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The Mechanical, Thermal, and Electrical Properties of Nanographene-Aluminum Metal Matrix Composites are Exploited to Create Shielding Materials.

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Abstract

The objective of this work is to examine the alterations in mechanical and thermodynamic characteristics resulting from the addition of multiwall nanographene as a filler into an aluminium (Al) matrix. The compositions and morphologies of nanocomposites were characterised using scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDAX). The range spanned from S1, which consisted of 100% AL, 0% Cu, and 0% Nano Graphene, to S4, which consisted of 73% AL, 21% Cu, and 6% Nano Graphene. Subsequently, and assessed the thermal stability of the composites by employing differential thermal analysis (DTA) and thermogravimetric analysis (TGA). The impact of nanographene on the physical and chemical characteristics of Al-copper-nanographene composites were investigated. These findings indicate that nanographene enhances the thermal properties of the composites, resulting in increased thermal resistance compared to pure aluminium. Notably, S3 exhibits a 5-fold improvement in weight retention properties. An electrical conductivity measurement was performed using a CDE ResMap 178 4-Point Probe. By taking the average of five distinct measurements, we determined the final value for electrical conductivity, which indicated a 40% rise in S4 electrical conductivity. Mechanical tests, including as tensile, hardness, wear, and flexural tests, provide insights into the possible applications of composites in the aerospace, transportation, and maritime sectors. The optimal values for tensile and hardness are S4, for wear are S3, and for flexural are S2.

Keywords: Nanographene, Metal Matrix composites, Mechanical and Thermal Properties.

1.Introduction

Aluminium metal matrix composites (AMMCs) are a group of materials that combine the lightweight properties of aluminium with advanced mechanical and thermal properties through added strength The most hardened component is copper, which provides mechanical strength. Nanographene is an emerging reinforcement with unique properties such as high strength and thermal stability[1]. The addition of copper to the aluminium matrix improves the mechanical properties of AMMC by strengthening the material and increasing its resistance to deformation. Copper also improves the heat transfer of the composite, providing it is suitable wherever it is necessary to improve thermal conductivity. The combination of aluminium and copper in AMMCs provides a product with a good balance between strength and thermal performance[2].

Nanographene, a unique two-dimensional structure with high aspect ratio, offers exceptional mechanical properties, including high strength, stiffness, load-bearing capacity, and thermal stability, making it an attractive energy component[3]. The mechanical and thermal behaviours of AMMCs containing copper nanographene have been extensively studied. Researchers looked into how changing the distribution of copper and nanographene affected mechanical parameters like tensile strength, yield strength, and toughness, as well as thermal conductivity and coefficient of thermal expansion. This study showed that copper and nanographene incorporation can provide mechanical performance has greatly improved and heat transfer to AMMCs[4].SEM analysis is crucial for evaluating the thermal properties of composites reinforced with nanographene, enhancing their mechanical and mechanical properties[5]. SEM analysis provides detailed information on material surfaces, microstructure, and reinforcement phases, enabling researchers to observe matrix-reinforcement interface, nanoparticle dispersion, and overall composite quality and homogeneity[6].SEM analysis is utilized in research studies to characterize AMMCs containing copper nanographene, examining microstructure, particle distribution, interface bonding, and fracture behavior, often complemented by EDS or elemental mapping[7]The thermal conductivity of AMMCs, reinforced with copper nanographene, is crucial for efficient heat transfer in various applications. DSC and thermal diffusion analysis have been used to monitor the thermal stability and adjustability of these composites, enhancing their potential for thermal applications. Researchers studied the thermal conductivity of aluminium, copper, and nanographene composites using laser-flash experimental techniques. The addition of nanographene significantly enhanced the composite's thermal conductivity, making it a promising material for waste product thermal analysis[8]. In a study AMMCs with different thickness fractions of copper and nanographene were investigated. Utilising DSC analysis, the researchers determined the thermal properties of the composites and monitored their melting point under varying temperatures. The study also revealed its potential for high-temperature applications[9].

Previous studies have shown that standard materials such as aluminium and copper are prone to failure because they lack sufficient wettability, thermal stability, and electromagnetic absorption. Our goal is to address this issue. It is recommended to produce Advanced Metal Matrix Composites (AMMCs) by combining aluminium, copper, and nanographene. To determine the most efficient composition, we utilised the design of experiments technique in MiniTab software and discovered four ideal combinations. In order to evaluate their flexural strength and tensile hardness, mechanical experiments were conducted on these combinations. Additionally, with thermal properties using TGA analysis, evaluated their wear resistance by tribological testing, and assessed their electrical conductivity using the CDE ResMap 178 4-Point Probe. These tests aimed to discover the qualities of AMMCs. Mechanical, thermal, electrical, and tribological tests were conducted on these combinations to evaluate their performance and potential as stealth materials. These materials are crucial for achieving success in the fields of electronics, automotive components, and aerospace systems.

