Experimental evaluation of wear behaviour of Al6061 hybrid metal matrix composites reinforced with SiC and graphite fabricated by stir casting

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Abstract. The Composites is a group of sophisticated materials made up of a metal alloy matrix that is strengthened using ceramic or organic particles. Commonly used matrix are aluminium, titanium, and copper, whereas reinforcements may comprise ceramic particles such as aluminium oxide (Al_2O_3), silicon carbide (SiC), boron carbide (B_4C) and as well as whiskers or fibers like carbon, boron, or steel. These composites exhibit several key characteristics, including a improved wear, high strength-to-weight ratio, thermal, and resistance to creep, enhanced stiffness and hardness, and superior fatigue performance. Due to these properties, MMCs are widely employed in aerospace, automotive, defence, electronics, and thermal management industries. The wear behaviour of the hybrid Al composites reinforced with SiC and graphite particles are tested in the present experimental work using laboratory-based pin-on-disc apparatus, with EN32 steel discs serving counter face material. The specimens were manufactured liquid metallurgy method. Parameters like sliding speed, load, and distance are varied and analysed in a systematic way to understand their effect on wear performance.

1 Introduction

Hybrid Composites are unique substances that are constructed by combining more than one different material to achieve a product with enhanced properties surpassing those of the individual components. Major constituents of a composite are matrix, reinforcement. Matrix is the adhesive that holds the structure together and protects the reinforcement, while reinforcement provides strength, stiffness, and other mechanical benefits.

These materials are designed to realize a grouping of properties like resistance to corrosion, improved fatigue performance, which is difficult to achieve with monolithic materials like metals, ceramics, or polymers alone [1-3]. Composites can be classified broadly according to the type of matrix into ceramic matrix composites, metal matrix composites and polymer matrix composites. The PMCs are most widely used because of their light weight and adaptable features, finding applications related to automotive, aeronautics, sports. Metal Matrix Composites are composed of aluminum or titanium along with particles

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or fibers of ceramics such as B_4C or SiC. They have been known to possess great intensity, deterioration conflict, and thermal strength. CMCs, normally used in high-temperature applications like thermal protection systems and aerospace engines, consist of ceramic matrices and reinforcements for great thermal and oxidative stability [4-7]. Properties of composites depend on a variety of factors like type, shape, orientation, in addition to bonding strength at the matrix-reinforcement interface [8-11]. Fabrication techniques are dependent on the type of matrix and reinforcement used. Metal and ceramic composites necessitate powder metallurgy methods, squeeze casting, or chemical vapor infiltration. Novel approaches like additive manufacturing are being researched and developed for the fabrication of complicated composite parts with less wastage and high accuracy [12-15]. The effect of graphite and silicon carbide content will reduce the wear. To address environmental concerns, researchers are creating eco-friendly composites with natural fibers (such as jute, flax, and hemp) along with biodegradable matrices. As innovations continue, composites are expected increasingly important role in sustainable engineering and advanced manufacturing. This experimental study fills the gap of addition of graphite and SiC content in wear and hardness of hybrid composites.

2 Experimental information

2.1 Materials

Aluminium 6061(Al 6061) is suggested the matrix owing to its light weight, good machinability, great rust-resistant, durable and lightweight, and thermic conductivity. To enhance the composite's wear and mechanical performance, silicon carbide (SiC) and graphite powders, each through a mean particulate proportion of 50 microns, utilized as support materials. Silicon carbide is selected for its excellent wear resistance, hardness and capacity to improve load-bearing capacity, while graphite is incorporated to provide solid lubrication, reduce friction, and improve thermal stability.

2.2 Fabrication of composite specimen

Aluminum alloy Al6061 is chosen as matrix material because of its exceptional systematic possessions, competent castability and corrosion endurance. To enhance its performance, particularly in wear and friction-related applications, hybrid composites are developed through the stir casting process, melt temperature (750°C), stirring speed (500 rpm for 10 minutes) [Figure 1]. Two groups of combined specimens are made by strengthening the Al6061 matrix with 10% silicon carbide (SiC) particles and varying weight percentages of graphite particles—10% in the first specimen and 15% in the second [Figure 2]. Continuous mechanical stirring at controlled speed and temperature ensures uniform dispersion of the reinforcements within the matrix. SiC particles, being hard and brittle, contribute significantly to improving the stretchable intensity, rigidity and wear endurance of the composite. Meanwhile, graphite, a soft solid lubricant, enhances tribological properties by reducing friction and improving machinability [5,6].

