Mechanical And Wear Characteristics of Aluminium 6061 Hybrid Metal Matrix Composite

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Abstract

Aluminium hybrid metal matrix composites are currently in great demand because they have improved mechanical qualities and can meet the demands of sophisticated technical applications. The selection of the right mix of reinforcing materials significantly impacts the performance of these composites. Oxides, nitrides, and carbides are among the materials used for reinforcement. When creating these composites, the most popular reinforcement ingredients are ceramic particles such as silicon carbide and aluminium oxide. In this work, a hybrid composite (AL6061) reinforced with different ratios of ZnO particles is created using conventional casting techniques. Impact energy, hardness, and tensile strength are mechanical attributes that need to be evaluated for each material combination to anticipate suitable replacements. According to an analysis of the material wear characteristics, the combination of ZnO and fly ash is projected to yield better results for the recommended material than the existing aluminium alloy.

Keywords: AMMC, Hardness, Tensile strength, Pin-on-Disc

1. INTRODUCTION

The demand for lightweight, fuel-efficient, and comfortable materials in the automobile sector has led to the rise in popularity of metal-matrix composites, or MMCs. Because of their high mechanical properties and resistance to wear, MMCs are widely employed in several sectors. They have taken on the role of conventional lightweight metallic alloys, such as aluminium alloys, in applications where energy efficiency and low weight are essential. A metallic matrix containing three-dimensional inclusions, often an alloy of Al, Cu, Fe, Mg, Ti, or Pb, makes up MMCs. They can be customized to have better mechanical, electrical, and chemical capabilities by using the right reinforcements and matrix material mix.

MMCs are able to endure high compressive and tensile stresses with exceptional durability because of a process that transfers load from the ductile matrix to the reinforcing phase. Discontinuous particles, whiskers, and continuous fibres are a few examples of inclusions seen in MMCs. Particulate metal matrix composites, often known as PMMCs, are gaining popularity because of their favourable mechanical, thermal, and tribological characteristics. Automotive components such as cylinder liners, callipers, brake rotors, pistons, and connecting rods are being considered for PMMC use because of their superior wear resistance compared to unreinforced matrix metal. Alumina or silicon carbide (SIC) particles are found in aluminium PMMCs; these particles show reduced rates of sliding and abrasive wear compared to unreinforced aluminium matrix. Because of their improved wear resistance and greater thermal conductivity, AlSiC PMMCs are being explored for use in automobile brake rotors. The mechanical properties of aluminium reinforced with titanium dioxide particles were studied by researchers N. Mathan Kumar et al. [1]. The researchers found that the concentration of titanium dioxide in the base metal matrix rose with density, average hardness, impact strength, and ultimate tensile strength. The compressive strength, however, dropped as the titanium dioxide reinforcing concentration increased. The investigation came to the conclusion that the reinforcement's wettability feature and the strong link between the reinforcement particles and base matrix may be responsible for the improved qualities.

Pardeep Sharma and colleagues [2] examined a hybrid aluminium matrix composite created using stir casting. For the current investigation, graphite (Gr) and titanium oxide (ZrO2) particles were employed as reinforcing phases. A set amount of 3% graphite was combined with variable ZrO_2 particle volume fractions, ranging from 5% to 10%, to create the hybrid MMC. Particles reinforced with graphite and ZrO_2 typically measure 25 and 45 microns, respectively. The stirring procedure was done at 200 rev/min for fifteen minutes. The mechanical properties and microstructure of the produced MMCs are analyzed. Because of their low wear and seizure resistance, cast iron and bronze alloys have been replaced with composites, which R. Ambigai et al. [3] have investigated. They decided on titanium oxide as the matrix phase and aluminium as the reinforcing phase for their study. The objective was to investigate how an aluminium metal matrix with different degrees of reinforcement behaved under wear. Three distinct specimens were created using titanium oxide and aluminium weights of 5%, 10%, and 15%. Stir casting was selected because of its affordability and ease of use. Aluminium was melted, and magnesium was added to make it more wettable. The wear behaviour of the composites was evaluated using pin-on-disc wear test equipment to ascertain their potential as a wear-resistant material.

The work of Hongyan wang et al. [4] was examined. Because of its low weight, high heat conductivity, mild casting temperature, and resistance to corrosion, AMC is highly sought after. Reinforced aluminium matrix composites are used in the fabrication of engine blocks, pistons, and other elements of automobiles and airplanes that are subjected to high levels of friction. ZrO_2 particles were used to strengthen the pure aluminium at weight percentages of 5%, 10%, and 15%. Testing for wear, tensile, compressive, hardness, impact, and XRD in addition to TGA was necessary to determine the mechanical properties of the composites. Muhammad Abdullah and colleagues [5] looked at the microhardness, wear properties, and microstructure of surface composites. It has been determined that dynamic recrystallization is responsible for the finely equiaxed grain structure observed in the stir zone. Because of insufficient material flow and strain, particles clumped together in the first pass surface composite sample. With the second pass, the advancing and retreating sides of the composite plate changed due to a small amount of grain size variation and a uniform microstructure. Upon evaluating the tribological performance with a pin-on-disk tribometer, the findings demonstrated that the aluminium supplied was not as wear resistant as the surface composites created by the second pass.

