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Experimental Investigation on Enhancing Wear Resistance of Aluminium and the Impact of Graphene Reinforcement on Metal Matrix Composites

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Abstract: ***Aluminium components have gained significant importance in aerospace, naval, sports, and structural applications due to their lightweight, corrosion resistance, and high strength - to - weight ratio. However, pure Aluminium has limitations, such as high wear rate and low hardness, restricting its use in specialized applications. Carbon, known for its exceptional strength and hardness due to its tetra - valent bonding, exists in multiple allotropes, including Diamond and Graphite. Graphene, a single - layer allotrope of carbon derived from Graphite, exhibits outstanding mechanical properties, including high tensile strength, superior wear resistance, and a low coefficient of friction. Reinforcing Aluminium 6061 with Graphene enhances its properties, making it more suitable for advanced applications. This study focuses on fabricating Aluminium 6061 - Graphene metal matrix composites (MMC) using the stir casting technique, incorporating Graphene reinforcement in weight percentages of 0%, 0.5%, and 1%. The casted composites undergo heat treatment, and specimens are prepared following ASTM standards for wear testing. Wear behavior is analyzed under dry friction conditions using an EN - 32 steel rotating disc with a surface roughness of 0.394µm and hardness of 62 HRC. The experiment is conducted at a fixed track length of 2000 meters, a sliding velocity of 1.256 m/sec, and normal loads of 20N, 30N, and 40N. The results indicate that Graphene reinforcement significantly enhances the wear resistance of Aluminium 6061, reducing frictional force and improving the coefficient of friction. The mechanical properties of the composite vary based on the Graphene content and applied load, demonstrating an improvement over as - cast specimens. This study highlights the effectiveness of Graphene as a reinforcing material for Aluminium - based MMCs, offering improved wear resistance and mechanical performance for specialized applications. The findings contribute to the development of advanced materials for industries requiring high - strength, wear - resistant components.***

Keywords: Aluminium Metal Matrix Composites, Wear, wear strength, Graphene Hydroxyl

1. Introduction

In the present scenario, the demand for lightweight materials with high strength and an improved strength - to - weight ratio has driven the development of aluminium alloy - based composites, particularly for the automotive and aerospace industries. Metal matrix composites (MMCs) have gained prominence due to their superior mechanical properties, making them ideal for applications in aerospace, automotive, naval, sports, and construction sectors.

Aluminium alloys are widely preferred for their low density, excellent corrosion resistance, and high thermal and electrical conductivity. Their mechanical properties are influenced by their chemical composition and the type of reinforcement used. To enhance their strength, wear resistance, and overall performance, aluminium matrix composites (AMCs) are reinforced with materials such as alumina, silicon carbide, silicon dioxide, graphite, graphene, boron nitride, and boron carbide. Among these, graphene has emerged as a highly effective reinforcement due to its exceptional strength, hardness, and low coefficient of friction, making aluminium - graphene composites suitable for advanced engineering applications.

2. Selection of Matrix Material

a) Aluminium 6061:

Aluminium 6061 material is a precipitation of aluminium alloy with magnesium and silicon as the main constituents. It is one of the most widely used aluminium alloys in the 6000 series. It is an extruded alloy that can be heat treated, forged and has medium and high strength properties and has good toughness, surface finish, resistant to atmospheric corrosion. Low wear resistance of aluminium is the main disadvantage of this material for its application where wear is a common phenomenon. So it is reinforced with graphene hydroxyl which has a noble wear resistance as it is an allotropic form of carbon. The chemical abd physical properties of Aluminium 6061 are tabulated in table1 and table2.

Figure 1: 6061 Aluminium Material

Chemical Properties of Aluminium:
The Chemical Properties of Graphene are as follows;

Table 1: Chemical Properties of Aluminium

Constituent	Mg	Si	Cu	Fe	Cr	Zn	Mn	Ti	Al
Wt. %	1.49	0.68	0.60	0.49	0.36	0.30	0.27	0.25	Balance

Mechanical Properties of Aluminium:
The Mechanical Properties of Aluminium are as follows;

Table 2: Mechanical Properties

S. No.	Property	Value
1	Density	2700 Kg/m^3
2	Young's Modulus	68.9G
3	Poisson's Ration	0.33
4	Elongation	12.25%
5	Tensile Yield Strength	276Mpa
6	Ultimate Yield Strength	310Mpa
7	Shear Strength	207Mpa
8	Fracture Strength	96.5Mpa
9	Brinell Hardness Number	95
10	Melting Temperature	650^{0}C

b) Graphene Hydroxyl:
Graphene (Gr) is an allotrope of carbon consisting of a single layer of atoms arranged in a two - dimensional honeycomb lattice. It is the fundamental building block of graphite, where multiple graphene layers are stacked together. Due to its unique atomic structure, graphene exhibits remarkable properties, including exceptional mechanical strength, high electrical and thermal conductivity, and superior flexibility.

