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A Comprehensive Analysis on Fatigue Behavior of Graphite - Reinforced Aluminium 2024 Composites

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Abstract: ***Aluminium components play a crucial role in aerospace, naval, sports, and structural applications due to their lightweight nature, excellent corrosion resistance, and high strength - to - weight ratio. However, pure Aluminium has inherent limitations, such as a high wear rate and low hardness, which restrict its use in high - performance applications. Carbon, known for its exceptional strength and hardness due to tetra - valent bonding, exists in various allotropes, including Diamond and Graphite. Among these, Graphene—a single - layer allotrope of carbon derived from Graphite—exhibits outstanding mechanical properties such as high tensile strength, superior wear resistance, and a low coefficient of friction. Reinforcing Aluminium 6061 with Graphene significantly enhances its mechanical and tribological properties, making it a promising material for advanced engineering applications. This study focuses on the fabrication and wear analysis of Aluminium 6061 - Graphene metal matrix composites (MMC) using the stir casting technique. Graphene is incorporated as a reinforcement in weight percentages of 0%, 0.5%, and 1%. The casted composites are further subjected to heat treatment, and test specimens are prepared following ASTM standards for wear analysis. The wear behavior of the composites is studied under dry friction conditions using an EN - 32 steel rotating disc with a surface roughness of 0.394μm and hardness of 62 HRC. The experiments are conducted at a fixed track length of 2000 meters, a sliding velocity of 1.256 m/sec, and varying normal loads of 20N, 30N, and 40N. The results demonstrate that Graphene reinforcement significantly enhances the wear resistance of Aluminium 6061 by reducing material loss, frictional force, and wear rate. The coefficient of friction is also improved, making the composite more durable under high - stress conditions. The mechanical properties of the composite are influenced by both the Graphene content and the applied load, showing superior performance compared to as - cast Aluminium 6061. This study underscores the effectiveness of Graphene as a reinforcing agent in Aluminium - based MMCs, paving the way for the development of high - strength, wear - resistant materials for aerospace, automotive, and other industrial applications.***

Keywords: Aluminium Metal Matrix Composites, Wear Resistance, Graphene Reinforcement, Tribological Properties, Stir Casting.

1. Introduction

Composite materials are engineered by combining different substances to achieve superior properties compared to their individual constituents. The primary advantage of composites is their high strength - to - weight ratio, making them ideal for aerospace, automotive, naval, and structural applications. For instance, carbon - fiber - reinforced composites (CFRP) can be five times stronger than 1020 - grade steel while weighing only a fifth of its mass. Aluminium 6061, though heavier than CFRP, offers twice the modulus and up to seven times the strength, making it a viable alternative.

The composite materials industry is constantly evolving, with innovations in hybrid materials, recycled fibers, and automated manufacturing processes. Compared to conventional engineering materials, composites offer higher specific strength with fewer weaknesses, making them highly adaptable. However, their development requires careful selection of reinforcements and other materials to achieve the desired properties.

One of the critical challenges in composite materials is fatigue failure, which occurs due to repeated cyclic loading below the ultimate tensile strength. Under dynamic loading, stress fluctuates between maximum and minimum values, leading to progressive material degradation. Unlike static loading, where strain develops gradually, fatigue loading results in structural failure at stress levels much lower than the material's yield strength.

2. Literature Survey

Kunio Asai et al. [1] studied fatigue performance in 12% Cr steel under high contact pressure, analyzing mean stress and material strength. Their findings revealed that as contact pressure increased, fatigue strength decreased, with fatigue life being minimized when Hertzian contact pressure was 1.5 times the 0.2% proof stress.

S. Sathish Kumar et al. [2] investigated the wear behavior of aluminium alloy reinforced with graphite particles using a pin - on - disc test. The composite, processed via liquid casting with 8 wt% graphite, demonstrated self - lubricating properties under dry sliding conditions.

S. Eslamian et al. [3] analyzed fatigue crack initiation under prolonged operation, particularly in aircraft structures and naval components. The study highlighted that fatigue damage increased with stress cycles, with crack initiation observed at 30–60% of the material's lifespan.