For use in aircraft applications, A. Lotfy and his colleagues [6] have created a composite material made of titanium carbide, titanium oxide, and aluminium. Powder metallurgy will be used to mechanically create the composites, and various material percentage compositions will be examined. In order to evaluate the process's outcomes with those of pure aluminium, titanium oxide and titanium carbide reinforced with various compositions are mixed with an aluminium matrix. A hardness test will be used to assess the material's phase composition and shape. In order to better understand how ZrO_2 and TiC are continuously distributed throughout the metal matrix and improve the material's tensile strength, the specimen's microstructure will be made visible. The addition of ZrO_2 and TiC to the aluminium matrix will result in a stable interface and even dispersion of the reinforced materials that are submicron in size.

According to a study by Pardeep Sharma et al. [7], calcium carbonate ($CaCO_3$) and leftover eggshell particles were added to an aluminium alloy (AA2014) matrix alloy in order to increase its tensile strength, hardness, and fatigue strength. But it also made the objects less strong and ductile. The inclusion of eggshell particles up to 12.5 weight percent and SiC particles up to 7.5 weight percent reduced the rate of corrosion. SiC reinforcing particles enhanced the qualities of hardness and heat treatability, but they also raised the cost and porosity. The rate of corrosion increased in all reinforced metal matrix composites after heat treatment. When compared to SiC particles, carbonized eggshell was shown to have superior physical attributes at a lesser cost. In contrast to the AA2014 alloy, which had acceptable wettability for both particles between the reinforcement material and the matrix, the CaCO3 reinforcement particles did not have any wettability at all. The inadequate wettability of the composite reduced its mechanical properties. With an emphasis on the impacts of particulate and ionic nanoparticles, Everthon Rodrigues et al. [8] studied several analytical methods for nanoparticle characterization. With representative NMs like aluminium and aluminium oxide, they examined the bio solubility and complexation behaviour of NMs in physiological environments. Nanoparticle dispersions were quickly discovered through the assessment of methods such as dynamic light scattering and nanoparticle tracking analysis and monitoring. Inductively coupled plasma mass spectrometry (SP-ICP-MS) was utilized to quantify and characterize certain nanoparticles. Additional methods employed included small angle X-ray scattering (SAXS) and transmission electron microscopy (TEM). NM contaminants were found to be present, and their colocalization with biomolecules was ascertained, by examining the particle surface with confocal Raman microscopy (CRM) and ion beam microscopy (IBM). The analysis determined the benefits and drawbacks of various methods and offered suggestions on how to best complement each other.

Through the use of powder metallurgy manufacturing techniques, Sachin Ghalme et al. [9] investigated the mechanical characteristics of aluminium matrix-TiC-ZrO2 composites. One of the main ingredients in high performance composites that result in better mechanical characteristics is the considerably smaller particles in the TiC-ZrO2 submicron range that are used to strengthen the aluminium matrix. There are various percentages of reinforcements deployed. Al-TiC-ZrO2 blends can be subjected to high intensity ball milling in order to evenly distribute the TiC-ZrO2 reinforcing phase throughout the Al matrix. Hardness, wear resistance, and density tests are performed on the powder metallurgy-produced samples. Al-TiC-ZrO2 composites are increasingly being produced using powder metallurgical techniques. The interfacial connection between the particles and matrix is evaluated by comparing the hardness under constant load and time in a hardness test. Ankit Tyagi et al. [10] used titanium oxide (ZrO2) particles as reinforcement in addition to Al6082 as the matrix material. The semi-solid state compo casting process was used to create reinforced aluminum-ZrO2 composites with different weight percentages (0, 3, 6, and 9 wt.%). The microstructure of monolithic metals and composites was examined using an optical microscope (OP). The resulting composites' hardness and ultimate tensile strength (UTS) were examined. The testing's findings demonstrate that adding more titanium oxide improves the composites' mechanical properties. A larger amount of ZrO2 added to the composite resulted in improved UTS and hardness.

A multitude of advantages, such as excellent tensile strength, low density, strong wear resistance, and a smooth surface, have made composite material more and more important in the modern era. Two of the most affordable and low-density reinforcements that are readily available in large numbers as solid waste byproducts from ceramic factories are zinc oxide and fly ash. Strength and hardness should also be taken into account. All the components required to achieve the previously described objectives are present in the experimental setup. The goal of this effort is to create a composite material by mixing different percentages of fly ash and zinc oxide (Zn) at a fixed mass ratio with aluminium metal. The mechanical properties of the composite must be investigated after it is created using the sand-casting technique.

2. MATERIALS AND METHODS

2.1. Al 6061

Al 6061 is easily anodized, has an excellent surface polish, and is very resistant to corrosion. It is also a useful material for welding. It is most frequently found in the T6 temper, while it is also formable in the T4 condition. The same uses as 6061 aluminium are applicable to the aluminium alloy 6061. Additionally, it is utilized in extreme sports equipment and rail and road transportation. The heat-treated alloy has good machining qualities; nevertheless, high-speed steel tools are the best choice, and they need to be kept sharp. It is possible to anticipate a rather high rate of tool wear. Applying a generous amount of cutting lubricant is vital.