2.Materials and methods

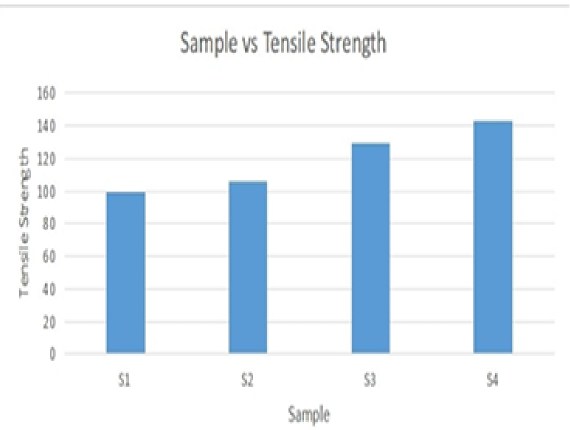
In this study, aluminium alloy served as the matrix material. Aluminium was used as the primary material for this. Copper and nanographene reinforcements were used. Four categories of Al-based samples were characterised: S1 (100 % AL, 0% Cu, 0% Nano Graphene), S2 (AL 91% + 7% Cu + 2% Nano Graphene), S3 (AL 82% + 14% Cu + 4% Nano Graphene), S4 (AL 73% + 21% Cu + 6% Nano Graphene) is the fourth sample. Aluminium alloy was chosen due to its excellent ductility and castability. The Al-Cu-Gr particle composite is produced using a pit furnace with a 12.5-kilowatt capacity and four 14-gauge heating coils. The furnace is a PLC automatic temperature control with a maximum operating temperature of 1,200°C and a control precision of 5°C for molten aluminium. The process involves melting around 0.450 kg of Al metal matrix alloy in a graphite crucible at 1150°C, using magnesium ribbons for wettability and uniform strength distribution. A mechanical stirrer covered with alumina and equipped with four coated blades is used to blend the reinforcement with the molten metal, creating a vortex. The molten metal is stirred forcefully at 500 rpm in an organogas atmosphere to prevent oxidation. To create cast specimens measuring 100 x 16 x 5 mm, the high-temperature molten metal is poured into a preheated cast iron mold at 800°C.

3.Mechanical Testing's

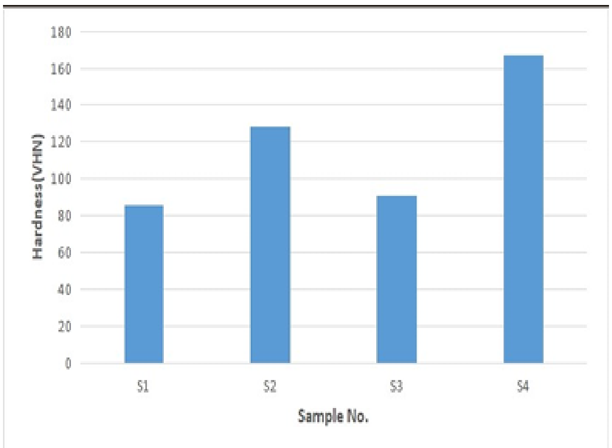
The tensile strength of nanocomposites was tested using an electro-mechanical UTM 'Instron Make' at room temperature and a strain rate of 1×10^{-4} s^{-1}. Four specimens of Al (base metal), unreinforced S1, and each reinforced composite were fabricated for tensile testing. The results showed that friction stir processing (FSP) of the base matrix led to a 5.94% decrease in ultimate tensile strength, while smaller particle size increased tensile fracture strength[10]. The addition of nanoscale second-phase reinforcement particles increased the composites' elastic modulus, yield strengths, ultimate tensile strengths, and tensile failure stresses compared to an S1 matrix without reinforcement as shown in fig 2 and fig 3. The gradual improvement of properties from the unreinforced S1 matrix to the hybrid composite suggests equal refinement of grains and uniform distribution of dislocations in the matrix. The tensile properties of the unreinforced S1 specimen decreased from 53 m to 18 m while the average particle size decreased. The addition of nanographene to composite samples increases Vickers hardness from Hv 85.44 to Hv 167. However, the hardness decreases with higher amounts of graphene. Composite samples containing four weights % of nanographene have lower hardness than those containing 2 weight %. Al/GO composite samples have higher microhardness values than unreinforced Al alloy. The weight percentage of nanoparticles in the Al matrix can be raised by up to 1% without affecting hardness values. The hardness value of metal matrix composites is influenced by reinforcement amount and surface characteristics. The wear rate of hybrid composites made of aluminium-copper-nano graphene (MMCs) was studied using microns as a measure of wear. Sample 3 had the least wear, measuring 78.13 microns. The study found that higher graphene content percentages significantly reduced wear loss in MMCs. Hybrid composites made of Al + 4% Gr exhibited greater wear resistance than unreinforced S1 and other composites, regardless of load and sliding velocity circumstances. The graph depicting the wear rate over time demonstrates how nanoparticles affect the wear rate throughout periodic intervals. The flexural test examines the reaction of composite materials to deflection, using test samples created in accordance with ASTM A: 370 standards. Sample 2 exhibited higher flexural strength due to copper and nanographene content, while its deflection was smaller due to aluminium distribution. The result values of tests are shown in table 1 and represented graphically in figure 1.