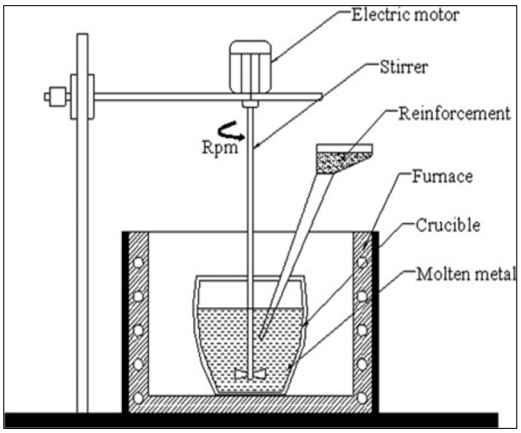

Fig. 1. Stir casting method.

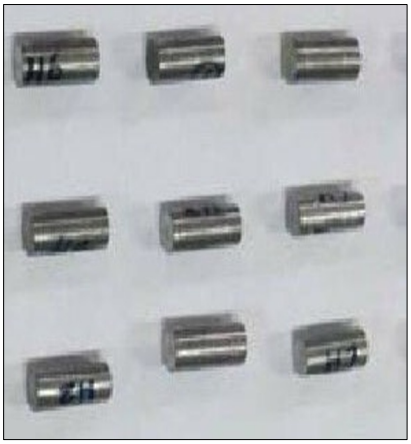

Fig. 2. Composite specimens for wear test.

2.3 Wear testing

Wear test of fused samples must be conducted by applying a pin-on-disc apparatus [Figure 3], widely accepted method for evaluating the dried out slipping wear performance of materials. In this setup, a pin made from the composite specimen (Al6061 strengthened with Gr and SiC particles), the material is kept stationary while pressing against the rotating EN32 steel disc under a certain load. The disc rotates at a given speed and radius, causing frictional contact between the surfaces. Factors such as the load applied, velocity of sliding, and distance of sliding are maintained to closely approximate real wear conditions. During the test, the sample erode is evaluated by assessing the reduction in mass value of pin before and after examination using a precision weighing balance. After completion, the wear down coats of the samples are often inspected using microscopy techniques such as Scanning Electron Microscopy (SEM) to detect the influential wear procedures, which may include abrasive, adhesive, or oxidative wear.

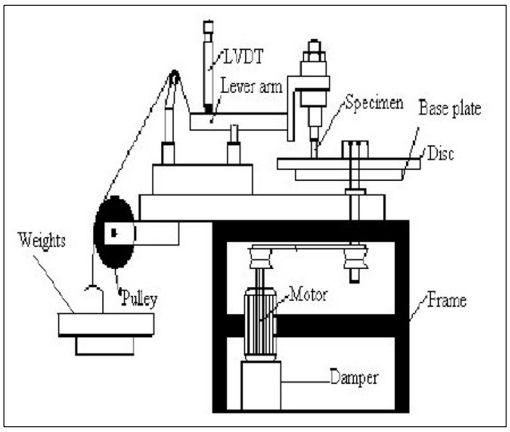

Fig. 3. Outline of pin on disc wear test machine.

2.4 Hardness testing

The Rockwell hardness test [Figure 4] is a popular technique for assessing the hardness of materials by evaluating how deeply an indenter penetrates under a specified load. This process includes the application of a minor load of 10 kgf to properly position the indenter, followed by a major load, which can be 60, 100, or 150 kgf, based on the chosen scale. After the major load is lifted, the difference in depth is recorded to calculate the hardness. Various scales like HRB and HRC use different indenters (steel ball or diamond cone) for different materials.