Table 1 chemical composition for aluminium alloy 6061

Elements	Si	Fe	Cu	Mn	Mg	Ti	Cr	Al
Percentage (%)	0.6	0.36	0.1	0.45	0.1	0.1	0.1	Remaining

Table 2 Typical physical properties of aluminum alloy 6061

Properties	**Values**
Density	2700 Kg/m^3
Melting Point	600^0C
Modulus of Elasticity	69.5Gpa
Thermal conductivity	200 W/m.K
Thermal expansion	23.5 x 10^{-6} /K
Electrical resistivity	0.035x10^{-6} Ω.m

Good machining qualities are present in the heat-treated alloy; nevertheless, high-speed steel tools are the best choice and need to be maintained sharp. Tool wear might be anticipated to occur at a somewhat high rate. It is best to use a generous amount of cutting grease.

2.2. Zinc Oxide (ZnO)

Because of its antibacterial and deodorizing properties, zinc oxide, a common white chemical, has gained a lot of attention recently. It has reached a mature engineering material status, with an annual output nearing 1.5 million tons. Zinc oxide finds application in many sectors, such as rubber, glass, ceramics, and paints, as a white pigment, filler, and bulking agent. In addition, it serves as a corrosion inhibitor in paints and a catalyst in the chemical sector. Zinc oxide powder is still essential for rubber, even though it has historically been employed as a white colour and additive. Table 3.6 provides an illustration of the characteristics of zinc oxide.

Table 3 Properties of Zinc Oxide

Properties	**Values**
Composition	Zn-(80.34%), O-(19.66%)
Density	5.606 Kg/m3
Melting Point	1975 ℃
Particle Size	325 mesh
Form	White Powder

ZnO has seen significant changes in applications throughout time. Some important uses, such as linoleum and photocopy paper (where it was the second-largest volume consumed as a photoconductive ingredient in the 1970s), have all but disappeared. Moreover, ZnO is no longer the main white pigment used in paint. These days, its primary uses are in the ceramics and rubber sectors, despite its numerous specialized applications, such as drilling fluids for the oil and gas sector. ZnO has been studied recently for application in memory devices, solar cells, LEDs, transparent transistors, and as the foundation for a transparent conducting oxide for consumer electronics.

2.3. Fly ash

Fly ash, often referred to as flue ash, is a residue that is produced when coal is burned. It is made up of small particles that ascend along with the flue gases. Particle filtration devices or electrostatic precipitators often catch it before it reaches the chimneys of coal-fired power stations. Bottom ash as well as fly ash are referred to as coal ash. It has high concentrations of calcium oxide and silicon dioxide (SiO2), two elements that are common in many strata that support coal. The coal bed's composition can contain toxic elements like dioxins, arsenic, and other compounds. 43% of fly ash is recycled and used to augment Portland cement in concrete manufacturing, highlighting the importance of responsible waste management. Fly ash is normally stockpiled in coal power stations or dumped in landfills in the US. Fly ash, which is produced when solid waste is burned to create energy, may contain more toxins than bottom ash, which increases certain health risks. While fly ash alone would be considered hazardous trash, mixing fly and bottom ash can help classify fly ash as non-hazardous waste.

Table 4 Typical properties of fly ash

Properties	Values
Density	1.93 g/cm^3
Bulk Density	1.26 g/cm^3
Moisture content	2 %
Particle Shape	Spherical
color	Grey

3. EXPERIMENTAL METHODS AND CHARACTERISTICS

The components of an aluminium metal matrix composite material are filler and matrix materials bonded with fibre or particle composites. The casting technique is said to be the most cost-effective option when it comes to processing through liquid cast metal technology, powder metallurgy, or a unique production process. In order to produce an alloy, aluminium, 6061 rod, fly ash, and zinc oxide must be purchased. The aluminium rod is then melted in a graphite crucible.

For this particular study, we used sand mold casting to get the required size. A metal casting process called sand casting, or sand molded casting, uses sand as the mold material. Even for usage in steel foundries, it is adequately refractory and reasonably priced. Sand and an appropriate bonding agent, typically clay, are combined or occur together. To give the clay more strength and pliability and to prepare the aggregate for molding, water is added to the mixture. A casting produced by the sand-casting method is also known as sand casting. Specialized firms called foundries are responsible for producing sand castings. Sand casting is the method used to create more than 70% of all metal castings.

There are six steps in this process:

- To make a mold, press a design into the sand.
- Add sand and the pattern to a gating system.
- Take out the pattern.

- Melt the metal and pour it into the mold cavity.
- Let the metal cool.
- Remove the casting by breaking off the sand mold.

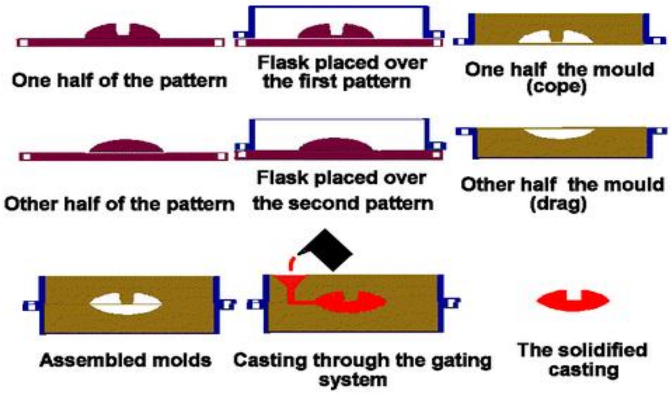

Figure 1. Sand Casting Process

- Sample 1: Al 6061 95%+FA5%+ZnO 0%
- Sample 2: Al 6061 + FA5%+ZnO 1%
- Sample 3: Al 6061 + FA5%+ZnO 2.5%
- Sample 4: Al 6061 + FA5%+ZnO 5%