Quazi Md. Zobaer Shah [4] explored fretting fatigue in Al - Mg - Si alloy (6061 - T6) using FEM simulations in ANSYS 14.5. Their research indicated that fretting fatigue significantly reduces the material's lifespan compared to conventional fatigue, leading to premature crack propagation.

Geun Won Kim et al. [5] characterized fretting fatigue behavior, studying cyclic micro- slip and stress distribution through finite element analysis (FEA). Their research aimed to optimize pad geometries and eliminate fretting fatigue issues, which are costly and time - consuming to test experimentally.

These studies highlight the significance of fatigue analysis in composite materials, emphasizing the need for advanced reinforcements to enhance durability and performance under cyclic loading conditions.

3. Material Fabrication

a) Development of Al - 2024 - Gr Composite:

Aluminium 2024 alloy in initial melts at the melting temperature is 670c. Heating continued for 2 hour and added the Graphene. The percentage of Graphene are varying with 0%, 0.25%, 0.5%, 0.75%, 1% weight percentage of Graphene with aluminium and specimen is prepared. It converts the mixture from molten state and pours to mould box the specimen dimension is specified and allowance. Aluminium is used as a metal matrix material and Graphene is reinforcement with the weight ratio as a cast 0%, 0.25%, 0.5%, 0.75%, 1% and weight percentage of aluminium. By using stir casting method the specimen is too prepared. The raw material of aluminium is melts at the temperature of 670c and it is converting to molten state. Graphene is added by fixture and stirred gently for 7 minutes by clockwise and anticlockwise direction for uniform mixture of aluminium and Graphene.

b) Machining

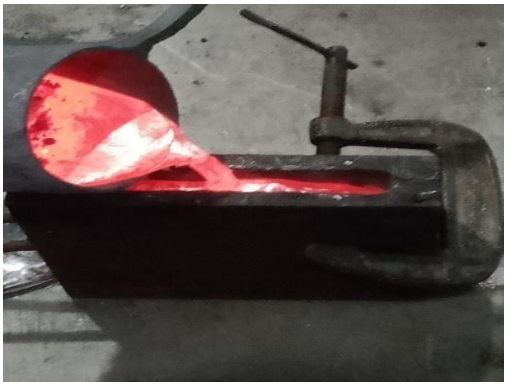

Figure 1: Pouring of Metal

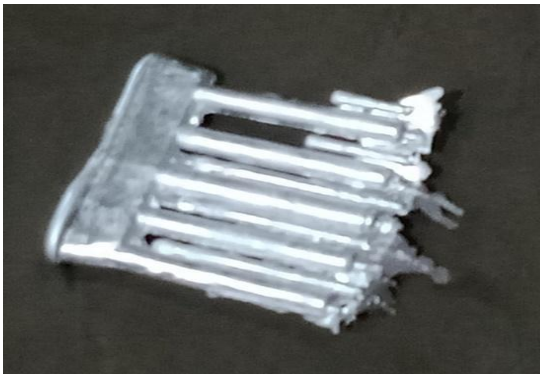

Figure 2: Casted material

A lathe machine is a versatile tool used for shaping work pieces by rotating them around a central axis. It enables various operations such as cutting, sanding, drilling, knurling, deformation, facing, and turning. By applying different tools to the rotating work piece, the machine creates symmetrical objects with precision.

A CNC (Computer Numerical Control) machine is an advanced tool that automates machining processes through computer - controlled inputs. Unlike conventional lathes, CNC machines are motorized and programmed with specific instructions, allowing for high precision, repeatability, and efficiency in manufacturing.