Fig. 4. Hardness testing machine.

3 Findings and analysis

3.1 Microscopic examination (investigation)

Microscopic examination gets organized using a JEOL model with SEM (Scanning Electron Microscope). The wear surface micrographs of Al 6061 hybrid composite specimens are presented in Figure 5.1, 5.2 and 5.3. Post-wear examination revealed non-uniform surface damage characterized by grooves, micro-cutting, and scratch marks caused by the reinforcing particles. These characteristics recommend that the predominant wear out procedure is abrasive in nature. Additionally, delamination was witnessed on the eroded coats, indicating the initiation of subsurface cracks. When the reinforcement particle are uniformly distributed then the wear grooves and delamination will be minimum.

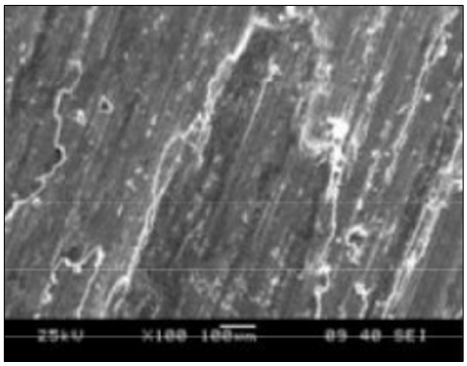

Fig. 5.1 Microstructure of composite Specimens after wear testing.

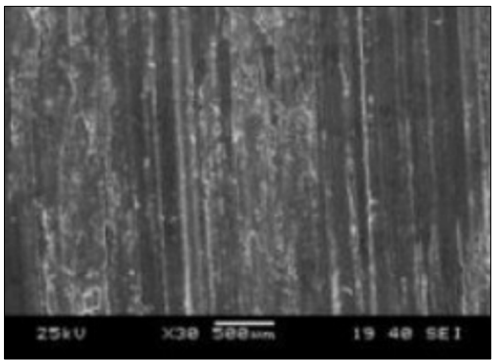

Fig. 5.2 Microstructure of composite Specimens after wear testing.

Fig. 5.3 Microstructure of composite Specimens after wear testing.

3.2 Hardness testing

The Rockwell hardness values of Al 6061 composites with varying reinforcement content are presented in Table 1. Hardness assessments were performed utilizing a Rockwell stiffness testing machine through a hundred kgf indentation load, and measurements were recorded on the B scale. The results indicate a noticeable increase in Rockwell hardness with a decrease in gr particle. Trend can be lead to dislocation density behavior. A higher amount of reinforcement in the matrix alloy generates greater dislocation densities during solidification because of the thermic incompatibility amongst the matrix and the strengthening. In order to balance mechanical strength with better tribological performance, graphite's solid lubrication somewhat reduces hardness, while SiC's efficient load-sharing is responsible for the observed hardness trend.

Table 1. Density and Hardness measurements of Al 6061 and its composites.

S.No	Specimen Composition	Composite material Density (g/cm^3)	Rockwell Hardness (HRB)	Average Wear (mg)
1	Al6061	2.701	47.0	38.6
2	Al6061+10wt% SiC+10wt% Graphite Particles	2.723	62.1	28.6
3	Al6061+10wt% SiC+15wt% Graphite Particles	2.715	61.9	24.5

3.3 Wear testing

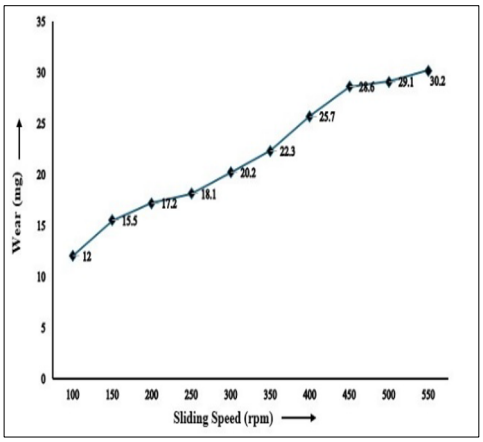

Fig. 6. Impact of sliding speed on the wear of Al6061+10%SiC+10% graphite particles.