Table 1: Samples and their respective test values

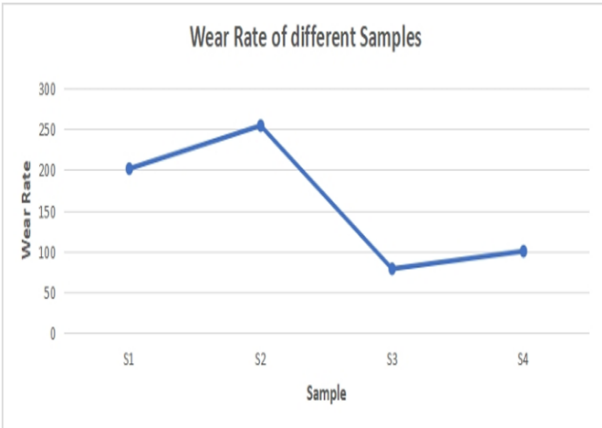
SAMPLE	TENSILE STRENGTH	HARDNESS	AVERAGE WEAR	FLEXURAL STRENGTH
S1	99.74	85.44	201.49	213.21
S2	106.04	128.5	254.52	319.42
S3	130.16	90.5	78.13	281.32
S4	142.94	167	99.84	285.52

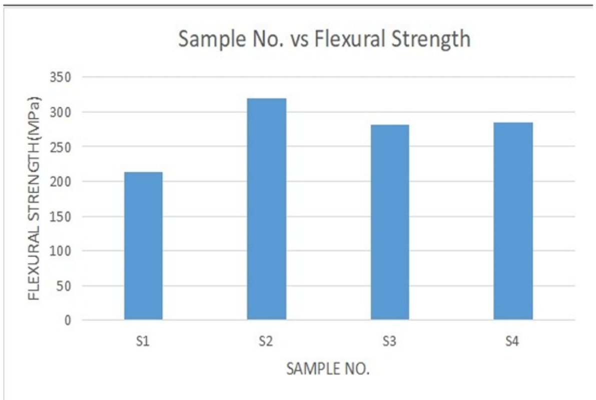


Sample vs Tensile Strength



Sample vs Hardness Number





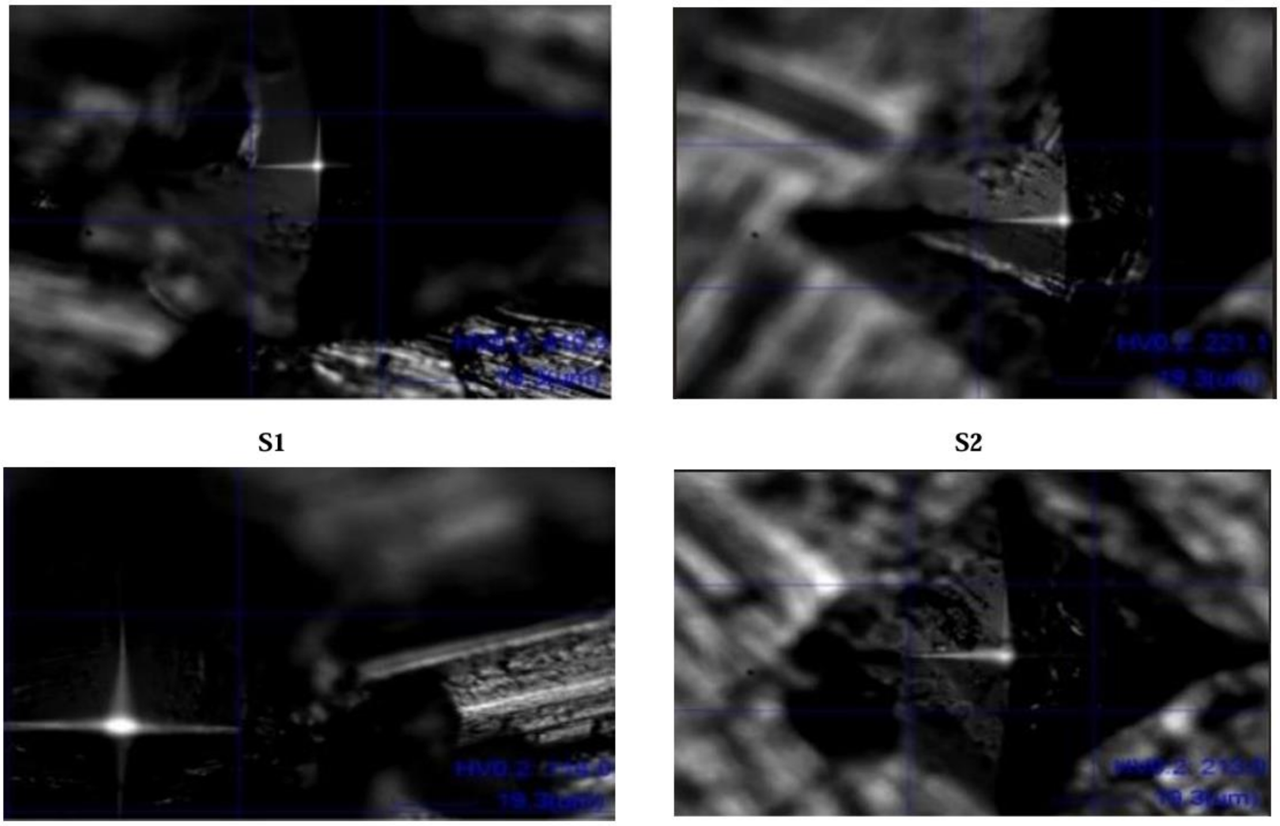
Sample vs Wear rate **Sample vs Flexural Strength**