c) Specimen Dimention

The dimensions of the specimen used for Morre Fatigue Test are as shown in Fig.3

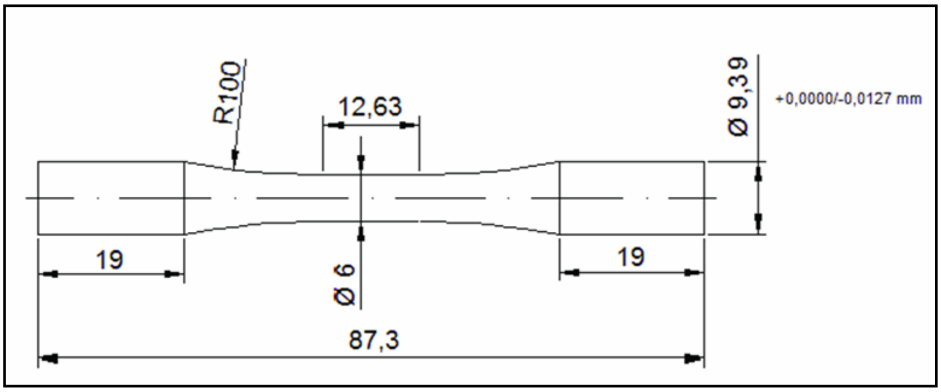

Figure 3: 2D Diagram of specimen (*Dimentions in mm*)

Figure 4: Fatigue Test Specimen

4. Experimentation

The fatigue test was performed using a rotating beam testing machine, as illustrated in Figure 5. The test specimen was prepared according to ASTM E - 466 standards. During the test, the specimen was mounted on the machine, which operated at a constant speed of 2000 rpm.

The applied load started at 5 kg, and the test was repeated with identical specimens at the same speed while progressively reducing the load until the endurance limit was reached.

Figure 5: Moore Test Rig

The number of cycles required for the specimen to fail was recorded for each loading condition, and the corresponding stress for each load was calculated. The results obtained from the rotating beam bending test are valuable for finite - life design calculations. The S - N curve for this analysis can be modelled using Basquin's equation: σf= A (Nf) B. When plotted on a log - log scale, this equation becomes linear. By determining the material - specific constants A and B, this equation can be effectively used for design calculations and fatigue life predictions.

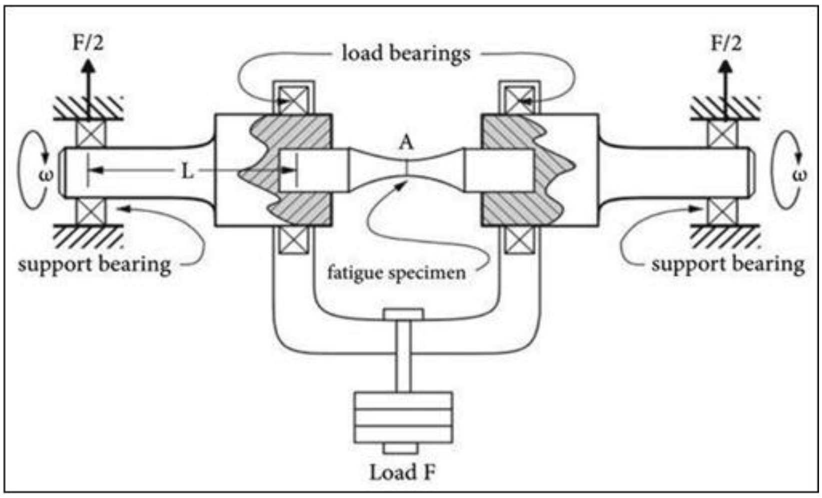

Figure 6: Schematic diagram of the rotating bending machine

Table 1: Specifications of Rotating Bending Machine

Machine type	Rotatry BendingFatigue Tester
Make:	Magnam Engineers, Bangalore
Maximum bending Moment	up to 200 Kg - cm
Speed Range	1000 – 3000 r. p. m.
Prsent counter with speed	6 digit indicator
Maximum load applied	up to 20 kg
Specimen dimentions	Length 90 mm with neck (gauge) diameter 4, 6 and 8 mm.
Distance between load bearing point ti hinge bearing point	100 mm

The fatigue test was performed using a rotating beam fatigue testing machine, as shown in the figure. The test specimen was prepared following ASTM E466 standards. During the experiment, the specimen was mounted on the rotating beam fatigue testing machine, which operated at a constant speed of 2000 rpm. The test began with an applied load of 3 kg, and the experiment continued with the same specimen and speed while progressively reducing the applied load until the endurance limit was reached. The number of cycles required for the specimen to fail was recorded for each loading condition, and the corresponding stress was calculated.

