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Study on Mechanical, Wear and Thermal Properties of AL2O3/Graphite Reinforced AA2024 Aluminum Alloy Based Metal Matrix Composites

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Abstract: ***Metal matrix composites (MMC) play a vital role to satisfy global needs for low low-cost and high-performance mechanical, and thermal properties and quality materials in the composite industry. Aluminium MMCs are preferred to other conventional materials in the fields of aerospace, automotive and marine applications owing to their improved properties like high strength-to-weight ratio, good wear resistance, etc. In the present work, an attempt has been made to synthesize metal matrix composite using AA2024 as matrix material reinforced with Al_2O_3 and Graphite (Gr) particulates using a liquid metallurgy route in particular stir casting technique. 2024 aluminium alloy is reinforced by different weight fractions of Al_2O_3 and Gr particles up to 5 wt%. The effect of wt% of Al_2O_3 and Gr on the properties such as density, hardness, tensile strength, wear rate, flexural strength, and coefficient of thermal expansion were evaluated. Scanning electron microscope and X-ray Diffraction (XRD) were used to examine the microstructure of the produced hybrid MMC composite. The addition of Al_2O_3 and Gr pronounced improved mechanical properties and wear. Results indicated that aluminium ceramic composites can be considered as an alternate material for AA2024, where high strength and wear-resistant components are of major importance, particularly in the aerospace and automotive engineering sectors.***

Keywords: MMC's, Al_2O_3 Particulates, Graphite, AA2024, Stir-Casting

I. INTRODUCTION

The fabrication of hybrid MMCs requires various alloys like Al alloys, Mg alloys, Zinc alloys, etc., and among the various alloys, Aluminium alloy is the most commonly used as a base matrix because of its low density, and low corrosion providing high strength to weight ratio, good fatigue resistance and widely reached the highest production stage in all industries sectors.

Some of the applications of aluminium metal matrix composites (AMMCs) are engine pistons, and cylinder liners. The MMCs are made complete by the addition of the reinforcement in the base matrix by different process techniques. Some of the different methods which are adopted for producing MMCs are powder metallurgy, squeeze casting, spray deposition, stir casting, etc. Among this process, stir casting is generally used because of its availability and less economy. Atwo-step process mixing of reinforcement is adopted in stir casting because it results in increases in hardness, impact strength, and also excellent bonding between the ceramic and alloy. We can also observe that there will be no agglomeration where particles will be uniformly distributed andthere will be a lower wear rate than that of pure aluminium.There are different hard and soft ceramic particles available like B_4C, SiC, Al_2O_3, Graphite, Mica, ZrO_2, etc. These ceramic particles are reinforced into an Al matrix which helps in strengthening and increasing the property of the base matrix. The MMCS are strongly influenced by some of the parameters of the reinforced particulates such as shape, size, orientation, uniform distribution andweight. With the hard particles which are dispersed in a relatively ductile material, the Al matrix composite possesses an ideal structure wear-resistant material. In the above-mentioned ceramic particles Al_2O_3, SiC and Graphite are the most reinforcing material which is used in various applications. Al_2O_3 /SiC fibers and particles are the most commonly used reinforcements in MMCs and the addition of these reinforcements to aluminium alloys has been the subject of a considerable amount of research work. The application of Al_2O_3 or SiC-reinforced aluminium alloy matrix composites in the automotive and aircraft industries is gradually increasing for pistons, cylinder heads, etc., where the tribological properties of the material are very important. Therefore, the development of aluminium matrix composites is receiving considerable emphasis in meeting the requirements of various industries. The incorporation of hard second phase Particles in the alloy matrix to produce MMCs has also been reported to be more beneficial and economical.

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Particulate reinforced metal matrix composites are prepared by the stir casting technique, well-defined matrix and reinforcement particulate characteristics, uniform distribution of the particulate reinforcement phase in the aluminium alloy metal matrix, integrity at the particulate reinforcement–metal matrix interfaces, and low levels of porosity.

II. OBJECTIVE

To fabricate AA2024 reinforced with Al2O3/ Gr using the stir casting technique, and to study properties like physical, mechanical, wear, and thermal properties.

A. Al_2O_3 as a Reinforcement

Al2O3 is one of the cost-effective reinforcements among oxide ceramics. It also has excellent properties like Thermal Conductivity, High Strength and Stiffness, strong acidic alkali and wear resistance.

B. Graphite as a Reinforcement

Graphite (Gr) is a low-density reinforcement. Aluminum-based ceramic particles required improvement in their lubrication properties of Graphite (Gr) as a reinforcement when added to AA2024 with Al2O3 gives good lubrication properties.

III. RESEARCH DESCRIPTION AND GOALS

The goal of the research is to fabricate and improve the properties of AA2024 reinforcing with Al2O3/Gr using the stir casting technique and to study the physical, mechanical, tribological, and thermal properties of prepared hybrid metal matrix composites.
The fabrication of AA2024 and Al2O3/Gr hybrid metal matrix composite was done in a stir casting machine where first AA2024 alloy was heated and melted into a red-hot molten liquid and then cover all flux and degassing agents were added to remove oxidized material and gases from molten metal and then reinforcements are slowly added and the liquid metal is poured into a mold. A cylindrical rod 30x270mm was cast out, but specimen testing should follow ASTM standards. So the material was machined as per ASTM standards and performed different tests. The material is tested for tensile, hardness, and flexural to understand the mechanical properties and was done on it to identify the phases present, microstructural analysis was carried out to know the distribution of reinforcements, and wear analysis is conducted to understand the properties of wear. Dilatometry tests to study the coefficient of thermal expansion finally results were compared to know how the mechanical properties of composite changed with an increasing percentage of Al2O3

IV. TECHNICAL SPECIFICATION

A. Stir Casting Procedure

Initially, AA2024 alloy was charged into the crucible, and heated to about 750◦C, which is above the liquid temperature of the Al alloy. After the entire alloy in the crucible was melted, the pre-heated impeller was attached to the motor shaft, turned on and set to the pre-determined speed. Then, the mixer was lowered into the melt slowly to stir the molten metal, while the Al2O3 particles, which we reheated at 250◦C for 25min and air-cooled to room temperature (about 30◦C) before incorporation, were added into the uniformly formed vortex using a funnel-shaped pipe.

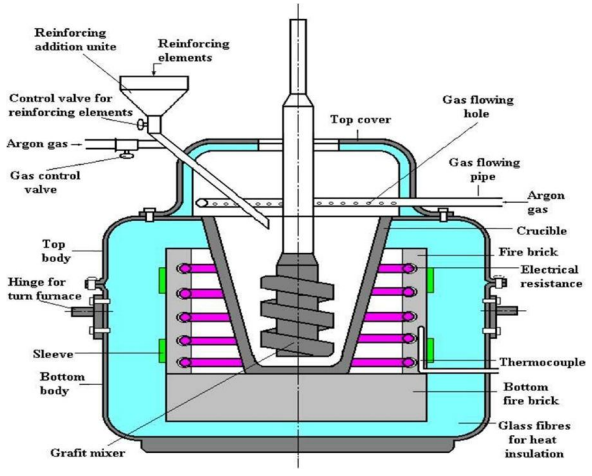


Fig. 3.1. Schematic stir casting setup.