Figure 1: Graphs showing samples vs Mechanical tests

Samples for Tensile Test **Samples for Flexural Test**

Samples for wear Test

Figure 2: Samples for Mechanical Tests (Tensile, Flexural and wear)



S1 S2

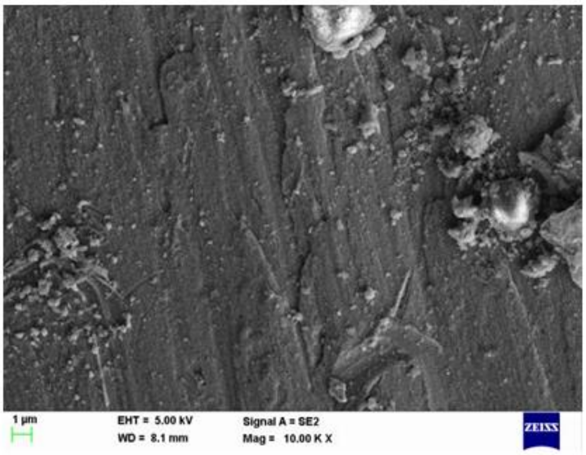
S3 S4

Figure 3: Microhardness Images of Composite Samples

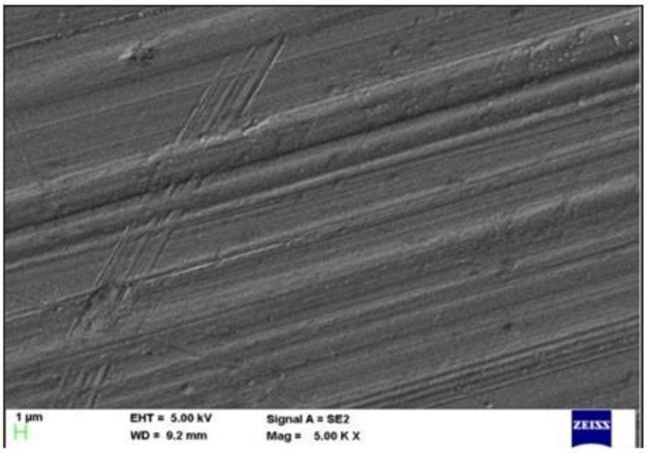
4. Characterization techniques

4.1 Scanning Electron Microscope and EDAX

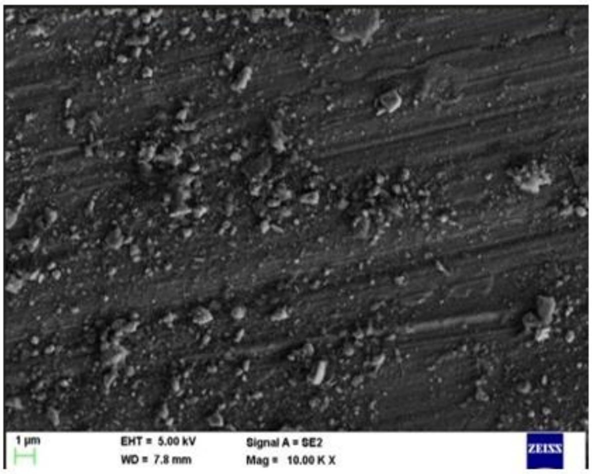
The study uses Scanning Electron Microscopy (SEM) and Electrode oxygenase (EDAX) to analyze stir-cast Al/Graphene/Copper composites. The composites show a compact structure with few pores and robust grain boundary sites. The synergetic strength of the hybrid reinforcement enhances mechanical and wear qualities. The high graphene content enhances graphene clustering, resulting in an integrated network that improves composite properties. The EDAX analysis confirms the presence of copper and graphene in the composites as shown in fig 5. The Al-Nano Graphene hybrid nanocomposite exhibits a unique microstructure influenced by nanoscale secondary particles, preventing dislocation mobility. The surface of the nanocomposite shows dispersed, fine-grained crystals, while SEM images (figure 4) reveal a uniform distribution of Copper and Graphene as second phase reinforcement particles. Graphene's tendency to aggregate during processing makes matrix dispersion challenging[11]. SEM spectrum analysis confirms the presence of carbon in the agitation zone, confirming the adequacy of the carbonaceous reinforcement shown in figure 6.



