

2.1 Casting and testing

A conventional stir casting process is an ideal route for processing AMCs compared to other fabrication techniques [6-8,21,30]. Al-8011 alloy is melted in the electrical resistance furnace to attain 750°C; the melt was agitated with the help of Zircon (Zr) coated stainless steel stirrer to form a good vortex then the C_2Cl_6 – solid hexachloroethane was added to remove the entrapped gases inside the melt and stirring is done at a speed 50rpm for a 5 min to ensure proper mixing of the degassing agent in the melt, latter slag was removed from the molten metal. At the temperature of 700°C, the preheated reinforcement particles with a wetting agent Mg [11] were added with different wt. % into the vortex. The different combinations of Rm and Grp wt. % used to prepare Al-Rm, Al-Gr, and Al-Rm-Gr composites are tabulated in table 3. After adding the reinforcement and wetting agent to the melt, a mechanical stirring was done at 150 rpm for 10mins to obtain a proper mixing and uniform distribution of particles in the matrix alloy. Then the mixture is kept in the furnace to get the required temperature for pouring. Before pouring the molten metal into the mold, cover flux (NaCl 45% + KCl 45% + NaF 10%) was added to the molten metal to reduce the atmospheric contamination and poured in to metal molds for solidification.

Table 3. The combination of Rm wt. % and Grp wt. % used to Prepare Al-Rm-Gr Hybrid Composites.

Compositions	Code
Al +8% RMp + 2% Grp	AR8G2
Al + 8% RMp + 4% Grp	AR8G4
Al + 8% RMp + 6% Grp	AR8G6
Al + 8% RMp + 8% Grp	AR8G8
Al + 8% RMp + 10% Grp	AR8G10
Al + 8% Grp + 2% Rmp	AG8R2
Al + 8% Grp + 4% Rmp	AG8R4
Al + 8% Grp + 6% Rmp	AG8R6
Al+ 8% Grp + 8% Rmp	AG8R8
Al + 8% Grp + 10% Rmp	AG8R10

The DUCOM, Bangalore-supplied PIN-ON-DISC TESTER-TR 20 LE was utilized to undertake dry slide wear analysis. For this test, cylinder specimens with an 8mm diameter and a 30mm length are made from a casting with a longitudinal axis parallel to the casting's longitudinal axis, as shown in figure 2 along with the test apparatus. Before and after each test, the samples and worn track were cleaned with acetone and weighed (to an accuracy of 0.001 gram using a microbalance). The prepared specimen was tested by rubbing it on the rubbing face of a spinning EN31 steel disc with a wear track diameter of 80mm at room temperature.

The specimen was loaded against the revolving steel disc using a deadweight loading method, and the test was carried out by varying the load, duration, and speed. The test conditions for two-body adhesive wear testing are listed in Table 4. Wear rates were calculated using the weight-loss approach and given as $mm^3/N\text{-}m$. An optical microscope and a scanning electron microscope were used to analyze the worn-out surfaces of the objects.

(a)

(b)

Fig 2. (a) Pin-on-Disc wear Test rig, (b) Test specimens.

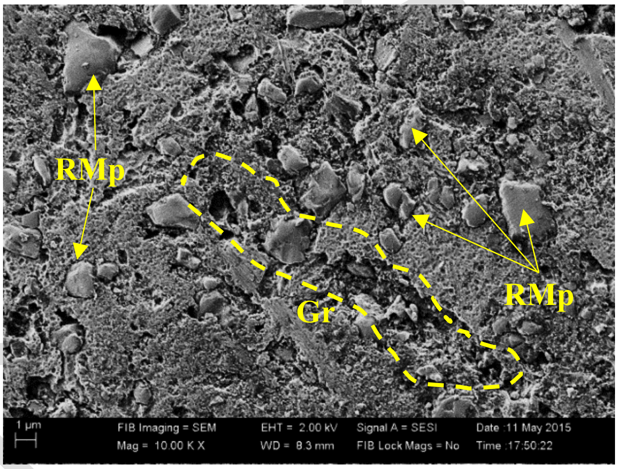
Table 4. Parameters for two- body wear test.