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After the completion of particle feeding, the mixing was continued for a further 5min. Then, the mixer was turned off, and the molten mixture was poured in the pre-heated mould by tipping the furnace. Finally, the mould was opened after 5min and the fabricated billets were air-cooled to room temperature. Unreinforced matrix alloy bars were also produced by the same method. The outside of this production unit was insulated with glass fibers as shown in Fig.3.1. The temperature control of the electric furnace and molten metal is carried out by an NR911 type thermostat. This thermostat has a special control unit and thermocouples. Thermocouples were inserted into the melt and the furnace to measure their temperature.

B. Materials Selection

In this study, AA2024 aluminium alloy with the theoretical density of 2.79g/cm^3 and its chemical composition was shown in table-3.1, was used as the matrix material while -Al2O3 (alumina) particles with various particle sizes of 16µm, Chemical composition of Al2O3 with a density of 3.950g/cm^3 was used as the reinforcements. The Al2O3 particles supplied by D K Enterprises, are short particles with a white color. The chemical analysis of the Al2O3 /Gr particles and the AA2024 alloy used in this study respectively. Table-3.2 shows the composition of raw materials used in preparation of HMMC. The Al2O3/Gr particle-reinforced AA2024 alloy metal matrix composites have been produced by using a vortex method.

Table-3.1 Chemical composition of AA2024

Element	Wt.%
Zn	0.2
Cu	4.5
Mn	0.6
Mg	0.6
Fe	0.4
Cr	0.1
Si	0.4
Ti	0.1
Al	Balance

Table -3.2 Sample compositions

Sample Identification code	AA2024 Wt%	Al2O3 Wt%	Gr Wt%
S1	95	2.5	2.5
S2	95	3	2
S3	95	3.5	1.5
S4	95	4	1

C. Design Standard Codes

Table-3.3 ASTM standard codes

S.no	Test Name	Standard code
1	Tensile test	ASTM E8/E8M-15A
2	Density test	ASTM D792
3	Micro structural	ASTM E407
4	Hardness test	ASTM E18
5	Flexural test	ASTMD790

D. Realistic Constraints

Adding of reinforcements should be done slowly for ideal distribution of reinforcements while stirring but slow mixture of reinforcements leads to quick solidification, mixture of reinforcements should be optimum.

V. EXPERIMENTAL PROCEDURE

A. Density and Porosity

The experimental density of the composites was obtained by the Archimedes method. While the theoretical density was calculated using the mixture rule according to the weight fraction of the Al2O3 /Gr particles. The porosities of the produced composites were evaluated from the difference between the expected and the observed density of each sample.

- Formula for density measurement

$$\rho_{composite} = \frac{1}{\frac{Wt\ \%\ of\ material-1}{density\ of\ material-1} + \frac{Wt\ \%\ of\ material-2}{Density\ of\ material-2} + \cdots\cdots\cdots\cdots}$$

- Formula for porosity

$$Porosity = \frac{\rho_{theoretical} - \rho_{experimental}}{\rho_{theoretical}}$$



Fig 4.1 Density measurement apparatus

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B. X-ray Diffraction

The prepared samples were characterized by a diffractometer (XRD 3000, SEIFERT) with agraphite monochromatic Cu-Kα radiation of 1.5406 Å operating at 30 kV and 40mA to study the X-ray powder diffraction (XRD). The XRD patterns were acquired in the 2θ range of 5°–80° to determine the phase evolution of different samples.

C. Microstructural Studies

The microstructures, fracture surface morphologies, and elemental compositions of the composites were examined using a Hitachi (S-3700N) ultra-high resolution field emission gun scanning electron microscope (FEG-SEM) equipped with an EDS. The surfaces of the specimensfor microstructural examination were metallographic ally prepared following a series of grindingand polishing steps to achieve a mirror-like surface finish. The samples were subsequently etchantusing Keller's reagent (92 ml of distilled water, 2 ml of HF, and 6 ml of HNO3) by swabbing before a microstructural examination was performed.

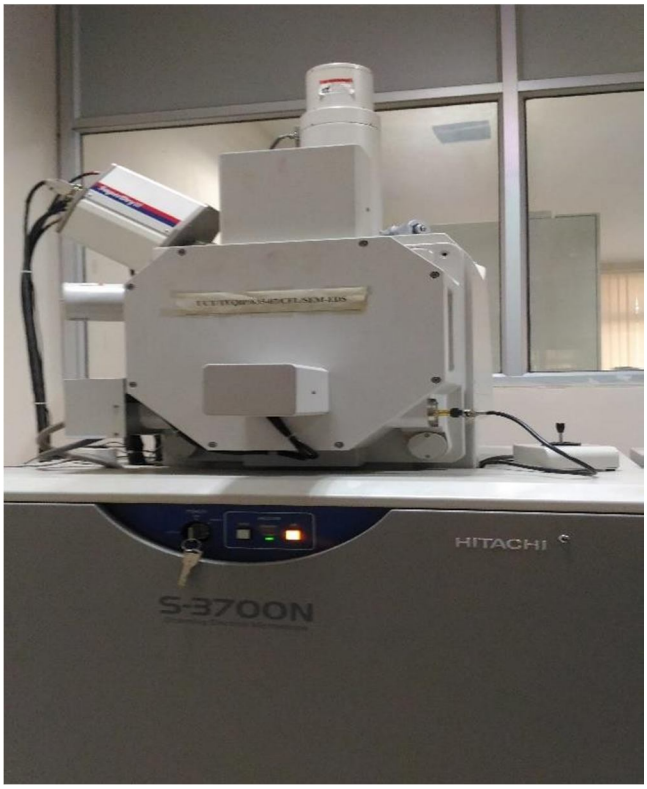


Fig 4.2 SEM apparatus

D. Hardness

Hardness is a mechanical characteristic of a material, not a fundamental physical property.It is defined as resistance to indentation, and it is determined by using permanent depth of indentation. More simply, when a fixed force and given indent, the smaller the indentation, the harder the material. The indentation hardness value is obtained by measuring the depth or area of indentation. The hardness tests were carried out according to ASTM E10-07 standards using a Brinell hardness testing machine with a 10 mm ball indenter and 500kg load for the 60s. The test was conducted at room temperature and the measurement of hardness was taken at five differentplaces on each specimen to eliminate possible segregation effects and to get a representative value of material hardness. Results were arranged out of five random test indentations.

E. Tensile Test

Tensile tests were used to assess the mechanical behavior of the composites and matrix alloy. The composite and matrix alloy rods were machined to tensile specimens with a diameterof 9mm and gauge length of 45mm. The tensile strength was done on a universal testing machineat a velocity of 0.5mm/min.