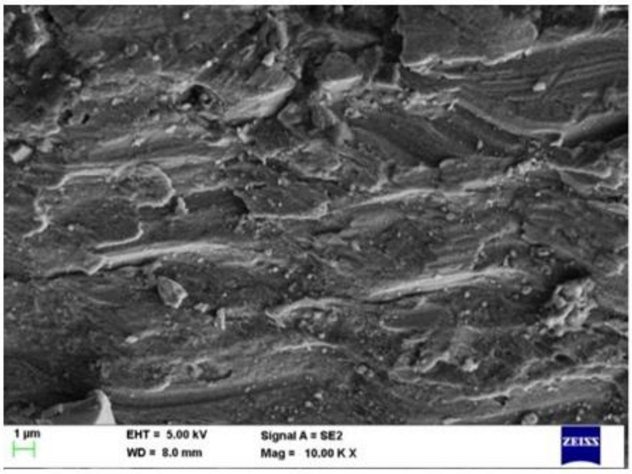
S1



S2

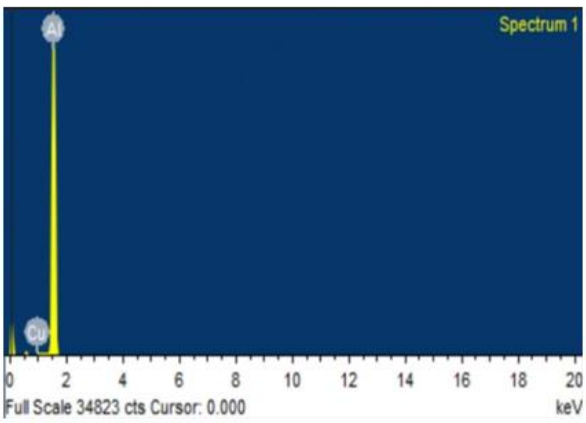


S3

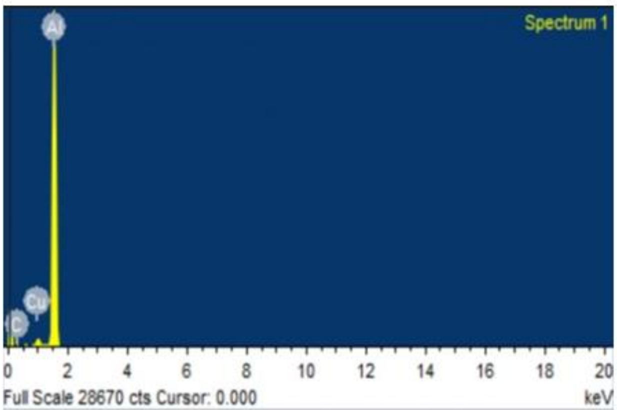


S4

Figure 4: Scanning Electron Microscope Images of Composite Samples



S1



S2

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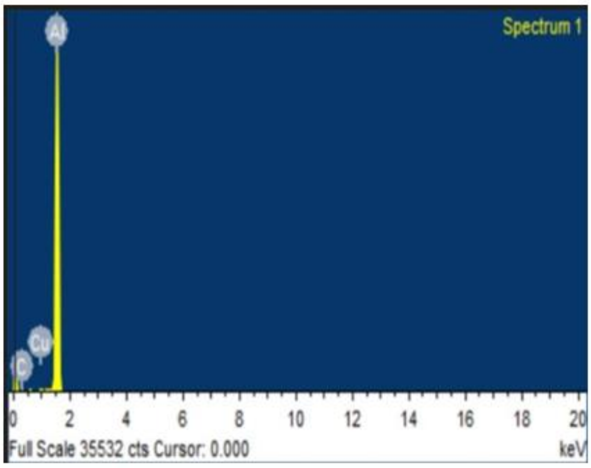
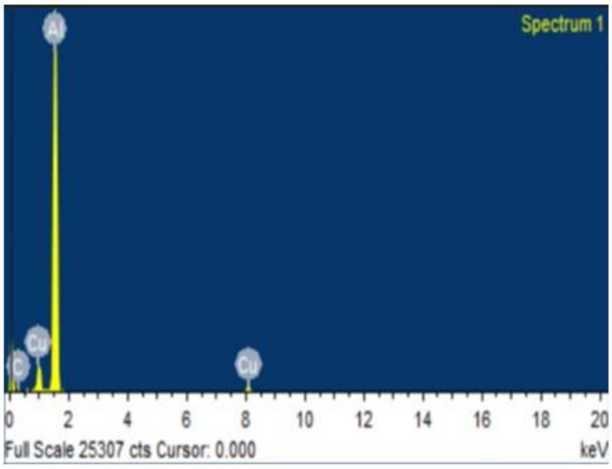
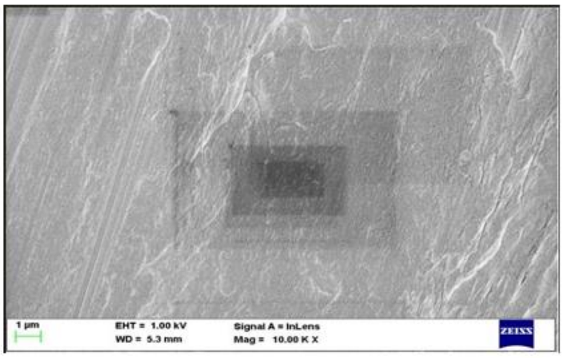