The discovery and isolation of graphene were achieved by Professors Andre Geim and Konstantin Novoselov at the University of Manchester. Their groundbreaking research led to the development of this revolutionary material, earning them the Nobel Prize in Physics in 2010. Graphene's outstanding properties have made it a subject of extensive research, with potential applications in various fields, including electronics, aerospace, energy storage, and composite materials. Its ability to enhance strength and wear resistance in metal matrix composites has made it a promising reinforcement material for advanced engineering applications.

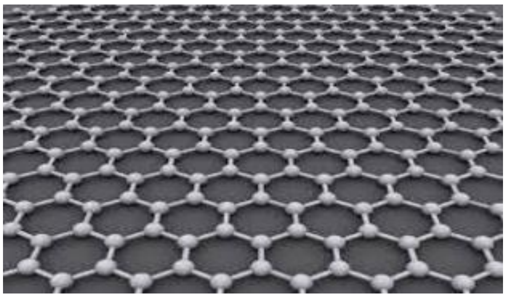


Figure 2: Structure f Graphene Reinforcement

Table 3: Chemical properties of Graphene Hydroxyl

Constituent	Mg	Si	Cu	Fe	Cr	Zn	Mn	Ti	Al
Wt. %	1.49	0.68	0.60	0.49	0.36	0.30	0.27	0.25	Balance

Table 4: Mechanical properties of Graphene Hydroxyl

Sl. No.	Property	Value
1	Density	2700 Kg/m3
2	Young's Modulus	68.9G
3	Poisson's Ratio	0.33
4	Elongation	12.25%
5	Tensile Yield Strength	276Mpa
6	Ultimate Yield Strength	310Mpa
7	Shear Strength	207Mpa
8	Fracture Strength	96.5Mpa
9	Brinell Hardness Number	95
10	Melting Temperature	650 °C

3. Literature Survey

Srinivasa M. R. et al. [1] conducted a study titled "Analysis on Wear Behavior of Aluminium Composites Reinforced with Graphene Hydroxyl." Aluminium is widely used in structural applications across aerospace, locomotive, and automotive industries due to its lightweight nature, corrosion resistance, and high thermal conductivity. However, its low wear resistance limits its use in applications where friction and surface degradation are critical factors. To enhance the wear properties of aluminium, carbon - based reinforcements such as graphene are introduced. Graphene, with its self - lubricating nature and exceptional mechanical properties, significantly improves hardness and wear resistance when used as reinforcement in aluminium composites. This study investigates the wear resistance of aluminium - graphene composites by analyzing key parameters such as the coefficient of friction, frictional force, and material loss due to wear. The results highlight the effectiveness of graphene hydroxyl as a reinforcing agent in improving the tribological performance of aluminium composites.

Anil Parmar et al. [2] explored the "Abrasion Resistance of Aluminium - Based Compounds During Stir Casting. " This study emphasizes the advantages of aluminium, such as its low density, high electrical and thermal conductivity, and ductility, making it a preferred material in various industries. However, to enhance its mechanical and wear properties, aluminium is reinforced with different materials through stir casting. The study examines how various reinforcing agents impact the wear resistance of aluminium - based composites. The research also investigates how different process parameters, such as stirring speed, temperature, and reinforcement type, influence the final properties of the composite. The findings suggest that the appropriate selection of reinforcements significantly improves the wear resistance and mechanical strength of aluminium composites, making them more suitable for demanding applications.