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The tensile properties of the composites produced were evaluated by tensile test using a universal testing machine. Specimens were machined to cylindrical rods of 13 mm diameter and 45 mm gauge length. The specimens were mounted on the testing platform and pulled monotonically at a velocity of 0.5mm/min until fracture. The tests were performed at room temperature following recommendations of ASTM 8M-91 standard. The tensile properties evaluated from the test are the ultimate tensile strength, yield strength and % of elongation (determined by calculating the area under the stress-strain curves generated).

$$\text{Formula for \% elongation} = \frac{\delta L}{L}$$

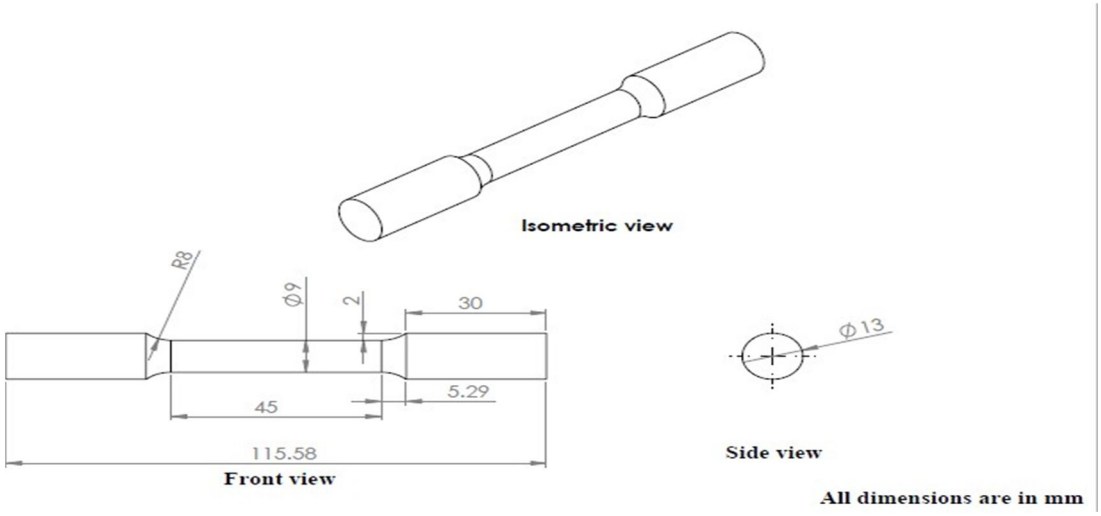


Fig 4.3 Dimensions of the tensile test specimen



Fig 4.4 Universal testing machine apparatus

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F. Flexural Test

The flexural strength was conducted on 4 samples prepared with a span length of 60 mm long, 25mm wide and 4mm thick. The measurements were performed using the three-point bending technique, using a universal testing machine (shimadzu). The crosshead speed in loading was 0.5 mm min−1.

G. Wear Test

The wear test rig employed was of the pin-on-disk type to investigate the dry sliding behaviour of AA2024/Al2O3 /Gr hybrid composites. The main drive shaft was rotated by an electric motor through pulleys. The sliding velocity of 0.785m/s was set by using a variable speedcontrolled at 637 rpm. Pin specimens of 8 mm diameter and 32 mm height were prepared from the above composites and were machined and polished metallographic ally. An Oil Hardened Nickel Steel (OHNS) 100 mm diameter steel disc was used as the counter surface in the wear test. Thetest was conducted with a load of 10kg at a sliding speed of 0.785 m/s for the constant sliding distance of 1000m for all the experiments. The test was conducted at room temperature (30°C) the wear test was carried out in dry conditions using a wear track diameter of 100mm. The diameter and sliding time of 60 min were kept constant for all the experiments of specimens to eliminate this as a further variable of the rubbing system. The wear test was conducted after the initial run-in period when the pin Specimens were entirely in contact with the disc surface. In each testafter running the fixed sliding distance, the specimen was removed, cleaned with acetone, driedand weighed to determine the weight loss due to wearing. The wear rates were determined using the weight loss method.

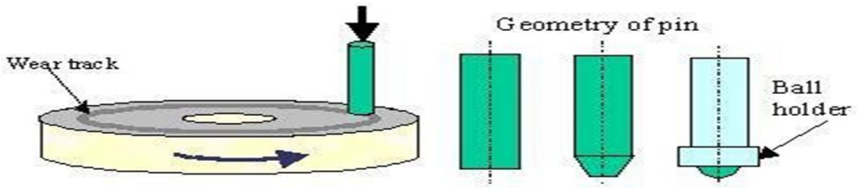


Fig-4.5 Pin on disc apparatus

H. Coefficient of Thermal Expansion

Thermal expansion is the tendency of matter to change in shape, area, and volume in response to a change in temperature. Thermo-mechanical analysis was conducted to measure the coefficient of thermal expansion with a dilatometer (VB model: from 70 °C to 800 °C at a heatingrate of 10 °C/min).

VI. RESULTS AND DISCUSSIONS

A. Physical Characterization

1) *Density and Porosity Analysis:* Presented with the comparison of theoretical density obtained by the rule of the mixture and measured density values by experiment for all the composites studied for different wt. % of reinforcements. Experimentally, the density of a composite is obtained by displacement techniqueusing a physical balance with Mettler Toledo ME204 apparatus as shown in Fig-4.1 is used for thedensity measurement as per ASTM: D 792-66 test method. Further, the porosity can also be calculated from density values (sample mass and dimensions). Both the theoretical, experimentalvalues and porosity values are given in table-5.1 It can be concluded that the experimental density of composites is less when compared to the theoretical density, which could be due to the presence of porosity. The presence of porosity in the sample is probably due to (i) An increase in surface area in contact with air (ii) Gas entrapment duringstirring (iii) The pouring distance from the crucible to the mold and (iv) Shrinkage during solidification.

Table-5.1 Density and porosity

Samples	Theoretical Values(g/cm^3)	Experimental Values(g/cm^3)	Porosity (%)
S1	1.905	1.84	3.4
S2	1.976	1.91	3.34
S3	2.0139	1.942	3.57
S4	2.052	1.967	4.14

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2) *X-Ray Diffraction Analysis:* Fig.5.1-5.4 shows the XRD analyses conducted on AA2024-based composites reinforced with Al_2O_3/Gr particles to confirm the presence of Al_2O_3 /Gr to identify other phases formed. In the X-ray diffraction pattern (Fig. 5.1), peaks have been obtained in the 2Θ span ranging from 10 to 80 and the peaks at 2Θ of 38.44°, 44.7°, 65.32° and 77.2°belongs to AA2024 and the peaks at 2Θ of 42.23° and 51.46° belongs to Al_2O_3 and the peaks at 2Θ of 26.5°,54.5° belongs to Gr and other remaining minor peaks attributed to impurity. Fig 6.2 Shows the X-ray diffraction pattern and results of AA2024 alloy with Al_2O_3/Gr hybrid MMCs. In X-ray diffraction (Figure 5.2), peaks have been obtained in the 2Θ span ranging from 10 to 80 and the peaks at 2Θ of 38.44 °,44.7°, 65.32° and 77.2° belong to AA2024and the peaks at 2Θ of 37.46°, 44.67°, 58.2°belongs to Al_2O_3 and Gr peaks are very small due tolow intensity. Other remaining minor peaks are attributed to impurity.