S3

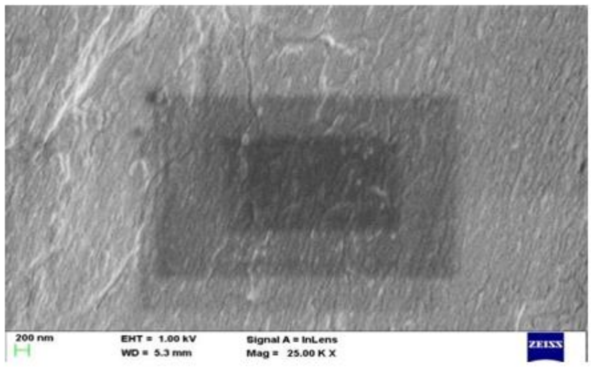


S4

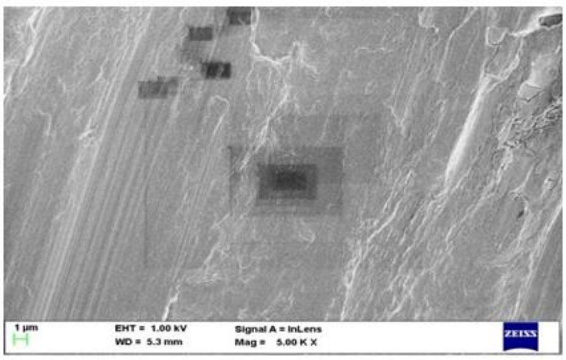
Figure 5: EDAX Images of Composite samples S1,S2,S3, and S4



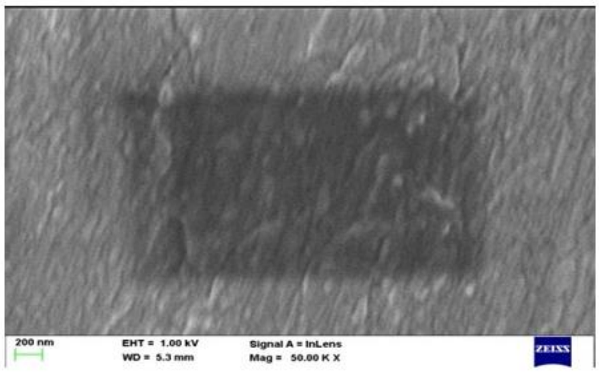
S1



S2



S3



S4

Figure 6: Scanning Electron Microscopy Images of Composite Samples with deep Magnification of Samples S1, S2, S3 and S4

5. Thermal analysis

5.1 Thermogravimetric analysis

The thermogravimetric analysis of Al and nanographene degradation rates revealed significant variation in the TGA curve, shown in figure 7. For Al + 0% nanographene, the curve fluctuated significantly with temperature, decreasing over the entire temperature range. The S3 and S4 samples showed nearly identical TGA curves, with nanographene particles occurring between 550 and 600 °C. All temperature graphs exhibit a similar pattern between 0 and 300 °C. This variation in behaviour between the samples may be due to the oxidation process. The TGA's linear behaviour and the little weight loss suggest that the nanocomposite has strong thermal stability, and it also shows that the addition of nanographene as a filler enhances the thermal stability of aluminium. At high temperatures, a minor slope suggests a change in the TGA's rate of change, which may be related to a speed-up rate of organic matter evaporation, which results in less weight loss. According to the TGA analysis, sample S3 exhibits improved weight stability.