The results obtained from this test are essential for finite - life design calculations, providing valuable insights into the material's fatigue behavior under cyclic loading. The rotating beam bending test helps determine the endurance limit and

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stress - life relationship, which are crucial for designing durable and reliable components in engineering applications.

5. Results and Discussions

Fatigue Test Result: +

Table 2: Fatigue Cycles with different Percentage of graphene Respected Load

Load (Kgs)	No. of cycle at which the material failure		
	For as - cast specimen	Al + 0.25 Gr	Al + 0.50 Gr
5.0	9872	12717	17437
4.5	30307	52313	88712
4.0	71312	136206	156414
3.5	312614	410721	482983
3.0	919995	956737	999756

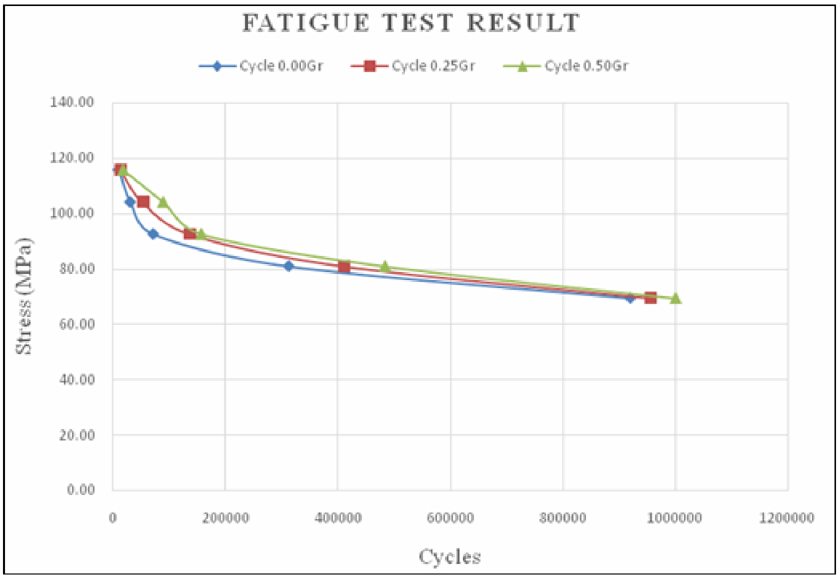

Figure 7: Fatigue Test Result Graph - Stress Vs cycles.

Fatigue limit, endurance limit, and fatigue strength refer to a material's ability to withstand cyclic stress without failure. Ferrous and titanium alloys exhibit a distinct fatigue limit, meaning there is a stress amplitude below which failure does not occur, regardless of the number of cycles. In contrast, metals like aluminium and copper lack a well - defined fatigue limit and will eventually fail, even under small stress amplitudes. For these materials, a specific number of cycles, typically 5×10^8, is used to define their fatigue life.

Understanding these properties is crucial for designing components that endure repeated loading without premature failure, ensuring durability and safety in structural and mechanical applications.

Table 3: Endurance limit table experimental and theoretical

Ultimate Tensile Strength (MPa)	Experimental Endurance limit (MPa)	Theoretical Endurance limit (MPa)
109.53	29.90	27.38
132.26	32.77	33.065
143.29	34.48	35.82

6. Conclusions

1) Based on the discussions and experimental findings, it can be concluded that the strength of the composite material improves significantly with an increasing percentage of Graphene as a reinforcing material. Graphene is known for its exceptional mechanical properties, particularly its high strength, making it an ideal reinforcement to enhance the overall performance of Aluminium - based composites.
2) The incorporation of Graphene contributes to a substantial increase in key mechanical properties, such as ultimate tensile strength and endurance limit. These improvements make the composite material more suitable for applications requiring high strength and durability, particularly in industries like aerospace, automotive, and structural engineering.
3) Overall, the study confirms that integrating Graphene into Aluminium - based composites enhances mechanical strength, durability, and stability, making it a promising material for advanced engineering applications.

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