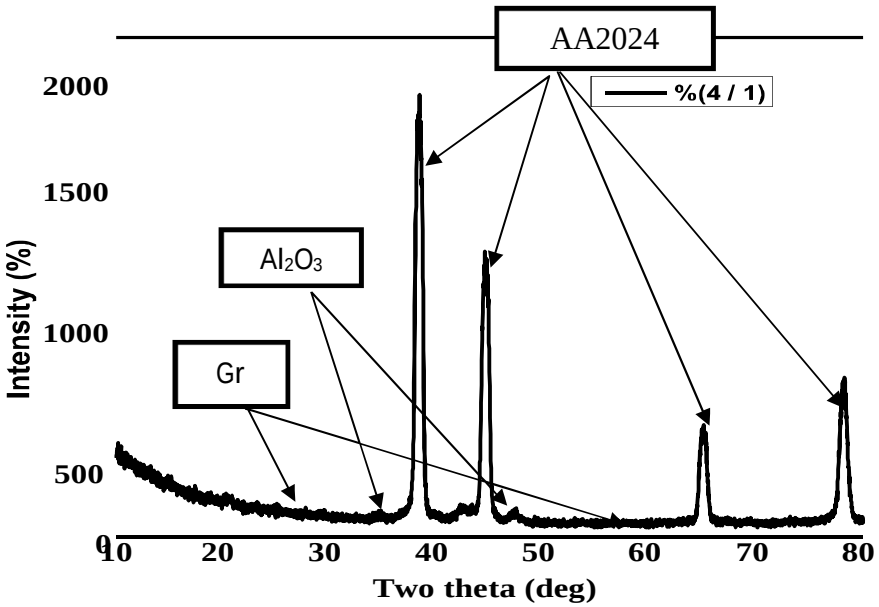


Fig-5.1 X-ray diffraction of AA2024 reinforced Al_2O_3 (4 Wt %) and Gr (1 Wt %)

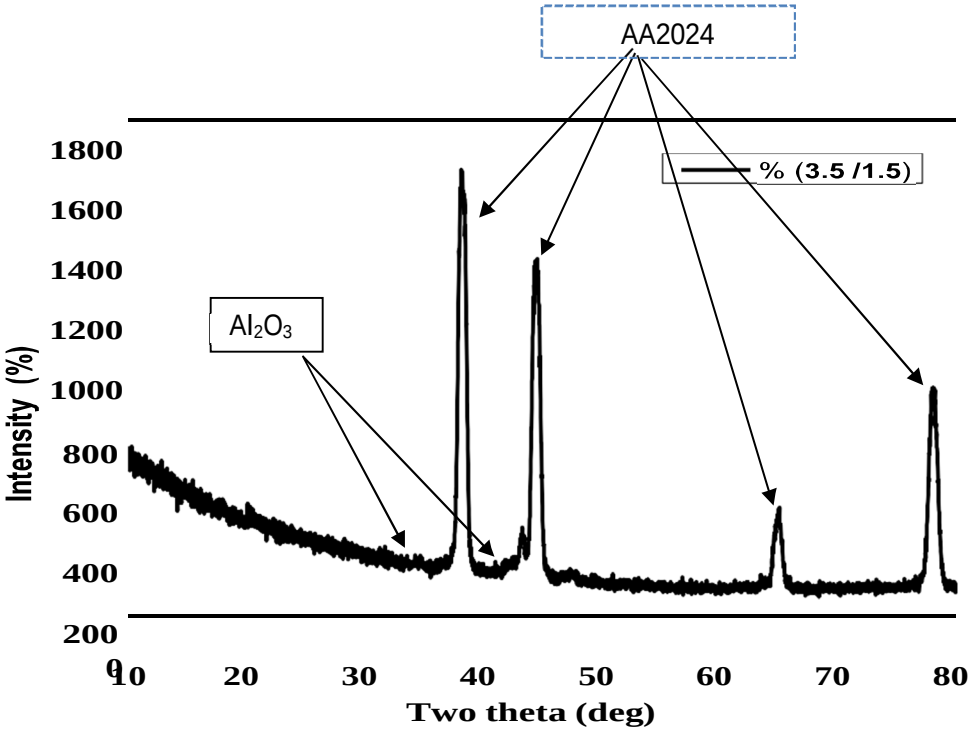


Fig-5.2 X-ray diffraction of AA2024 reinforced Al_2O_3 (3.5 Wt %) and Gr (1.5 Wt %)

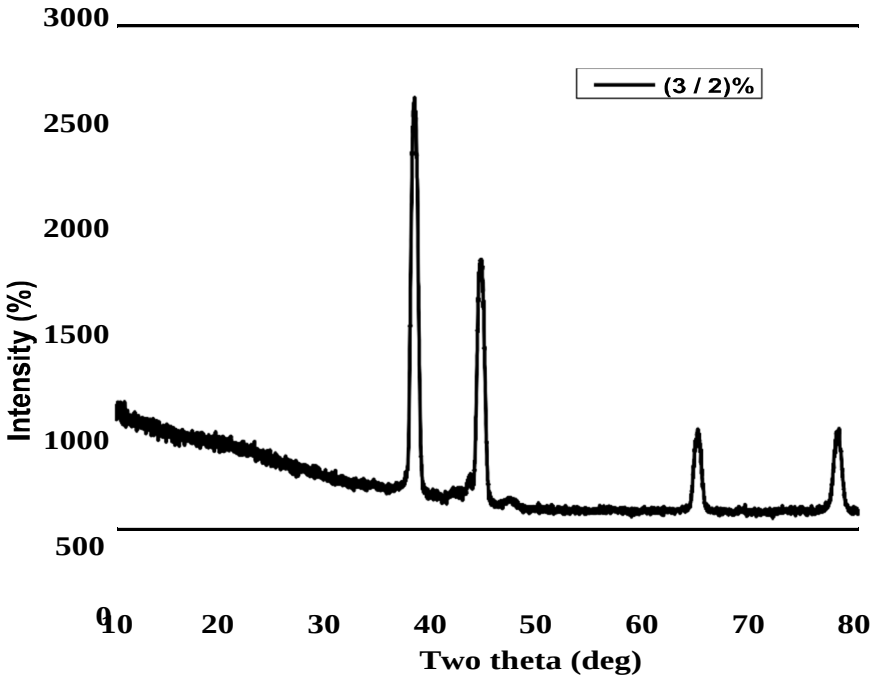


Fig-5.3 X-ray diffraction of AA2024 reinforced Al_2O_3 (3 Wt %) and Gr (2 Wt %)