Three exact test procedures are used by the metals industry to assess hardness: the Brinell, Rockwell, and Vickers tests. Because the concepts of metallurgical ultimate strength and hardness are so similar, it is widely thought that a strong metal is also a hard metal. Three different tests are used to determine a metal's hardness: a non-deformable ball or cone puncturing it, together with its resistance to penetration. The tests assess how far a ball or cone of that type will sink into the metal in a given length of time at a certain weight. Tensile testing is used to evaluate the mechanical properties of friction-processed joints. It is one of the most widely used methods of testing hardness in modern technology. Tensile characteristics like tensile strength, yield strength, percentage of elongation, percentage of area reduction, and modulus of elasticity can all be ascertained using a tensile test. The welding settings were selected at random from the machine's possible range. To test the joints' tensile strength and burn off, random factors were used in their construction. Following that, the joints were built and their metallurgical and mechanical characteristics evaluated. The friction-welded specimens were prepared in accordance with ASTM specifications. The test was carried out with a universal testing machine (UTM) and a 40-ton FIE.

Figure 2. Tensile Test and Rock-Well Hardness Test Machines right and left

4. RESULT AND DISCUSSIONS

4.1. Hardness

A mechanical process called a hardness test determines a material's ability to withstand distortion, particularly continuous deformation or indentation. One popular technique for determining the hardness of aluminum alloys is the Rockwell hardness test. To make an indentation on the surface of the material, a little load and a big load are applied successively. The hardness value is then ascertained by measuring the indentation's depth. The results of hardness tests are crucial for assessing the suitability of aluminium alloys for different purposes, as well as for quality control and material certification processes. Hardness test results are tabulated in Table 5 and Figure 3 for graphical comparison. These results provide valuable information for engineers and manufacturers in selecting the appropriate aluminium alloy for specific applications. By comparing the hardness values of different alloys, sample R4 has the highest hardness value, indicating it may be the most suitable for applications requiring high strength and wear resistance. ZnO nanoparticles could improve this alloy's mechanical qualities even more, making it even more appropriate for demanding applications.

\Table 5. Hardness Values of Proposed Samples

S. No	Composition	HRB
R1	Al 6061 95%+FA5%+ZnO 0%+ Mg-1%	51
R2	Al 6061 + FA5%+ZnO 1% + Mg-1%	62
R3	Al 6061 + FA5%+ZnO 2.5% + Mg-1%	69
R4	Al 6061 + FA5%+ZnO 5% + Mg-1%	72

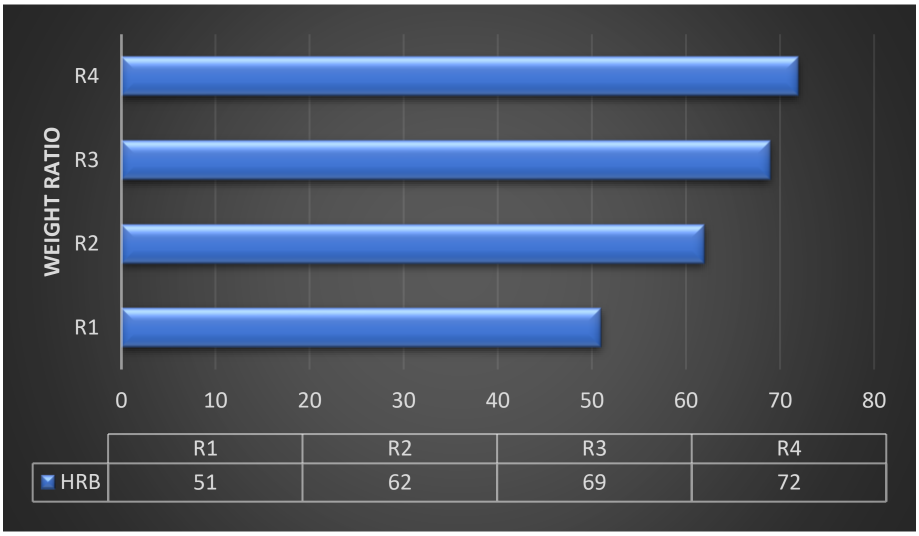

Figure 3 Weight Ratio Vs. Hardness Strength

4.2. Impact Strength

An important technique for determining how resilient aluminium alloys is to abrupt loads or impact pressures is the impact test. It aids in figuring out how well a material can withstand fracture and absorb energy in high-stress situations. The most commonly used technique is the Charpy impact test, which involves measuring the energy absorbed during a fracture by placing a notched specimen in a pendulum-style impact testing apparatus. The values for each suggested sample's impact strength are displayed in Table 6. Among the proposed samples, R1 has the highest impact strength, making it the most suitable choice for applications requiring high toughness and resistance to impact forces. And in this case, the impact strength of the addition of ZnO nanoparticles may be attributed to changes in the microstructure of the material. Figure 4 illustrates the graphical results between the weight ratio and impact strength of the samples, showing a clear correlation between the two variables.