Variables	values
Speed	100, 200, 300 rpm
Load	10, 15, 20 N
Time	5, 10, 15 min
Track Diameter	60 mm
Testing Condition	Room temperature

3. RESULTS AND DISCUSSIONS

3.1 Microstructure analysis and hardness

A few typical samples from the cast composite and hybrid composite series are subjected to SEM examination. According to Hitesh Bansal [8], pre-heating reinforcement before applying it may result in robust interfacial bonding. Figure 3 shows that the red mud particles and Gr are uniformly well distributed within the Al-8011 matrix material. No aggregates of the red mud particles can be seen in the mixture in Al-RMp-Grp, and Al-Grp-RMp hybrid composite by this, we can conclude that the wetting agent Mg. and casting parameters used to fabricate the composites are suitable to cast the said composite series. Also, figure shows a homogeneous mixture of Grp particles in Al-8011 alloy. However, Graphite particles' agglomeration in some regions is visible. This is because of the lower density of Graphite compared to red mud.



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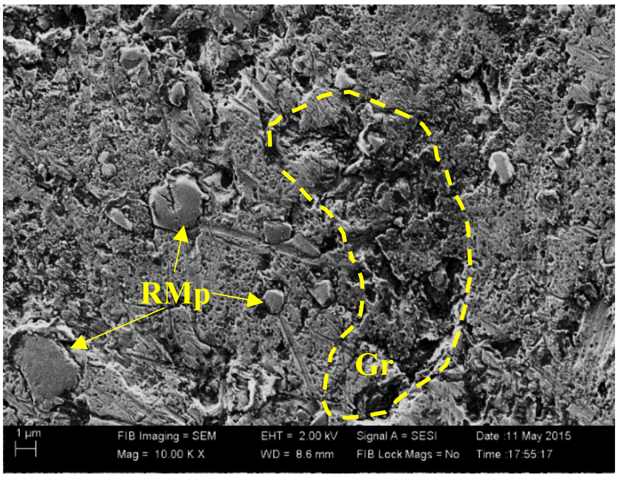


(b)

Fig. 3. SEM micrographs of (a) Al-RMp-Grp hybrid composite (b) Al-Grp-RMp hybrid composite.

The static indentation test was the test used in the present study to examine the specimens' hardness in which a ball indenter was forced into the specimens being tested. According to Seah et al. [32] and Sahin [33], the increased hardness is also attributed to the fact that the hard red mud particles act as barriers to the movement of the dislocations within the matrix. The effect of the addition of reinforcement on the composites' hardness is shown in table 5. As the percentage of reinforcement varies by weight, the composite hardness increases monotonically and dramatically from 21.26 to 42.64 BHN in Al-RMp-Grp hybrid composite series and 21.26 to 43.94 BHN in Al-Grp-RMp hybrid series.

Table 5. Hardness Values of the Al- RMp-Gr and Al-Gr-RMp Hybrid composites.

Compositions of composites	Hardness in BHN
BM	21.3
AR8G2	32.4
AR8G4	34.56
AR8G6	36.61
AR8G8	39.94
AR8G10	42.64
AG8R2	31.25
AG8R4	36.54
AG8R6	38.56
AG8R8	39.70
AG8R10	43.94