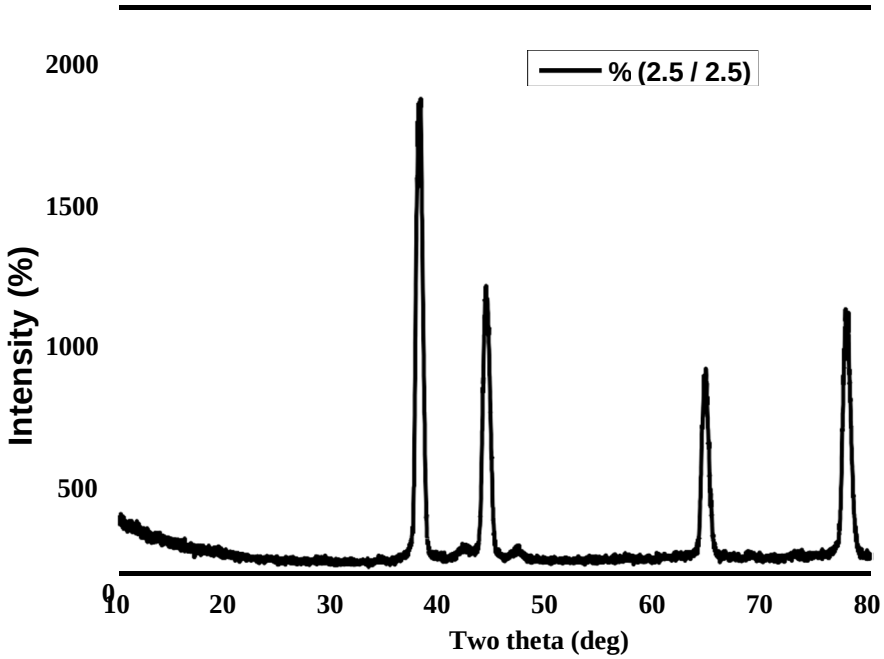


Fig-5.4 X-ray diffraction of AA2024 reinforced Al_2O_3 (2.5 Wt %) and Gr (2.5 Wt %)

B. Microstructural Characterization

1) Optical Microscope: Fabrication of metal–matrix composites with alumina particles by casting processes is usually difficult because of the very low wettability of alumina particles and agglomeration phenomena which results in non-uniform distribution and poor mechanical properties. In the current work, an attempt has been made to prepare AA2024 aluminium alloy matrix compositeswith alumina particles by stir casting method with preheating of the reinforcing particles. The magnitude of alumina powder used in the composites was 4, 3.5, 3 and 2.5wt. % of Al_2O_3 and 1, 1.5, 2 and 2.5% of Gr. The optical micrographs of the AA2024 alloy with Al_2O_3 and Gr particulates were shown in Fig 5.5(a-d).

Fig. 5.5a-d shows microstructure of as cast AA2024 with 4 and 1wt% of Al_2O_3/Gr, 3.5and 1.5 wt% of Al_2O_3/ Gr and 3 and 2wt% of Al_2O_3/Gr, 2.5 and 2.5 wt% of Al_2O_3/Gr particulates. The microstructure of the prepared composites contains primary AA2024 dendrites whileAl_2O_3/Gr particles are separated at inter-dendritic regions of AA2024. The stirring of melt beforeand after introducing particles has resulted in the breaking of dendrite-shaped structure into equatedform, addition of magnesium improves the wettability and incorporation of particles within the melt and also it causes to disperse the particles more uniformly in the matrix. The distribution ofalumina particles in different specimens it can be observed that there is a uniform distribution of particles and also agglomeration of particles at a few places was observed in the composites reinforced with 4, 3.5, 3, and 2.5 wt% of Al_2O_3 and 1, 1.5, 2, and 2.5% of Gr. The microphotographs also indicate that the Al_2O_3 particles tend to segregate and cluster at inter-dendritic regions which are surrounded by AA2024.