Sachith T. S. et al. [3] reviewed "Aluminium - Based Hybrid Nanocomposites: An Overview of Reinforcement, Mechanical, and Tribological Properties. " The study explores the development of Hybrid Nanomatrix Metal Manufacturing Composites (HNMMC), which meet the growing demands for advanced manufacturing applications. These nanocomposites are designed to enhance mechanical properties, reduce assembly costs, and achieve weight reduction without compromising structural integrity. The study highlights the importance of integrating multiple reinforcement materials into the aluminium matrix to improve hardness, tensile strength, and wear resistance. It discusses how factors such as particle size, distribution, and interfacial bonding between the matrix and reinforcement influence the overall performance of hybrid aluminium nanocomposites. The study concludes that hybrid nanocomposites exhibit superior mechanical and tribological properties compared to conventional aluminium alloys, making them ideal for next - generation engineering applications.

These studies collectively emphasize the significance of reinforcing aluminium with advanced materials like graphene and other nano - scale reinforcements. The use of stir casting and hybrid nanocomposites plays a crucial role in improving the wear resistance and mechanical strength of aluminium - based materials. By optimizing the composition and processing parameters, aluminium composites can be tailored to meet the specific demands of industries requiring lightweight, durable, and high - performance materials. The integration of graphene, in particular, has shown promising results in enhancing the tribological properties of aluminium, paving the way for its expanded use in aerospace, automotive, and other structural applications.

4. Material Synthesization

Stir Casting:
Aluminium material with a definite quantity is weighed and heated in a graphite crucible. It is heated to a temperature of 650°C. The heating is continued about 100 minutes and stabilizes within 15 minutes after reaching 700°C. The graphene reinforcement particles with a size of about 5 - 10 microns is heated to a temperature of 300 - 400°C for about 60 minutes and wrapped in aluminium foil paper to make it as a billet. It is added to molten aluminium in the weight percentage of as - cast, 0.5% and 1.0%. The hexa - chloro ethane degassing tablet is added to molten metal to remove the gasses entrapped during melting.

Immerse the stirrer in the molten metal and stirring action for about 6 minutes and billets of heated Graphene material is added slowly. The mixture is heated for 10 minutes and stirred for uniform mixing. After stirring, the molten composite mixture is poured into the pre - heated mould box. After the material cooled to room temperature, the cast composite is taken out of the mould. The casting process is shown in fig.4

5. Testing

Wear Test
The experiment was performed to check the dry friction and abrasion resistance of the composite material sample. A ground disc made of EN - 32 material with a surface roughness of 0.394 μm and a hardness of 62 HRC was used as the rotating component, and then the sample was cleaned with acetone. An electronic balance is employed to weigh the samples to the nearest 0.1 mg. The wear of the specimen is measured by the displacement of the specimen, measured with a LVDT mounted on one end of the arm holding the specimen. The pin is fixed and disc is made to rotate. The specifications of the setup are shown in Table 5. The experiment is conducted to a fixed track length of 2000 meters with sliding velocity of 1256 m/s and normal loads of range 20 N, 30 N and 40 N. As mentioned above, experiments are performed with different load condition.

The specimens are characterized by scanning electron microscope (SEM) to observe the worn surface of the selected sample to analyze the debris and material removal path. The specimen used for testing of wear and the pin - on disc setup is shown in fig.7 and fig.8 and the specification are tabulated in table5.

Figure 3: Specimen for wear test

Figure 4: Pin on Disc Set - Up

Table 5: Equipment Specifications

Equipment Specification	
Rotating Speed	Up To 2000 Rpm
Normal Load Range	Up To 200N
Track Diameter	40mm To 118mm
Wear or Displacement Range	±2000 Microns
Pin Size	25 to 30mm
Disc size	EN - 32 Steel, Dia. of 120 mm and Thickness 8 mm
Frictional Force	Up to 200N

6. Results and Discussions

The test is conducted for a normal weight of 20N, 30 N and 40 N. The material weight loss due to wear is taken as output parameter.

Table 6: Loss of material due to Wear for 20N

Percentage of reinforcement	Material Weight Loss (gms)		
	Untreated	Quenched	Annealed
As Cast	0.1632	0.0394	0.0413
0.5%	0.0185	0.0066	0.0132
1%	0.0153	0.0054	0.0118

The amount of wear decreases from 0.1632 gms to 0.0153 gms (90.62%) as the graphene percentage increases from 0 to 1 wt. % for un - heat treated composites, found decreased from 0.0394 gms to 0.0054 gms (86.29%) as the graphene content increases from 0 to 1 wt. % for heat treated (quenching) composites 20N and 0.0413 gms to 0.0118 gms as the graphene content increases from 0 to 1 wt. % for heat treated (Annealing) composites, under a normal load of 20N (71.42%). When the graphene content is increased from 0 % to 1.0% under a given load, a decrease in wear is observed. Here, the loss of mass is very less for quenching heat treatment compared to annealing and untreated specimens.