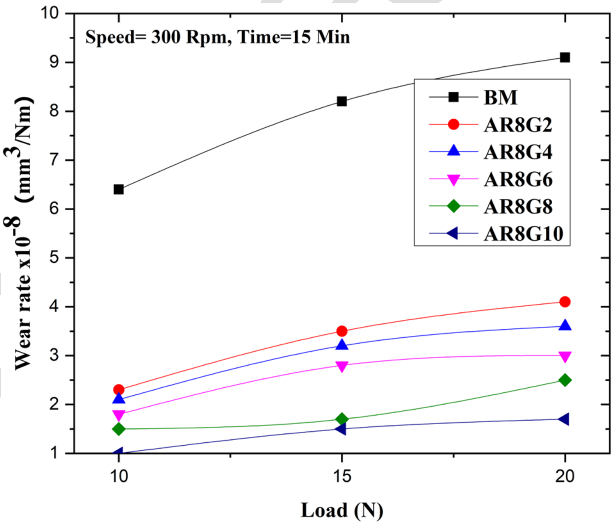
The increase of hardness is due to the increased area of bonding at the matrix's interfacial region and the reinforcement and refinement of grain structure. Also, the increase in hardness can be attributed to the addition of red mud and graphite particles which impart strength to the matrix alloy by enhanced resistance to crack or penetration. Enough researchers also reported that the addition of hard particulates in metal alloys could lead to improved strength and hardness.

3.2 Dry slide wear

The most important but least understood aspect of tribology is metal wear. Despite its practical relevance being known throughout history, wear is the most recent focus of scientific inquiry among friction, wear, and lubrication [9-10]. The automated pin-on-disc wear testing device shown in Figure 2 was utilized to perform the ASTM standard G99-95 wear test.

3.2.1 Effect of Load on Wear Rate

Figures 4 (a-b) show the effects of applied stress on composite wear rate. The graphs were plotted at a constant speed of 300 rpm for 15 minutes. Figures 4 (a–b) Shows how the wear rate of the base alloy and composites grows with increasing load. Solid ceramic reinforcements, when compared to the base alloy, provide a thin layer of oxide at the contact surface between the composites and the counter face, enhancing composite wear resistance at low loads [17-18]. The reinforcement provides wear resistance to the composites at low loads. However, when the load increases, the wear rate of the hybrid composites increases owing to fracture. Composites' load-bearing capacity deteriorates. As a result, the counter face comes into direct contact with the matrix alloy, resulting in high stresses and the removal of the surface layer.



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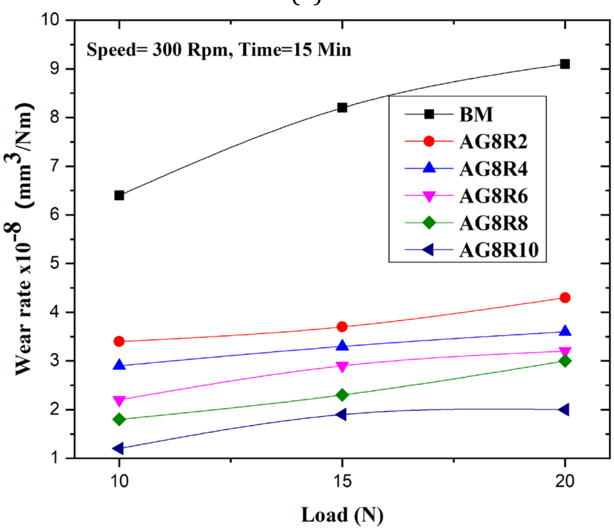
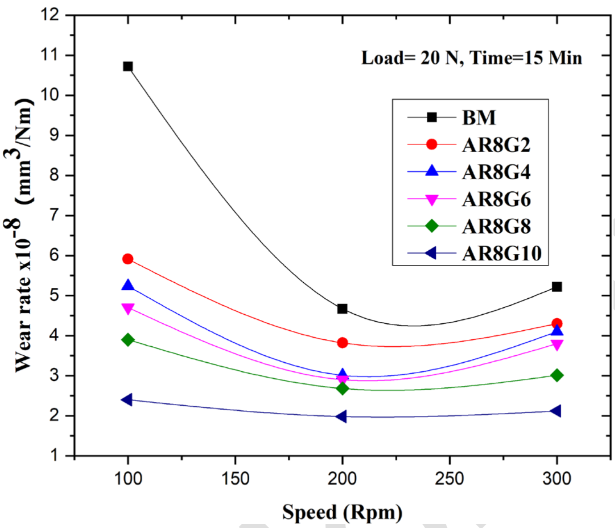


(b)

Fig. 4. Load Influence on the Wear Rate of (a) Al-RMp-Grp (b) Al-Grp-RMp Hybrid Composites.