Table 6. Impact Strength Results of Proposed Samples

S. No	Composition	Impact Strength (Joules)
R1	Al 6061 95%+FA5%+ZnO 0%+ Mg-1%	4
R2	Al 6061 + FA5%+ZnO 1% + Mg-1%	3
R3	Al 6061 + FA5%+ZnO 2.5% + Mg-1%	2
R4	Al 6061 + FA5%+ZnO 5% + Mg-1%	2

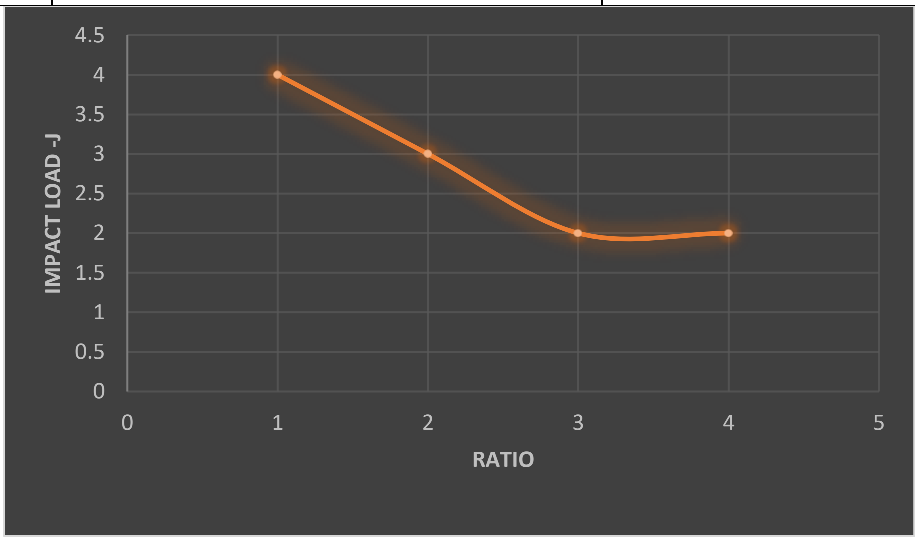

Figure 4. Weight Ratio Vs. Impact Strength

4.3. Tensile Strength

An aluminium alloy's tensile test is a mechanical procedure designed to ascertain how the material will respond to pulling or tensile forces. This usually entails shaping or machining the sample to a certain geometry and dimension, like a dog bone. The testing apparatus measures the force needed to generate this deformation as well as the sample's subsequent elongation. Stress (force per unit area) and strain (deformation as a percentage of the original length) are computed using this data. Table 7 shows the tensile strength results of different samples, with Sample R3 showing the highest strength before breaking. This indicates that Sample R3 is the most resistant to pulling or tensile forces. Figure 5 shows a positive correlation between weight ratio and tensile strength, with Sample R3 having the highest weight ratio and tensile strength among all tested samples.

Table 7. Tensile Strength Value of Proposed Samples

Sample	Dia (mm)	CSA (mm2)	TL (kN)	TS (N/mm^2
A1	16	201.06	14.70	73.15
A2	16	201.06	20.03	99.67
A3	16	201.06	31.38	156.15
A4	16	201.06	23.51	116.99

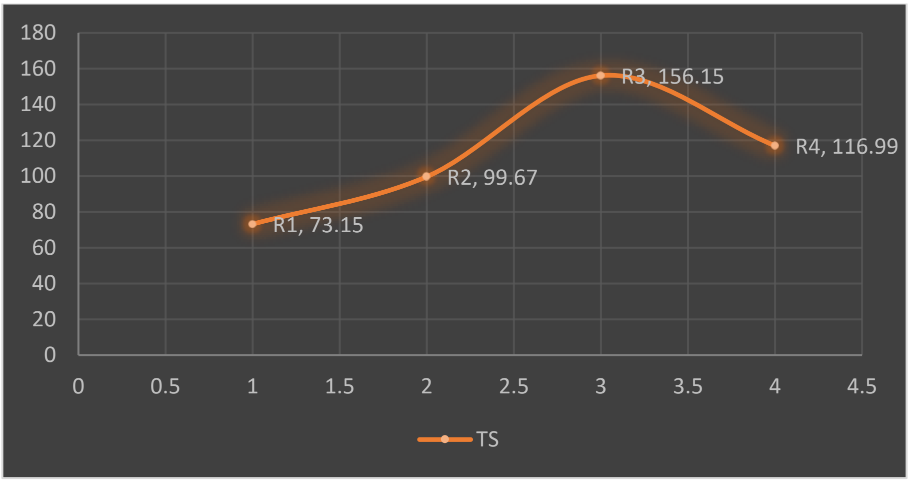

Figure 5. Weight Ratio Vs Tensile Strength

4.4. Compressive strength

One mechanical technique for figuring out how aluminium alloys react to compressive stresses is compression testing. It entails getting a sample ready, exerting controlled pressure on it, and noting the deformation that results. This data is analyzed by engineers and material scientists to find qualities like withstand ability and compressive yield strength. The suggested aluminium alloys' compression test results and matching compressive strengths are displayed in Table 8. Based on the comparison of these figures, sample R3's compressive strength is higher than samples R1 and R2, suggesting that it might find utility in situations where a higher resistance to compressive pressures is needed. The graph of compression findings for each sample is depicted in Figure 6, which makes the variation in compressive strength between the samples evident.