Table 2: Mass Gained Percentages of Samples

SAMPLE	MASS GAINED PERCENTAGE
S1	6.52173913
S2	5.076923077
S3	0.862068966
S4	5.03030303

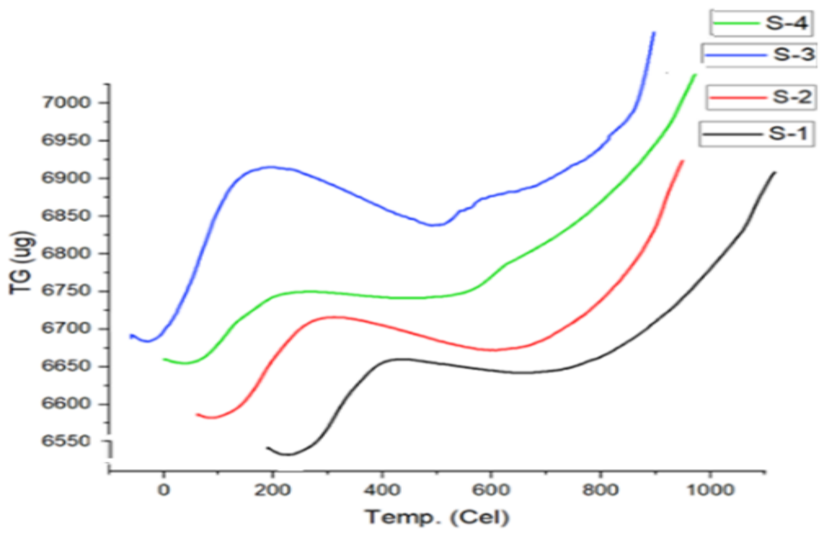


Figure 7:TGA Vs Temp for the samples S-1, S-2, S-3, & S-4

6. Electrical conductivity

Electrical conductivity is a crucial factor in the electrical behavior of a material, influenced by the unrestricted movement of electrons in a metallic tube. The Druid free electron theory suggests that electrons can flow in any direction, affecting electrical resistance and electron scattering. The resistivity of a metal is determined by its temperature (ρT) and residues (ρR), which are influenced by microstructures like lattice, impurities, precipitation, and grain boundary scattering[12,13].

It can be concluded that electrical reduction and electron scattering are inevitable, as opposed to conventional enrichment methods The Drude model can be used for electrochemical studies of metals such as Al at the bottom of the phrase.:

$$S0 = n\tau e2/m* \qquad (1)$$

where S0 represents the electrical conductivity of the matrix at the same temperature without any nanoparticles. e is for the charge carried by each electron, is the relaxation time of unconstrained mobile electrons in the matrix, and m∗ is the number of electrons that are actually present. In our model, the most essential electrical conductivity parameter is n, where an is the number of complex electrons. According to Nordheim's rule [14,15], the electrical conductivity of nanocomposites can be expressed as:

$$\frac{1}{S} = \frac{1}{s0} + k1x(1-x) + k2x \qquad (2)$$

Where S represents the nanocomposite's electrical conductivity, k1 represents the nanoparticle–metal interaction, k2 the influence of nanoparticles as secondary phases on electrical conductivity, and x the nanoparticle volume fraction.

A schematic diagram of the electron path of the metal matrix nanocomposite is shown in Figure 8, This schematic provides a comprehensive visual understanding of the complex interactions and scattering mechanisms within the Al-Cu nanocomposite system, essential for analyzing its electrical and thermal properties. The main types of scattering mechanisms in such a system include electron scattering, phonon scattering, interfacial scattering, and defect scattering. The topological impedance of the current density path will prevent electron transfer at the macroscopic level k2 (0.23505 u Ohm-cm in our example) k1 (0.00797 uOhm-cm in our case) (especially when x becomes greater than 0.2). This is because there are very few interactions between nanoparticles and the matrix (chemical and physical, such as changes in chemical reactions and electronic structure refinement, and changes in Gibbs free energy, interface energy, and phase energy) [16]. The nanoparticle phase dominates the nanocomposite's electrical conductivity, with resistance and volume percentage not linearly related due to electron valences in metal Al and nanographene.

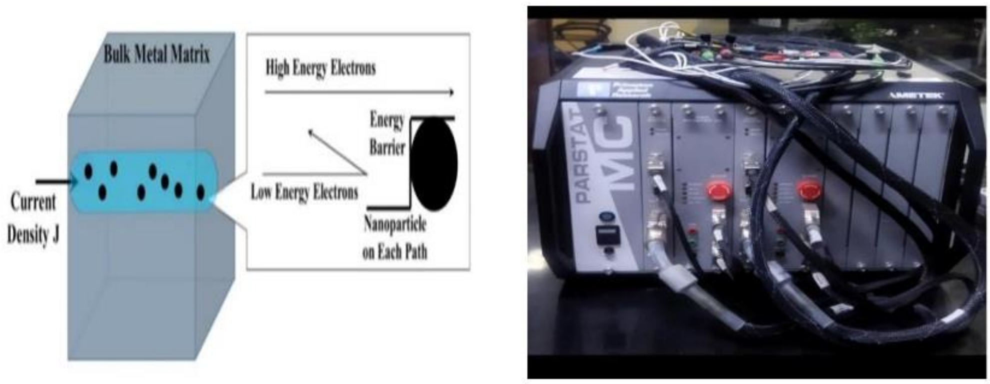


Figure 8: Schematic representation of scattering mechanisms in the Al-Copper nanocomposite system

The electrical conductivity of nanocomposites decreases due to interfacial scattering and interface contact. As the mass percentage of integrated nanoparticles increases with pressure coefficient, the electrical conductivity decreases. Graphene, a two-dimensional sheet, forms three covalent bonds with neighbouring atoms, allowing unbound electrons to roam around the lattice, resulting in reduced electrical conductivity[16,17]. The Electrical Conductivity of different samples is shown in table 3. The graphical representation of Electrical conductivity of samples is shown in Figure 9.