Several research works [9-10] have made the same observation. A.P. Verma et al. [11] showed that when load increases, so does the frictional force, leading to increasing debonding and fracture as well as to an increase in the wear rate. Comparing the two composite series, the one with Gr as the primary reinforcement had better wear resistance because it forms/creates a thin layer of lubricant between the machine disc surface and the rubbing surface of the specimen. Furthermore, composites using RMp as the main component have superior wear resistance at lower stresses. According to N. Radhika et al. [12], adding graphite as a primary reinforcement enhances wear resistance by forming a protective barrier between the pin and the counter face, but adding ceramic as a secondary reinforcement has a substantial influence on wear behavior.

3.2.2 Effect of Speed on Wear Rate



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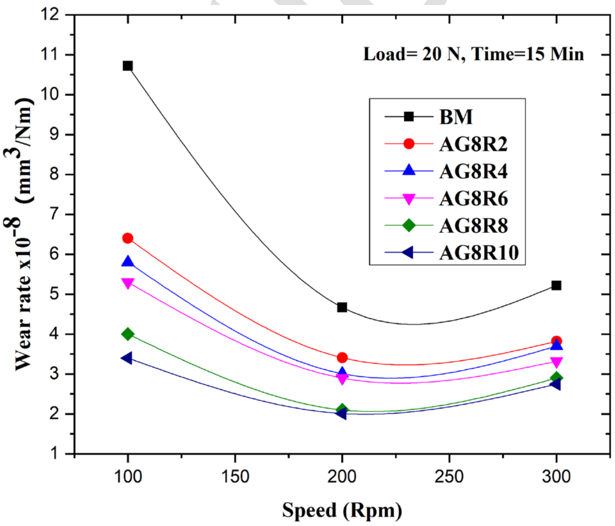

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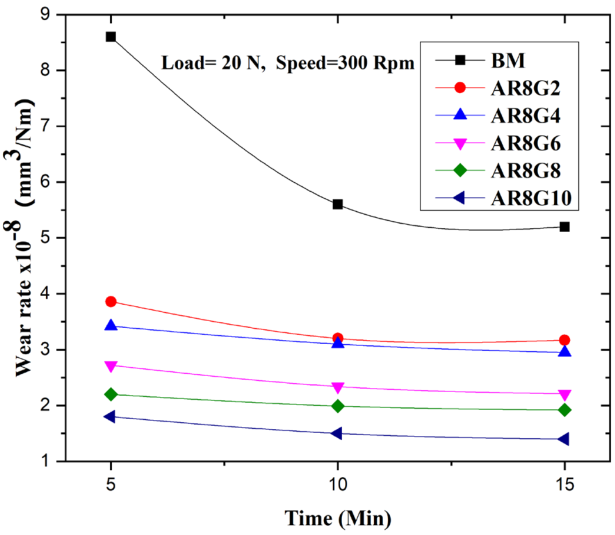
Fig. 5. The influence of speed on the wear rate of (a) Al-RMp-Grp (b) Al-Grp-RMp Hybrid composites.