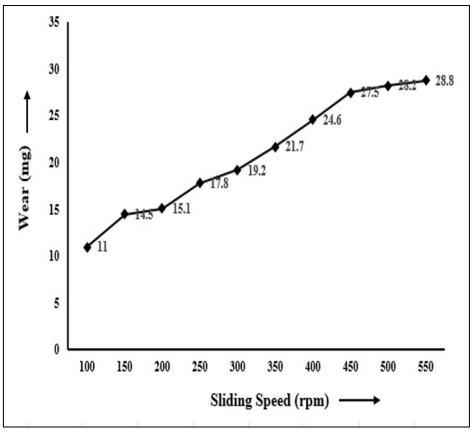

Fig. 9. Impact of sliding speed on the wear of Al6061+10%SiC+10% graphite particles.

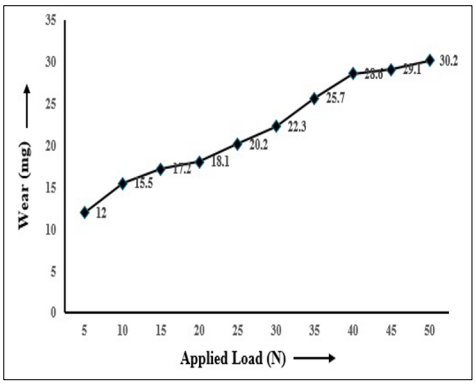

Fig. 7. Effect of applied load on the wear of Al6061+10%SiC+10% graphite.

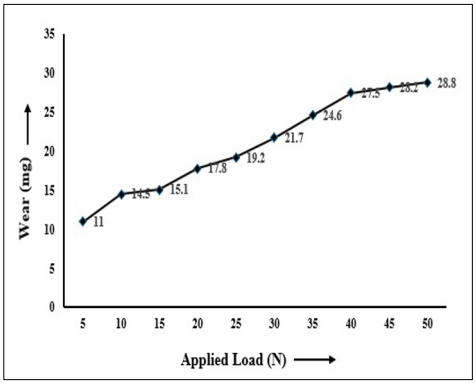

Fig. 10. Effect of applied load on the wear of Al6061+10%SiC+15% graphite.

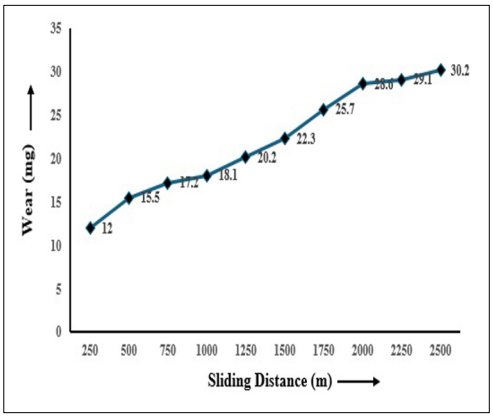

Fig. 8. Impact of sliding distance on the wear of Al6061&10%SiC and 10% graphite particles.

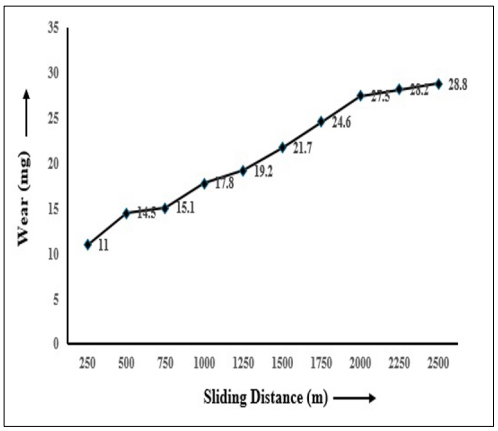

Fig. 11. Effect of sliding distance on the wear of Al6061&10%SiC and 15% graphite particles.