Table 7. Compression Strength Value of Proposed Samples

S. No	Composition	Compression Strength (N/mm^2)
R_1	Al 6061 95%+FA5%+ZnO 0%+ Mg-1%	33.93
R_2	Al 6061 + FA5%+ZnO 1% + Mg-1%	37.66
R_3	Al 6061 + FA5%+ZnO 2.5% + Mg-1%	214.74
R_4	Al 6061 + FA5%+ZnO 5% + Mg-1%	183.28

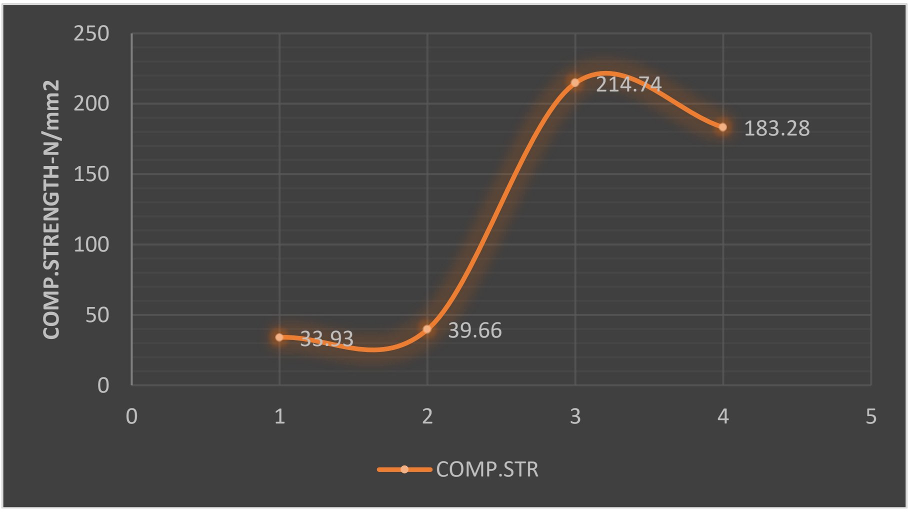

Figure 5. Weight Ratio Vs Compression Strength

4.5. Wear test

A tribometer measures tribological parameters from surfaces in contact, such as wear volume, friction force, and coefficient of friction. In tribology investigations, a device called a tribotester is used to simulate and measure wear, friction, and lubrication. These devices are often specific and manufactured by manufacturers to analyse the long-term performance of their products. For instance, orthopaedic implant manufacturers have developed tribotesters that accurately reproduce human hip joint motions and forces for accelerated wear tests of their products. Table 8 presents the rates of wear for the different samples that this work suggests. Sample R3 has better wear resistance characteristics than the other three samples, making it a promising option for applications requiring high durability. Figures 6 to 9 shows the wear rate of each sample over time, indicating that Sample R3 consistently outperforms the others in terms of wear resistance. This suggests that Sample R3 may be the most suitable choice for applications where longevity and durability are key factors.

Table 9. Wear Rate of the Different Composite Materials

S. No	Ratio	Before Weight	After Weight	Difference
R_1	Al 6061 95%+FA5%+ZnO0%+Mg-1%	6.5979	6.5821	0.016
R_2	Al 6061 + FA5%+ZnO 1% + Mg-1%	6.2458	6.2314	0.014
R_3	Al 6061 + FA5%+ZnO 2.5% + Mg-1%	6.0077	5.9944	0.013
R_4	Al 6061 + FA5%+ZnO 5% + Mg-1%	6.0712	6.0575	0.014