Figures 5 (a-b) demonstrate how speed affects the wear rate of Al-Grp-RMp and Al-RMp-Grp. Hybrid composites demonstrate that when speed rises, the wear rate of hybrid composites decreases. This is due to iron particle oxidation, which results in the formation of oxide layers on the counter face [9]. Friction between the two rubbing surfaces can be decreased as a result of the growing oxide layers. As previously stated, wear is mostly influenced by the interplay of the asperities of two rubbing surfaces. According to Sudarshan et al. [10], the mechanically mixed layer (MML) on the worn surface of MMCs has a hardness six times that of the composites' bulk hardness. As the sliding speed rises, the creation of a hardened work layer between the pin surface and the steel disc reduces the rate of wear. The MML layer was also shown to change wear and debris rates, indicating that considerable iron was transferred from the disc material. As a result, the wear rate increased as the wear load increased and dropped as the wear speed increased [11]. Aluminium alloy oxidation, according to Amro M. Al-Qutub et al. [13], forms an oxide layer at higher interfacial temperatures and hence decreases wear rate. At higher speeds, the integration of graphite particles in the composites series acts as a solid lubricant, resulting in a lower rate of wear [14-22]. Many scholars [23-26] believe that wear rate is not directly related to sliding distance. Figure 5 (a-b) shows a little increase in wear rate at 300 RPM due to the greater surface contact/sliding distance; the similar trend was seen in the hybrid composite series.

3.2.3 Effect of Time on Wear Rate.

The effects of time on the wear rate of Al-Grp-RMp and Al-RMp-Grp are investigated. Figure 6 depicts hybrid composites. The load and speed are maintained constant in the figures to investigate the effect of time on wear rate. Figure 6 depicts how the wear rate of basic alloys and hybrid composites decreases with time. The composites outperform the basic metal in terms of wear resistance. This is due to the fact that when the proportion of hard ceramic particles in the alloy increases, more hard particles come into contact with the rubbing disc, resulting in decreased matrix alloy exposure [27-29,31].



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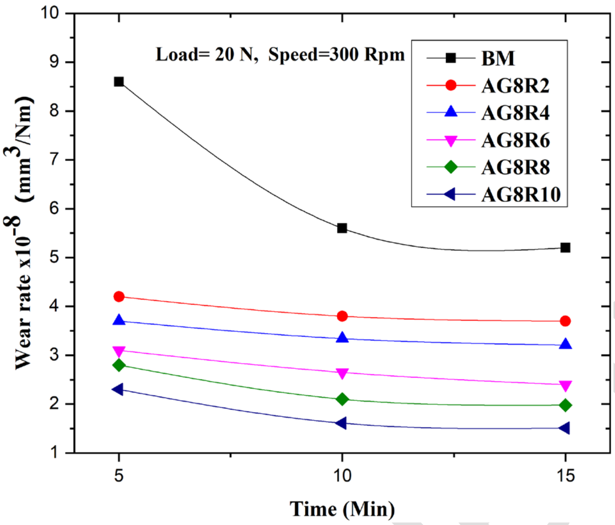


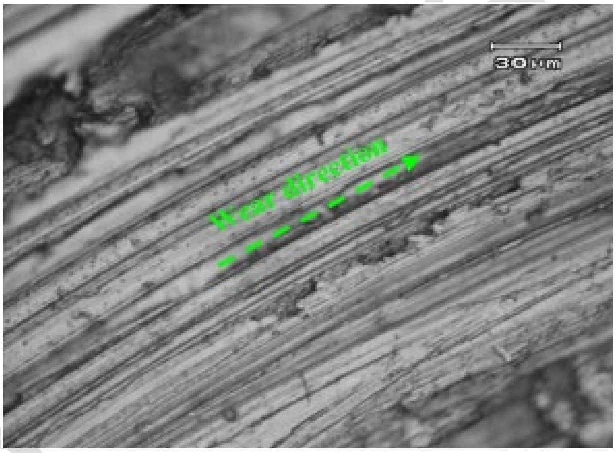
(b)

Fig. 6. The influence of Time on the wear rate of (a) Al-RMp-Grp (b) Al-Grp-RMp Hybrid composites.