Figure 6. explains the connection amongst sliding speediness and wear of a Aluminium 6061 composite material supported through ten percentage SiC elements and 10% graphite elements. The speediness increased from 100 to 525 rpm, the wear rises steadily from 12 mg to 30.2 mg. This indicates a positive correlation between speed and wear, attributed to increased frictional heat, material softening, and possible breakdown of protective oxide layers at higher speeds. The most significant rise in wear is observed beyond 400 rpm, suggesting the material experiences accelerated wear in this range. Overall, the composite shows better wear resistance at lower speeds and is more suitable for low to moderate-speed applications. Figure 7 indicates the correlation between applied load (N) and Wear (mg) of a Aluminium 6061 composite material toughened by ten percentage of SiC elements and 10% graphite elements. During the rise of the used stuff from 10 N to 50 N, wear also increases steadily from 12 mg to 30.2 mg, indicating the direct relation between load and wear; increasing the load is associated with higher loss of material in most tests. This increase is smooth starting from 10 N up to 30 N but, after this value, it becomes very sharp, referring to the reduction in the material resistance to wear due to high loading conditions that generate high friction and deteriorate the surface. This trend reflects the sensitivity of the material wear to the increase in mechanical stress. Figure 8 shows the correlation between sliding distance (m) and wear (mg) regarding Al6061 composite material toughened by ten percentage of SiC particles and 10% graphite particles. While distance increases from 250m to 2500m, wear also increases steadily from 12 mg to 30.2 mg. This indicates the direct relationship between the sliding distances and wear rate. The wear is increased smoothly, reflecting the uniform removal of material during the same test conditions. Nevertheless, there is notable increment ranging between 1250 m to 1750 m and 2000–2250 m, reflecting some variations in wear behavior due to material fatigue or surface deterioration. In general, longer sliding distances result in higher wear, which is commonly reported in tribological evaluations.

Figure 9: Wear (in mg) w. r. t sliding velocity (in rpm) for Al6061 composite material supported by 10% SiC particles &15 % graphite elements As the sliding speed increased from 100 rpm to 550 rpm, the wear continued to increase from 11 mg to 28.8 mg. This phenomenon shows that with increase in speed, material removal rate more because of increased friction and generation of heat at the contact surface. Beyond 400 rpm, wear rate grows more significantly. This threshold value might indicate that after this sliding speed, the surface degradation accelerates more rapidly. This is the general trend seen in many

tribological studies, which further suggests that control of sliding speed is necessary to minimize the wear of any engineering component. Figure 10: Correlation between applied load, N and wear, mg in Al6061 composite material containing 10% SiC particles and 15% graphite particles. When the used stuff increased 10N to 50N, the wear exhibits a constant growth from 11 mg to 28.8 mg. This is because larger loads would provide greater frictional forces at the contact area leading to a greater removal of material. In between 10 N to 35 N, wear rate increases rapidly. Beyond this, from 40 N to 50 N, the wear rate shows a slight saturation effect indicating surface hardening or stability in the wear mechanism at higher loads. In general, wear is directly proportional to applied load in this study. Figure 11: Sliding distance, in meters, vs wear, in mg of a Al6061 composite material supported by 10% SiC particles and 15% graphite elements. While distance increases 250m to 2500m, wear consistently rises from 11 mg to 28.8 mg. This indicates a direct correlation between sliding distance and material wear. Notable increments in wear occur at regular intervals, with wear values of 14.5 mg at 500 m, 21.7 mg at 1500 m, and 27.5 mg at 2000 m.

4 Conclusion

Wear behaviour of Al6061 mixture composites reinforced with silicon carbide and gr elements were evaluated using a wear test apparatus against EN32 steel discs. Wear increased with an growth in load, gap, and speed. Wear increases more steeply above 400 rpm and 30 N load, reflecting threshold levels beyond which material degradation accelerates as increased frictional heat and surface damage occur. As compared to the normal steady increase in wear with sliding distance, rapid wear at some sliding intervals has shown fatigue-based surface deterioration. These observations emphasize that there exists a direct correlation between operational parameters and wear, emphasizing the superior performance of the composite under low to moderate speeds and loads.. In future, design of experiments concept can be applied for conducting experiments and ANOVA techniques can be applied to develop model to calculate the wear of composites.

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