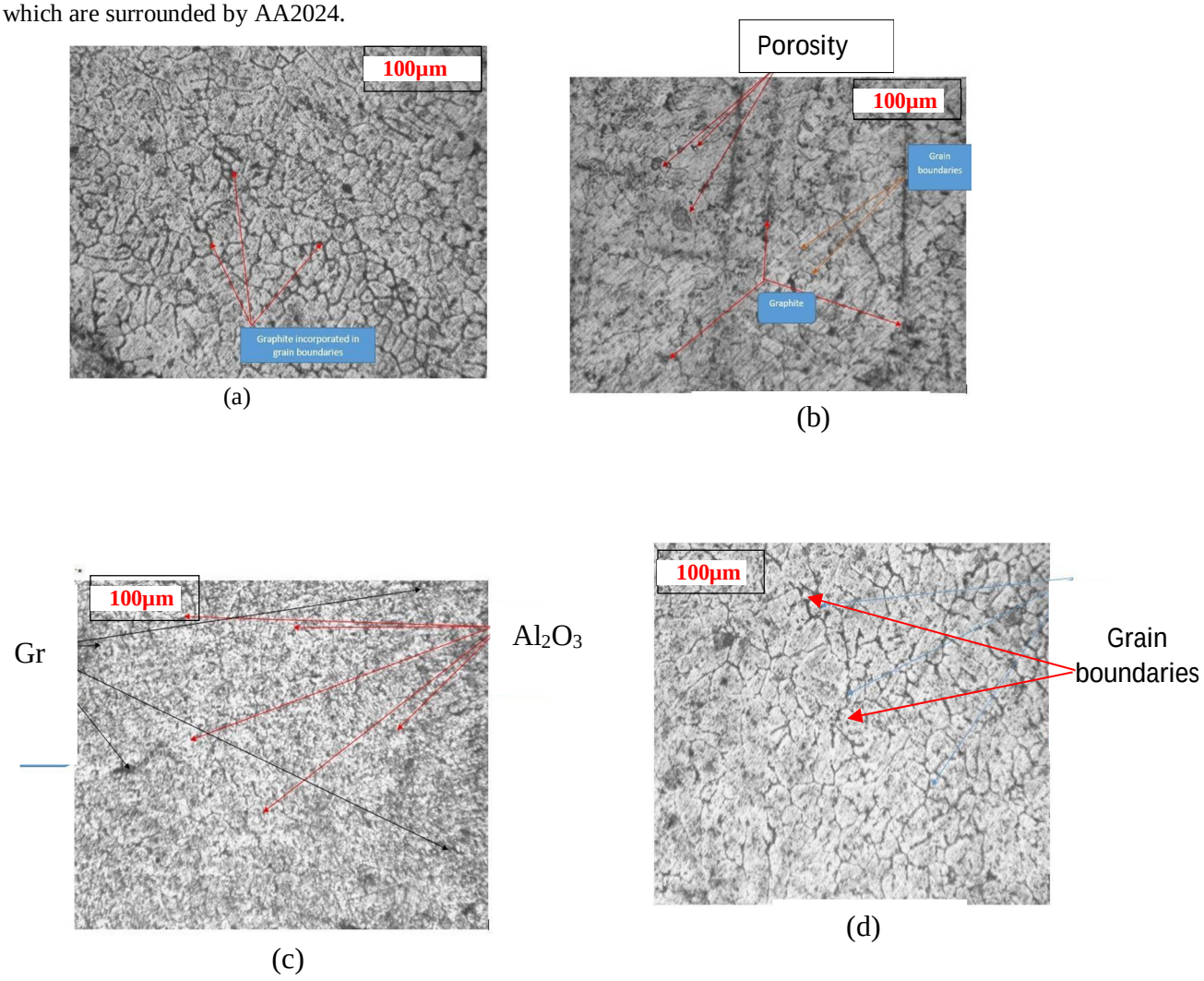


Fig 5.5 Microstructure of AA2024 reinforced (a)Al_2O_3 (3.5 wt%) and Gr (1.5 wt%) (b) Al_2O_3 (3 wt%) and Gr (2 wt%) (c) Al_2O_3 (2.5 wt%) and Gr (2.5 wt%) (d) Al_2O_3 (4 wt%) and Gr (1 wt%).

2) Scanning Electron Microscope: SEM photographs were obtained using Scanning Electron Microscope (make-Joel, Japan). Fig. 5.6(a-c) shows the SEM photographs of AA2024 reinforced with Al_2O_3 /Gr. It reveals the good distribution of particles and very low agglomeration. Moreover, the figure indicatesthat the Al_2O_3 particles tend to segregate and cluster at inter-dendritic regions which are surrounded by magnesium.

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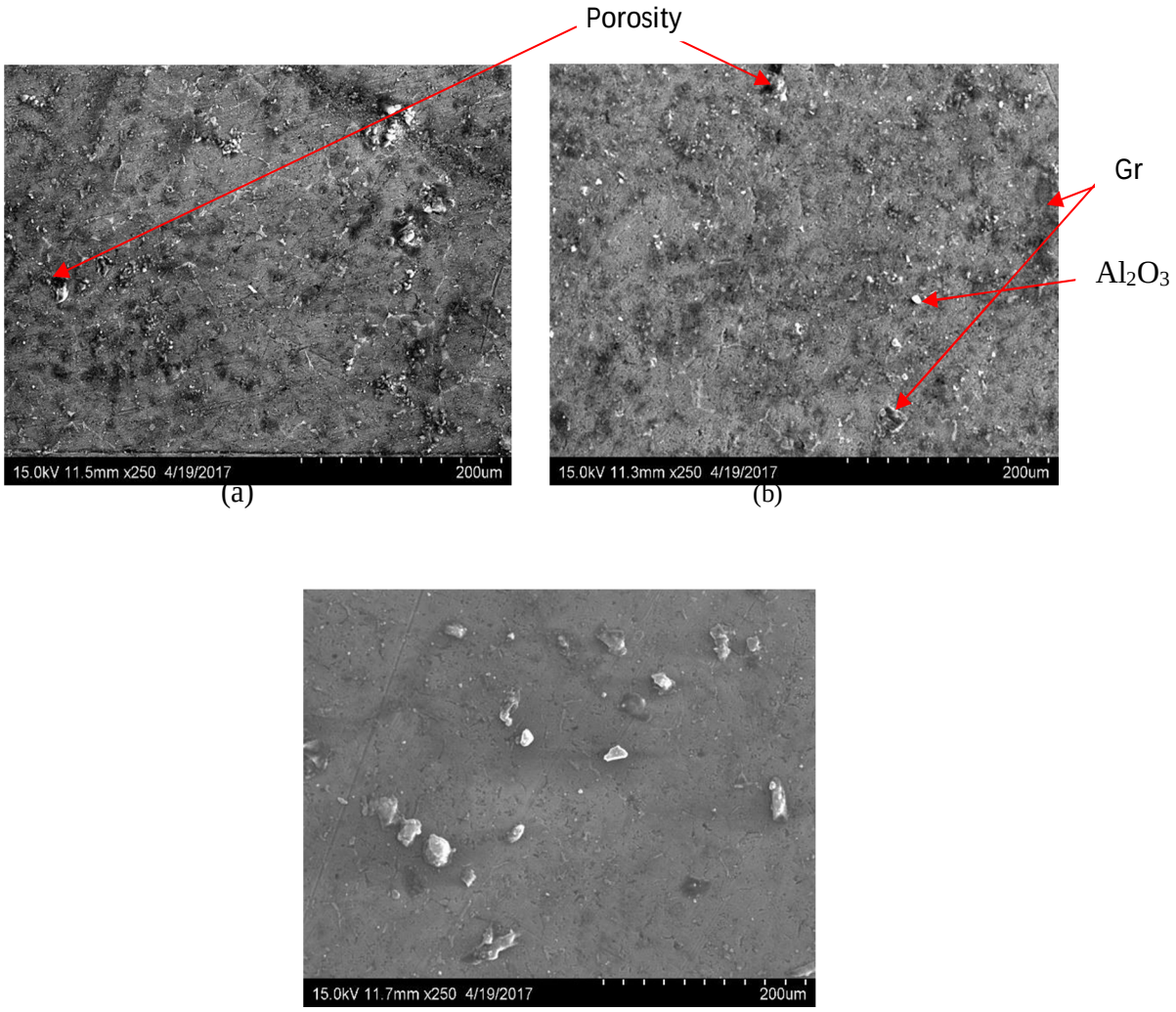


Fig-5.6 (a) SEM Micrographic of AA2024 reinforced (a) Al_2O_3 (3 Wt %) and Gr (2 Wt %) (b)Al_2O_3 (2.5 Wt %) and Gr (2.5 Wt %) (c) Al_2O_3 (3.5 Wt %) and Gr (1.5 Wt %)

C. Mechanical Characterization

1) Hardness: It is observed that the hardness of the AA2024/Al_2O_3/Gr hybrid composite increases with the addition of Al_2O_3. It was higher than that of the base alloy. The hardness of all the hybrid composite wassignificantly greater than that of the base alloy characterized hard nature of Al_2O_3 particles. Thehardness increases with the addition of Al_2O_3 particles to the AA2024 alloy as shown in Fig-5.7. Hybrid metal matrix composite sample S4 showed the highest hardness of 85BHN.