The graph clearly shows that the wear rate of the base alloy is higher during the first 5 minutes of exposure; later, at 10 and 15 minutes, the wear rate of the ductile alloy decreases due to strain/work hardening; and, as shown, time has no effect on the wear rate of the hybrid composite series; the wear rate of the composite series remains nearly constant. The presence of red mud particles causes the base metal to harden and become brittle. Friction will be reduced as a result of the decreased wear rate and the addition of graphite particles, resulting in less wear

3.3 Worn Surface Studies

Following the wear test, a worn-out surface of several selected/typical specimens using an Olympus-optical microscope. The worn surface of the basic alloy, as well as the Al-RMp-Grp and Al-Grp-RMp hybrid composites, are depicted in Figure 7, which were all evaluated at room temperature with constant load, duration, and speed. Many studies [8,12,28-29] have found that testing variables such as sliding distance, testing time, operation speed, applied force, and specimen hardness all have an impact on the worn surface. MMCs frequently create grooves and ridges parallel to the sliding direction, as seen in Figure 7 (a-f) by the red dashed arrow micrographs.



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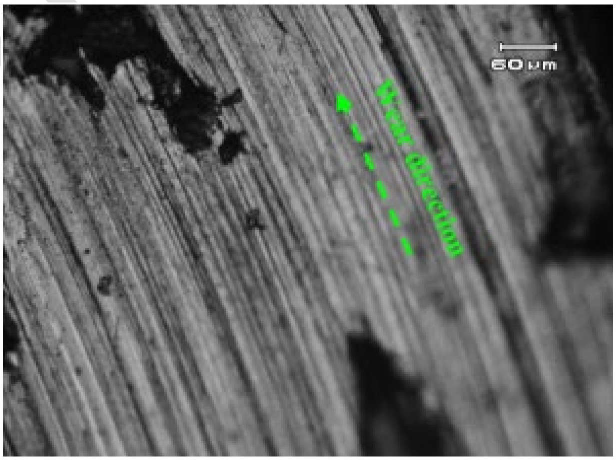

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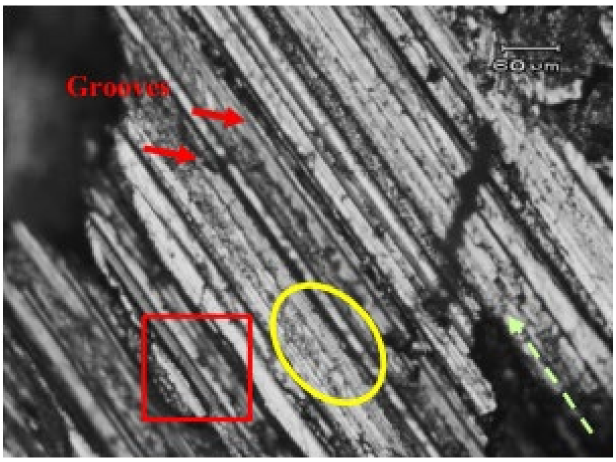

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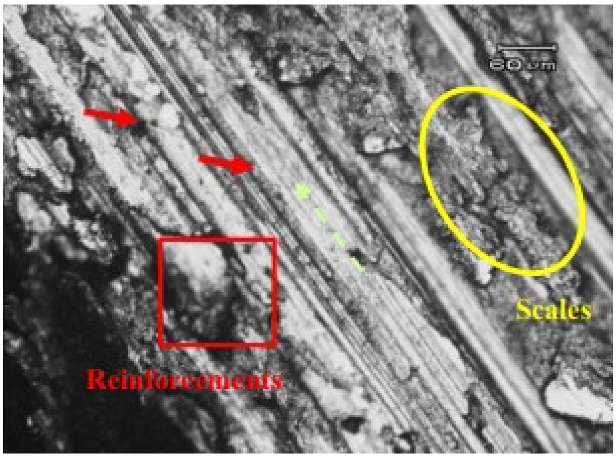