Table 3: Electrical Conductivity of samples

SAMPLE	ELECTRICAL CONDUCTIVITY
1	59.25
2	63
3	84.81
4	93

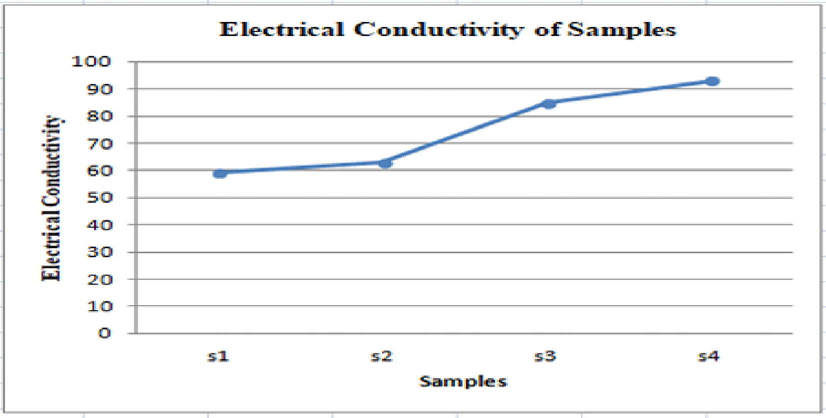


Figure 9: Electrical Conductivity vs Samples

7. Brauner-Emett-Teller (BET) Analysis

It was found that nanographene has a surface area of 4.4086E+01 [m2 g-1] and a total pore volume of 3.3550E-02 [cm3 g-1]. Both of these figures are quite large. The BJH method was applied in order to carry out the computations necessary to determine the related pore size distribution data for nanographene.

These results led to the conclusion that the pores are uniform and have a restricted pore size distribution that is centred at 3 nm. The findings of the BET isotherm plot indicate that the particles have a type II isotherm out of a possible 6, which indicates that they are capable of unrestricted mono-multilayer adsorption. This conclusion was reached as a consequence of the fact that the particles have a type II isotherm. The vast majority of the time, this phenomenon takes place when adsorption is taking place on powders that are either nonporous or have powders whose diameters are larger than micropores. The inflection point takes place at a moment that is quite near to the end of the process of forming the first monolayer of adsorbed particles. Strong van der Waals interactions between the graphene sheets cause graphene particles to have a tendency to stack on top of one another. Because functionalization increases the likelihood that graphene particles would stack on top of one another, the BET surface area of nanographene decreases as a direct consequence of this behaviour. The setup required for performing BET analysis and analysis graph are shown in the figures 10 and 11 respectively.

Figure 10: BET Analysis Set-up

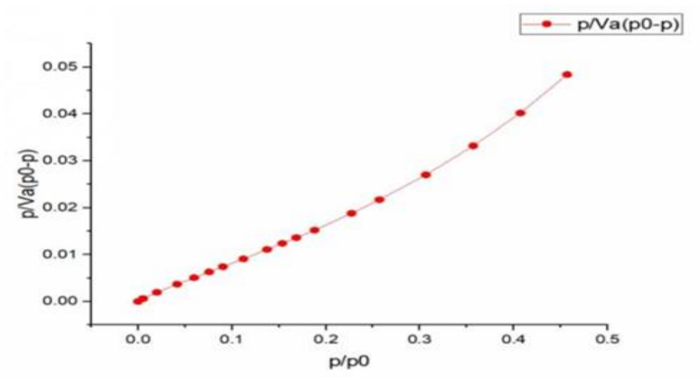


Figure 11: Graph showing BET Analysis

Conclusion

- By changing the weight proportion of reinforcements, stir casting composites of Al, Copper, and Nano Graphene may be made successfully.
- Higher tensile strength is observed in composite S4 (AL 73% + 21%Cu + 6% Nano Graphene) due to the formation strong bond among copper, nano Graphene and Al compound.
- The addition of varied amounts of reinforcement to the base material is found to boost hardness; the composite S4 (AL 73% + 21% Cu + 6% Nano Graphene) achieves the highest value. This is because Cu/Nano Graphene is present in the Al compound.
- It has been discovered that, in comparison to other combinations, adding copper to a nanographene compound increases the attribute of flexural strength because a strong link is formed.
- It has been demonstrated that the inclusion of different reinforcements to a base material increases its wear resistance. The composite S3 (AL 82% + 14% Cu + 4% Nano Graphene) exhibits the lowest wear loss; this is because Cu/Nano Graphene is present in the Al compound.
- Due to Nano Graphene's high electrical conductivity, when compared to other composites, S4(AL 73% + 21% Cu + 6% Nano Graphene) has a greater electrical conductivity.
- The composite S3 (AL 82% + 14% Cu + 4% Nano Graphene) has much higher corrosion resistance compared to other composites because graphene increases corrosion resistance, which is a crucial quality for maritime applications and automotive radiators, among other places.
- Characterization of samples of Al/Copper/Nano Graphene composites made by varying wt% of reinforcements are done by AFM, BET, SEM and EDAX.
- Thermal Analysis were carried by Thermo Gravimetric Analysis and Difference Thermogravimetry. The sample S3(AL 82% + 14%Cu + 4% Nano Graphene) shows greater weight stability in TGA analysis.

- DTG Analysis of composites with Copper and graphene the mass degradation range is lower than for the without Gr.

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