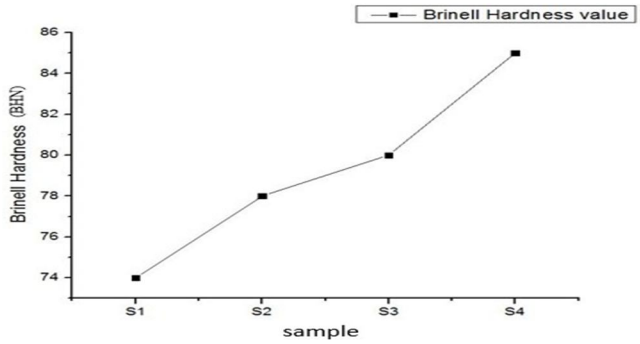


Fig 5.7 Brinell Hardness plot for hybrid metal matrix composites

2) *Tensile Test:* The tensile strength and yield strength values are also observed. It is observed that the ultimate tensile strength increases concerning the increase in Al_2O_3 content and yield strength decrease with an increase in the reinforcement particle. The less Gr content we add, the ultimate tensile strength get increases as shown in Fig-5.8. For the percentage elongation, it is observed that all grades of the composites produced have percentage elongation concerning the increase in Al_2O_3 content in the composites shown in Table 5.2, no consistent trend is discernible.

Table 5.2 Tensile strength of hybrid metal matrix composites

Samples	UTS (N/mm^2)	% Elongation	Yield strength
S1	155.063	3.2	97
S2	175.398	5.91	89
S3	180.495	5.11	84
S4	205.794	6.5	80

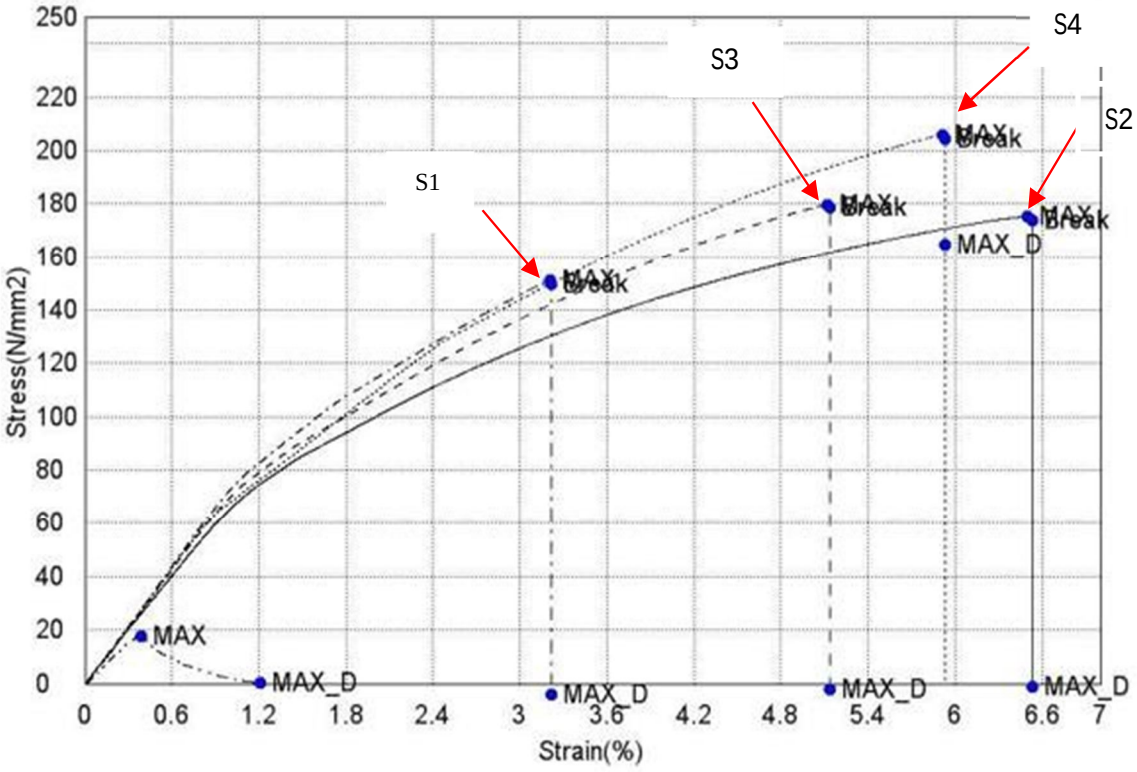


Fig-5.8 Stress vs Strain plot for hybrid metal matrix composites

3) *Flexural Test:* The flexural test results are presented in Table 5.3 from Fig-5.9 it is observed that the flexural strength of sample 4 is higher than other samples due to the presence of a high % of Al_2O_3.

Table-5.3 Flexural strength for hybrid metal matrix composites

Sample	Flexural Break Load (KN)	Flexural Strength (MPa)
S4	1.4	309
S3	1.32	297
S2	1.26	273
S1	1.12	258

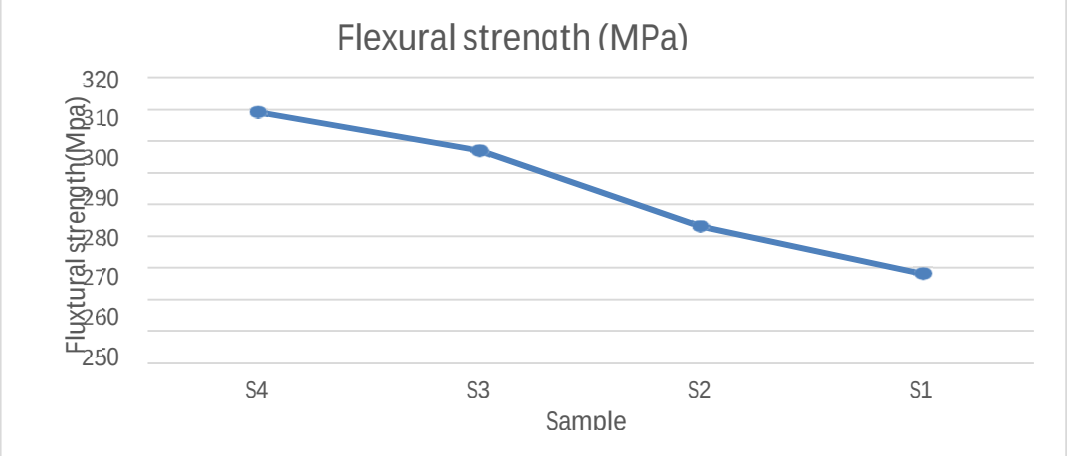


Fig-5.9 Flexural strength for hybrid metal matrix composite

D. Tribological Characterization

1) Wear Behavior: From the wear of all the composites produced it is observed that the best wear resistance was obtained with the increase of Gr. Specifically it is observed that for all composites produced,the composites with higher Gr exhibited greater wear susceptibility in comparison to the composite without Gr. The presence of Gr is reported to help reduce the wear rate of the composites by providing a solid lubricating layer between the composite and the rubbing hard counter surface. Fig- 5.10 represents the wear values of the samples at a constant load of 10kg.