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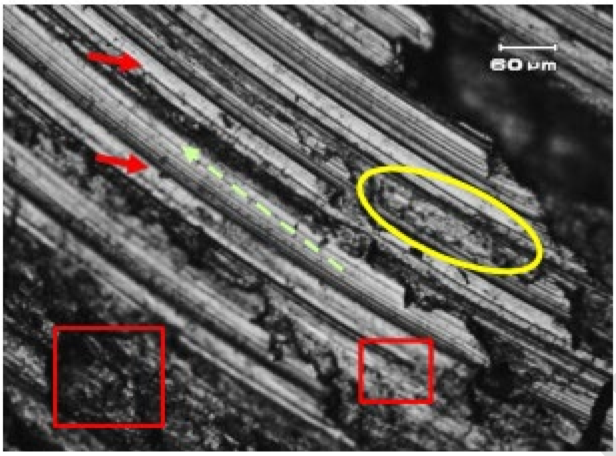

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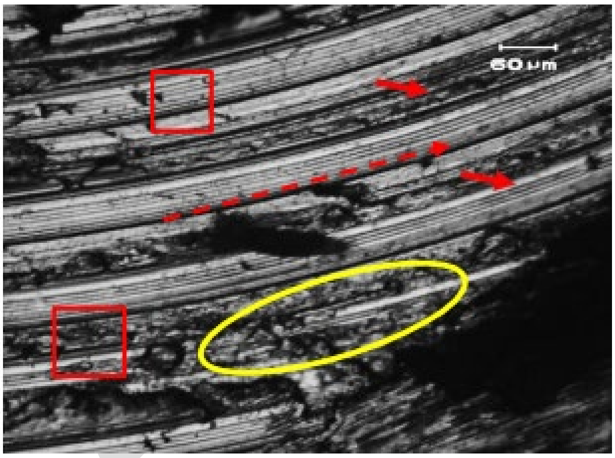

(f)

Fig. 7. Micrographs of worn surfaces (a), (b) base metal (c) AR8G6 (d) AR8G10 (e) AG8R6 and (f) AG8R10 hybrid composites.

These are the first signs of abrasive wear. Further analysis reveals deeper grooves than the base metal seen in figure 7 (a, b). This is due to the plowing action of the hard ceramic particle (RMp). The addition of graphite particles to the matrix works as a lubricant between the specimen interface and the rotating disc, resulting in the formation of a thin layer/scales, as seen in the picture. Many of these studies [14-22] discovered that the graphite particles behave as solid lubricants on frictional surfaces, enhancing the wear characteristics of the component.

4. CONCLUSION

Wear is a typical occurrence in rubbing-motion materials, and it may be mitigated by using suitable reinforcing materials. Graphite (Gr) particles are used as reinforcement in AMCs to avoid wear by producing a lubricating layer between moving surfaces. Red mud (RM), a byproduct of bauxite ore, is also being studied as a composite reinforcement to increase wear resistance. The experimental details for investigating the wear characteristics of AMCs are provided. Wear tests for pin-on-discs are carried out using specialist equipment, and the wear rate is calculated using weight loss. The impacts of several elements on wear rate, such as load, speed, and duration, are explored, revealing information on wear behavior, Following are the conclusions that have been drawn from the present research work.

- Aluminium-8011 alloy reinforced with red mud, Graphite particulate composites and combination of both RMp and Grp hybrid composites were successfully fabricated with fairly uniform distribution using conventional stir casting route.
- Owing to the addition of red mud and graphite particles, the wear resistance of hybrid composites increases. There is a higher filler, wt. %, which gives the composite and hybrid composite series maximum wear resistance.
- The incorporation of graphite as primary reinforcement increases composites' wear resistance by providing a protective lubricating layer between the interface of pin and counter face and secondary reinforcement RMp has a significant effect on the wear behaviour by increasing the hardness.

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