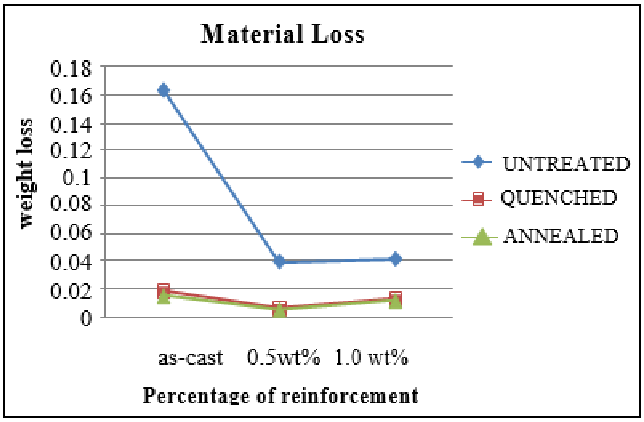


Figure 5: Comparison of Un - Heat Treated and Heat Treated (quenching, annealing) Composites at 20N

Table 7: Loss of material due to Wear for 30N

Percentage of reinforcement	Material Weight Loss (gms)		
	Untreated	Quenched	Annealed
As Cast	0.2869	0.0617	0.0823
0.5%	0.0399	0.0273	0.0234
1%	0.0342	0.050	0.0151

The amount of wear decreases from 0.2869 gms to 0.0342 gms (90.62%) as the graphene percentage increases from 0 to 1 wt. % for un - heat treated composites, found decreased from 0.0617gms to 0.050 gms (86.29%) as the graphene content increases from 0 to 1 wt. % for heat treated (quenching) composites 30N and 0.0823 gms to 000511 gms as the graphene content increases from 0 to 1 wt. % for heat treated (Annealing) composites, under a normal load of 30N (71.42%). When the graphene content is increased from 0 % to 1.0% under a given load, a decrease in wear is observed. Here, the loss of mass is very less for quenching heat treatment compared to annealing and untreated specimens.

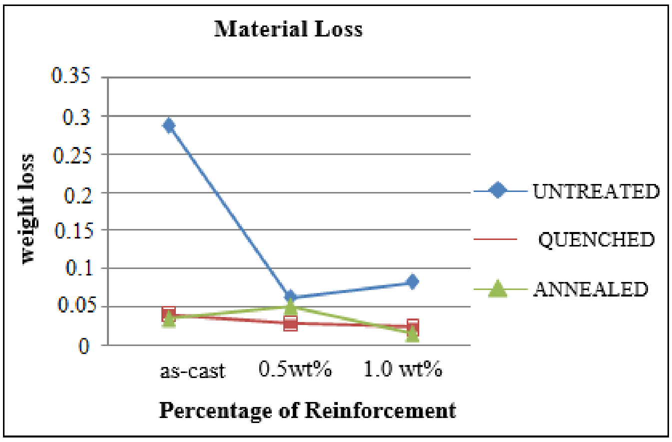


Figure 6: Comparison of un - treated and Heat Treated (quenching, annealing) Composites at 30N

Table 8: Loss of material due to Wear for 40N

Percentage of reinforcement	Material Weight Loss (gms)		
	Untreated	Quenched	Annealed
As Cast	0.6762	0.6006	0.5443
0.5%	0.6668	0.1616	0.3678
1%	0.5187	0.30840	0.3796

The amount of wear decreases from 0.6762 gms to 0.5187 gms (90.62%) as the graphene percentage increases from 0 to 1 wt. % for un - heat treated composites, found decreased from 0.3084gms to 0.050 gms (86.29%) as the graphene content increases from 0 to 1 wt. % for heat treated (quenching) composites 40N and 0.0823 gms to 000511 gms as the graphene content increases from 0 to 1 wt. % for heat treated (Annealing) composites, under a normal load of 40N (71.42%). When the graphene content is increased from 0 % to 1.0% under a given load, a decrease in wear is observed. Here, the loss of mass is very less for quenching heat treatment compared to annealing and untreated specimens.