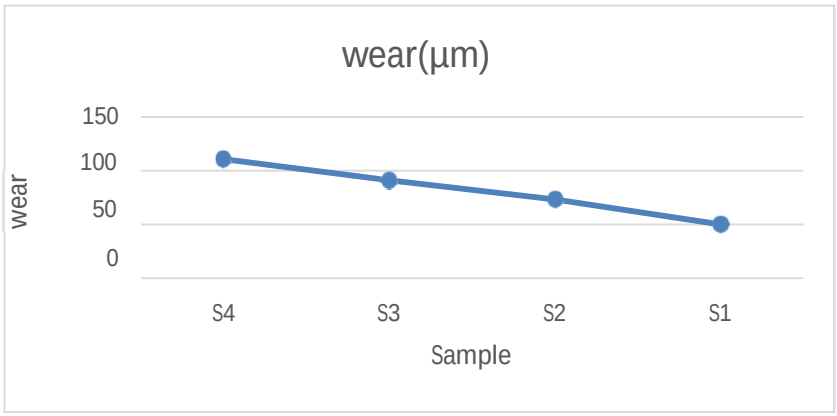


Fig-5.10 Wear for hybrid metal matrix composites

E. Thermal Characterization

1) Coefficient of Thermal Expansion (CTE): Table-5.4 shows the theoretical/experimental coefficient of thermal expansion for the prepared hybrid metal matrix composites increases with the addition of reinforcements with varying wt % S1 sample showed the lowest value of CTE is $2.289x10^{-6}$ $^{o}C^{-1}$. The observed change in CTE is due to the combined effect of Al_2O_3/Gr in the aluminium metal matrix composite.

Table-5.4 Theoretical/experimental of CTE for hybrid metal matrix composites

Sample Code	Theoretical Values ($*10^{-6}$ ^{o}C)	Experimental Values ($*10^{-6}$ ^{o}C)
S1	2.12	2.289
S2	2.37	2.607
S3	2.73	3.05
S4	2.915	3.23

VII. CONCLUSION

AA2024 Al alloy MMCs reinforced with different weight percentages of Al_2O_3 and Gr (up to 5 wt. %) have been successfully fabricated using the stir casting technique. Microstructural, mechanical and wear behavior was investigated. The following conclusions have been drawn:

1) XRD analysis showed the presence of crystalline phases.

2) SEM observations of the microstructures revealed uniform distribution of Al_2O_3 and Gr incorporated in the grain boundaries.

3) The density of the composites increased with the increasing weight percentage of Al_2O_3 at the expense of Gr.

4) The addition of reinforcements Al_2O_3 (4 wt %) and Gr (1 wt %) resulted in significant improvements in tensile strength (205.79 MPa) which is the highest value obtained.

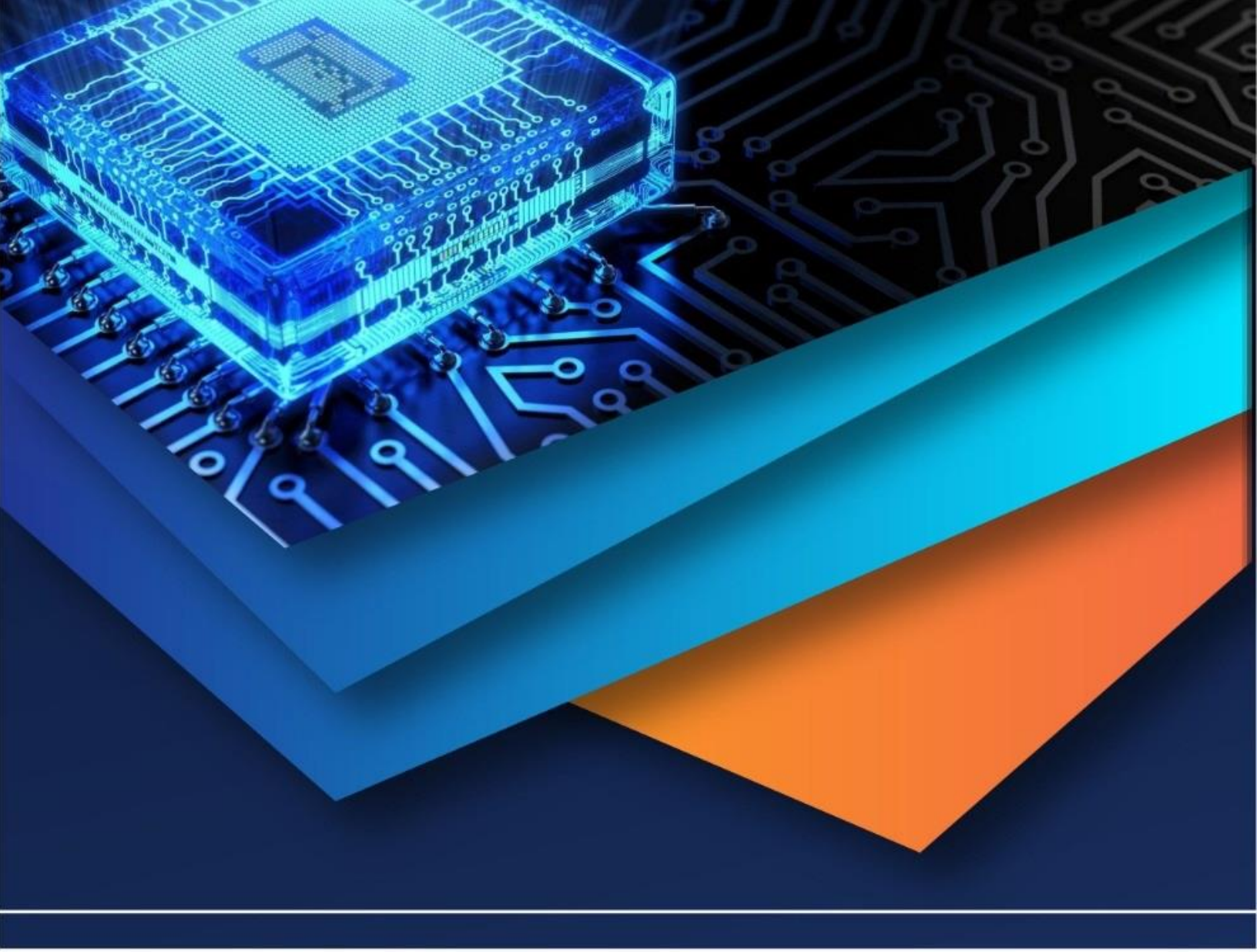
5) The hardness of hybrid composite samples improved with an increasing weight percentage of Al_2O_3 at the expense of Gr recorded 85 BHN

6) Composite samples with Al_2O_3 (1 wt%) and Gr (4 wt%) exhibited better wear resistance amongst other samples, as the presence of Gr acted as a load-bearing element during slidingwear.

7) The hybrid composite sample reinforced with Al_2O_3 (1 wt %) and Gr (4 wt %) exhibited low coefficients of thermal expansion value 2.289 X 10^{-6}/°C.

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