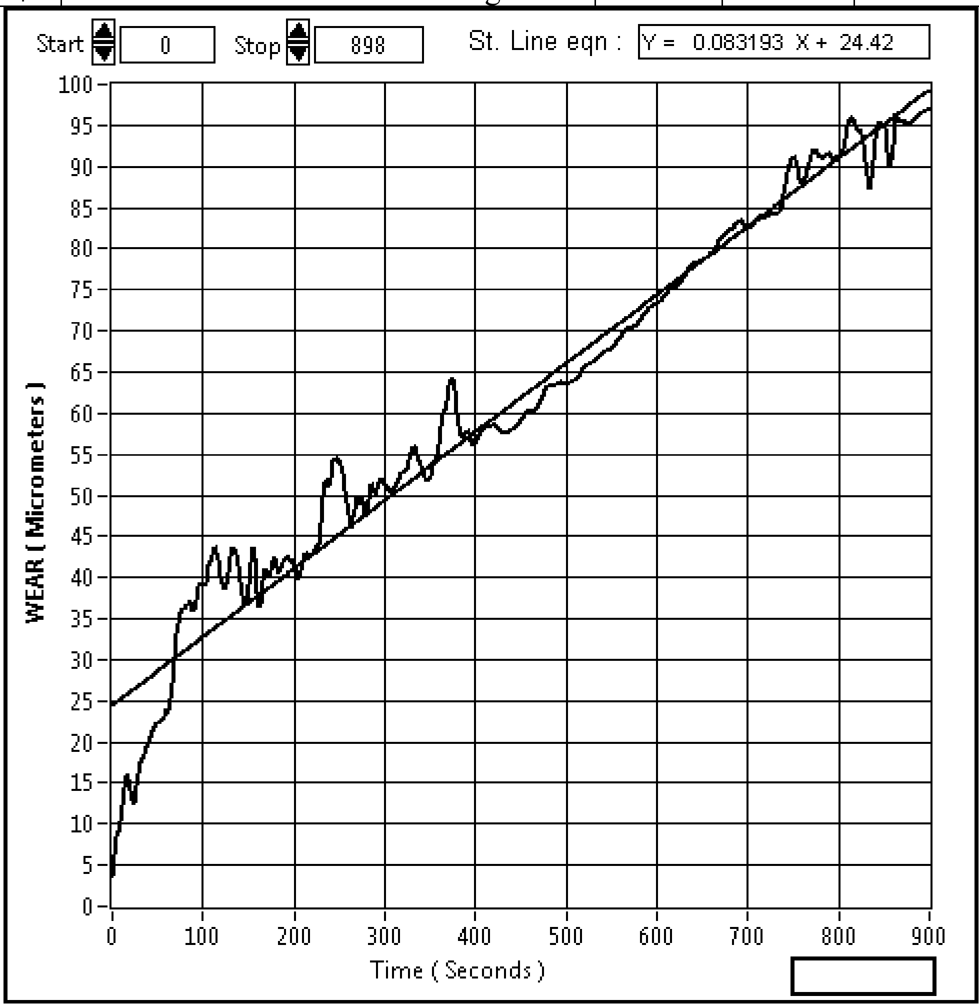

Figure 6. Weight Ratio vs. Wear Rate for R1

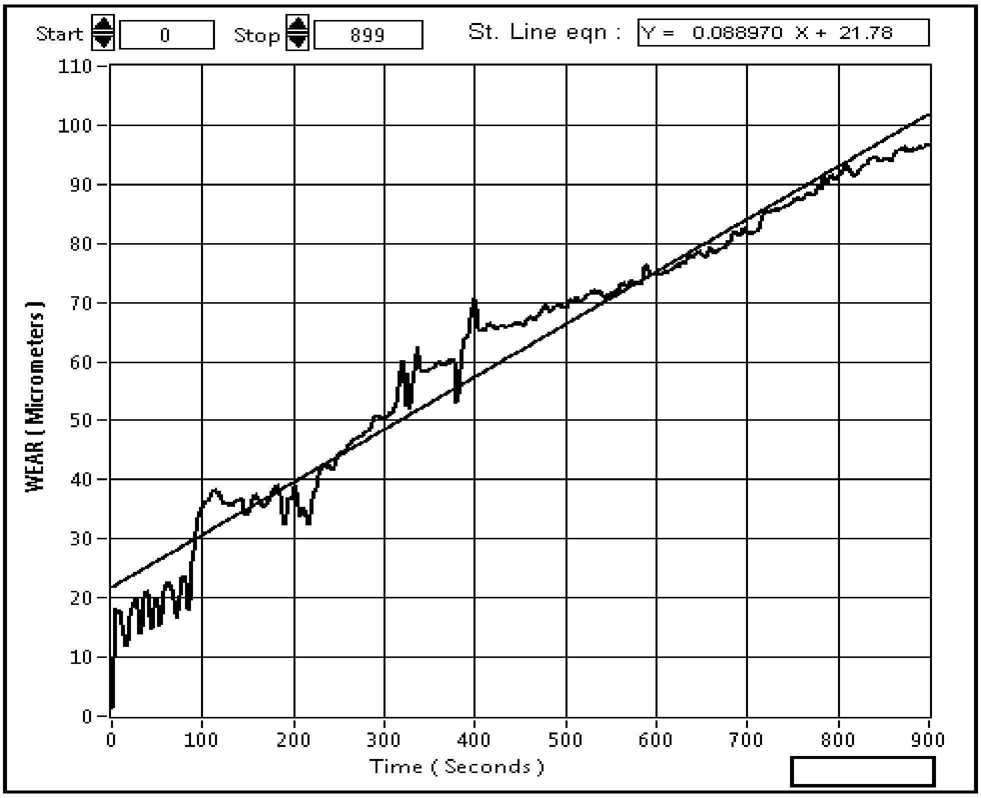

Figure 7. Weight Ratio vs. Wear Rate for R2

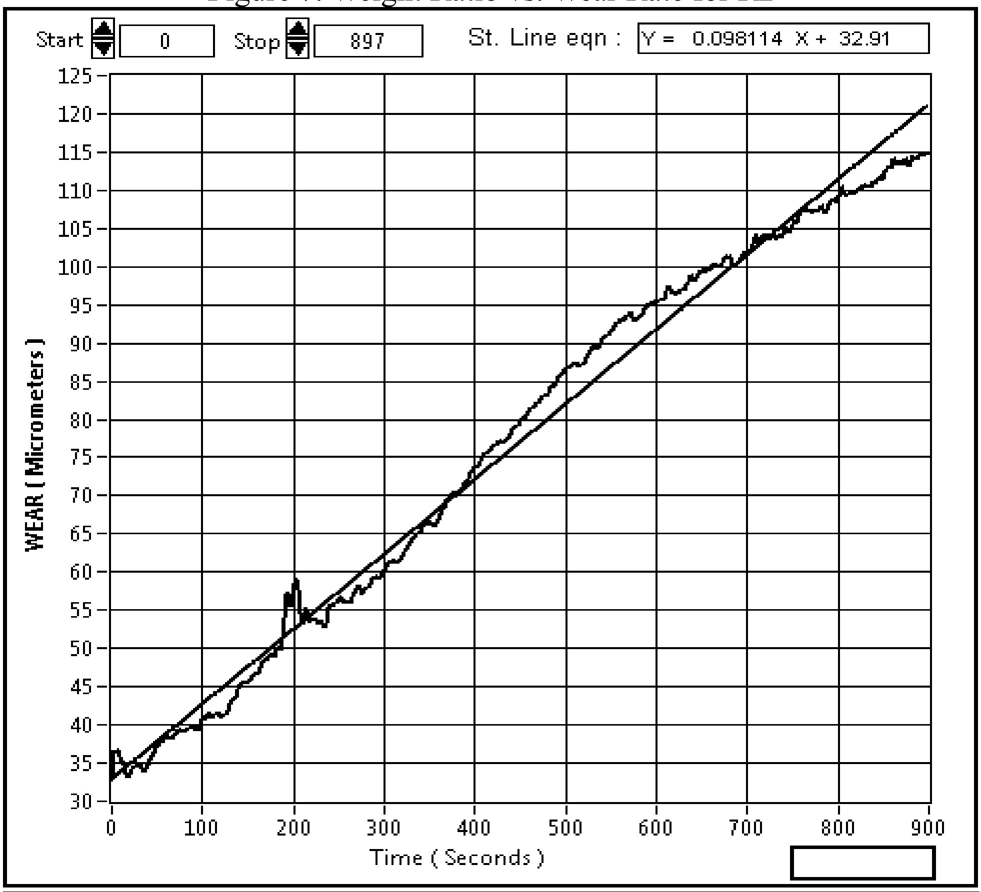

Figure 8. Weight Ratio vs. Wear Rate for R3

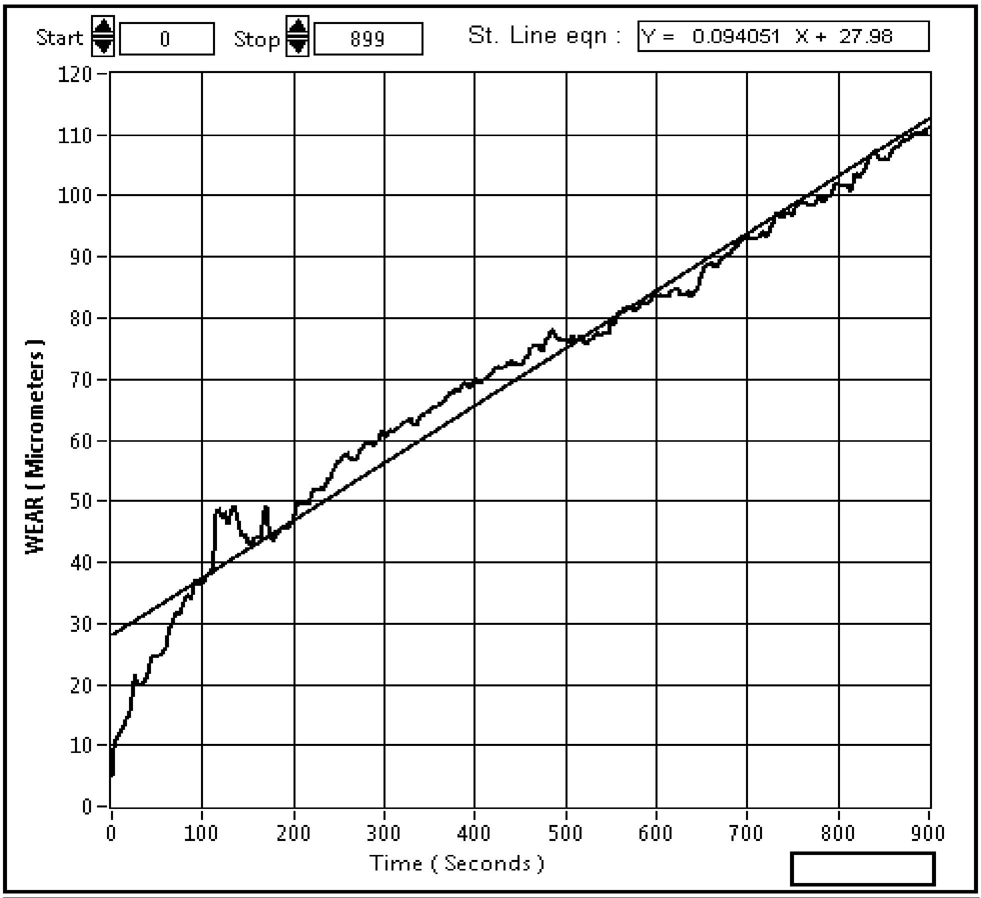

Figure 9. Weight Ratio vs. Wear Rate for R4

5. Conclusion

In particular, fly ash, zinc oxide, and aluminum 6061 are hybrid metal matrix composite materials with superior mechanical qualities above traditional materials. Due to their exceptional durability and low weight, these materials are used in many different industrial applications. The slightly increased weight of the base reinforcement, which improved the properties of metal matrix composites, is responsible for the maximum at ratio 3 (Al 6061 + FA5% + ZnO 2.5% + Mg 1%) found in the results of the compression value analysis and tensile test. Al 6061 + FA5% + ZnO 5% + Mg 1%) ratio 4 displays the hardest value, 72 HRB. During the wear investigation, a ratio of three indicated an extremely low wear rate. The materials that produce the least amount of wear are 1% magnesium reinforcement, 2.5% zinc oxide, and 5% fly ash. When more reinforcement composites are used, there is more agglomeration in the metal matrix, which results in brittleness, which is the maximum impact strength that pure Al6061 can achieve.

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