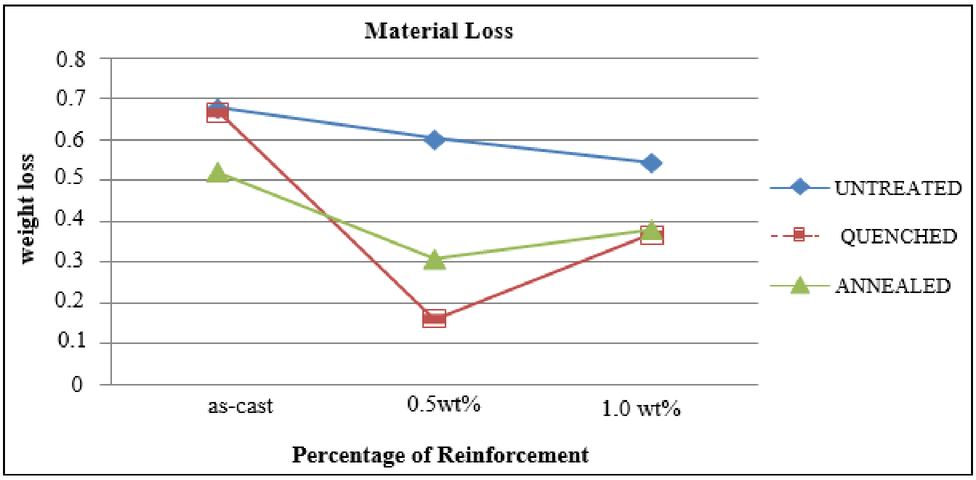
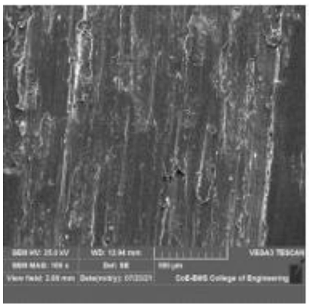
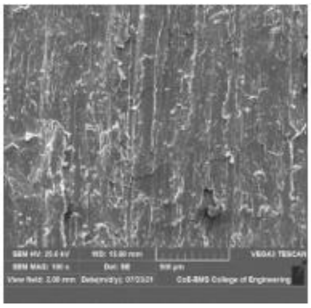
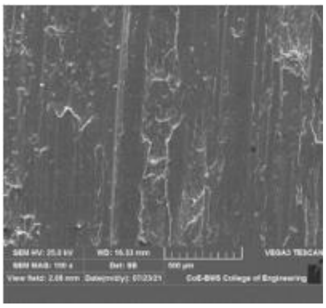


Figure 7: Comparison graph between Un - Heat Treated and Heat Treated (quenching, annealing) Composites at 40N

SEM analysis of the worn surface:

Fig 8: SEM Representation of Un - Heat treated and Heat Treated (Quenching, Annealing) Wear Specimen For 0%.0.5% and 1% (wt. %) of graphene.

In this study, a scanning electron microscope (SEM) was used to analyse the composite material, a microstructure analysis was performed to check the worm surface area, porosity, particle size and dispersion concentration of the reinforcement, and the sample was analysed by SEM. Scanning electron microscope (SEM) is used to analyse the distribution of graphene particles in the aluminium matrix material.

7. Conclusions

Referring to the results and discussions, the following conclusions can be depicted:

1) Graphene as a Reinforcement: The addition of graphene significantly enhances the wear properties of Aluminium 6061. Its self - lubricating nature and high mechanical strength contribute to reduced material loss and improved frictional performance.
2) Effectiveness of Stir Casting: The stir casting process ensures better dispersion of reinforcing particles, leading to improved composite properties. This uniform distribution of graphene enhances the overall wear resistance of the aluminium matrix.
3) Impact of Heat Treatment: Heat treatment further improves the wear properties of Aluminium 6061 composites. It is observed that heat - treated composites exhibit significantly lower material loss compared to untreated composites, making them more durable and wear - resistant.
4) Graphene Content and Wear Resistance: A higher graphene content in the composite material leads to increased wear resistance. As the graphene percentage increases, the material shows improved tribological performance, making it more suitable for applications requiring high durability and reduced friction.
5) The study confirms that graphene - reinforced Aluminium 6061 composites, especially when processed through stir casting and heat treatment, exhibit superior wear resistance, making them ideal for advanced engineering applications.

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