Investigating the Microstructure and Mechanical Performance of Ceria and Graphene-Reinforced Aluminum Hybrid Composites

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ABSTRACT

Metal matrix composites (MMCs) are complex materials comprising a metal or alloy matrix and reinforcing particles, whiskers, or continuous fibers. Reinforcement improves base metal mechanical, thermal, and electrical properties. Advanced hybrid metal matrix composites (HMMCs) use reinforcing chemicals to strengthen the metal matrix. Hybrid aluminium metal matrix composites (HAMMCs) use aluminium or its alloys and two or more reinforcements as the main material. These composites boost performance by combining reinforcements with different properties. This study focuses on the mechanical and microstructural properties of hybrid composites of Al6061, GNPs, and CeO_2. As reinforcement, graphene nanoplatelets (GNPs) and cerium oxide (CeO_2) are employed with the Al-6061 alloy matrix. The hybrid composites were stir-cast in two steps with Al-6061: GNPs: CeO_2 ratio of 94:1:3, 96:3:3, and 94:3:1. The optimum ratio was 96:3:3, which increased hardness by 24.47% and had the lowest particle size of 6.36nm. The same percentage HAMMCs specimens have maximum tensile (148.239 MPa), flexural (265 MPa), and impact (13.062 Joules) mechanical characteristics. The 96:3:3 percentage HAMMCs specimen had the best grain structure matrix and reinforcement dispersion. Tensile-tested specimens failed during fracture analysis due to dimples, porosity, and reinforcing particle buildup in the Al-6061 matrix.

Keywords: Al-6061, REPs, GNPs, 2-step stir-casting, FESEM, EDS, Fracture Analysis.

1. Introduction

In the evolving landscape of materials engineering, composites have emerged as a pivotal category of materials, known for their ability to combine distinct constituents to achieve superior properties [1]. These materials are engineered by embedding a reinforcing phase within a matrix material, leading to enhanced mechanical, thermal, and electrical characteristics compared to the individual components [2]. Within this broad category, metal matrix composites (MMCs) stand out, particularly for applications requiring high strength, stiffness, and wear resistance [3]. MMCs typically consist of a metal or alloy matrix reinforced with ceramics, fibers, or nanoparticles, thereby offering improved performance in demanding environments. Taking innovation a step further, hybrid metal matrix composites (HMMCs) integrate multiple types of reinforcements within a single metal matrix [4]. This approach harnesses the synergistic effects of different reinforcing materials, thereby optimizing the composite's properties for specific applications. For instance, the combination of particles and fibers can simultaneously enhance both the mechanical strength and toughness of the composite [5]. Among the various HMMCs, hybrid aluminum metal matrix composites (HAMMCs) have garnered significant attention due to the inherent advantages of aluminum, such as its low density, high thermal conductivity, and excellent corrosion resistance [6]. HAMMCs, which utilize aluminum or its alloys as the matrix material, are reinforced with diverse agents like graphene nanoplatelets and cerium oxide [7]. These reinforcements not only boost the mechanical properties but also improve thermal stability and wear resistance [8]. The manufacturing of HAMMCs often involves sophisticated techniques like stir casting or powder metallurgy to ensure a uniform distribution of reinforcements and robust interface bonding [9]. The resultant material exhibits a remarkable strength-to-weight ratio, making it ideal for high-performance applications in aerospace, automotive, and military industries, where both lightweight and high strength are paramount [10]. As research progresses, HAMMCs continue to evolve, promising even greater enhancements in material performance and broadening their application horizons. In modern composite fabrication, nano-reinforcing particles are increasingly utilized due to their ability to significantly enhance material properties. These particles come in various sizes and are integral to the development of hybrid aluminum metal matrix composites (HAMMCs) [11]. The nano-level reinforcements can be uniformly distributed within the matrix material, leading to stronger interfacial bonding and improved load transfer capacity. This uniform distribution helps reduce the occurrence of surface cracks, which are typically generated under stress. Surface cracks and gaps can lead to brittle fractures when the composite is subjected to tensile loads, thereby compromising the material's toughness, ductility, and overall strength [12]. By increasing the weight percentage (wt.%) of nano-reinforcements, these issues can be mitigated, enhancing the composite's performance. However, this enhancement is optimal up to a limit of 10% wt.% of the nano-reinforcement, beyond which the benefits may not proportionately increase or could potentially lead to other fabrication challenges [13]. The study compared the hardness and wear rates of forged versus non-forged composites. The Brinell hardness values for the unforged and forged composites were 71 and 75, respectively, at a weight of 6 wt.%. Additionally, the lowest coefficient of wear was observed at 6 wt.% [14]. Liu et al. prepared stir-cast Al-7075 MMC reinforcing 12 wt.% boron carbide and 3 wt.% molybdenum sulphide to enhance the mechanical and tribological performance. B4C particles helped maintain a coefficient of friction in the range of 0.48-0.49 under all wear test conditions [15]. Seven-layered aluminum alloy composite reinforced with alumina and graphene shows the enhancement in different mechanical properties. The 56.1% increment in hardness, tensile strength (51.5 %), and yield strength (68.6%) was observed in the seven-layered aluminum MMCs [16]. REPs are increasingly being used as strengthening agents in the fabrication of HAMMCs because they have the capacity to improve mechanical strength, thermal conductivity, and metallurgical performance. Govindaraju et al. examined the mechanical properties of Al-Zn alloys both with and without the inclusion of cerium (Ce). Their results demonstrated significant improvements in tensile strength (16.5%), compressive strength (17%), and impact strength (22%). However, the hardness values were reduced by 4% compared to the original alloys. The inclusion of 0.7% Ce resulted in an enhancement in the microstructure of the MMCs, as shown by SEM analysis [17]. A similar increment in hardness and tensile properties was also noted in MMCs of erbium-based reinforced aluminum alloys [18]. MMC's have become more popular in the automotive sector because of their exceptional mechanical properties, including high strength, stiffness, and wear resistance, and their capacity to endure high temperatures. MMC features enable the substitution of several automobile components, hence enhancing performance and longevity. Engine components such as pistons, connecting rods, and cylinder liners constructed from Metal Matrix Composites (MMCs) can function at elevated temperatures, leading to improved performance and fuel economy. Similarly, the rigidity and endurance of MMCs enhance suspension components such as control arms, ball joints, and strut housings, resulting in enhanced handling and ride quality. Brake rotors made with Metal Matrix Composites (MMCs) have improved durability against wear and better ability to dissipate heat. This results in higher braking performance and a longer lifespan [19]–[22]. The details of some of the relevant research papers are mentioned in Table 1.

Table 1 shows the previous research carried out on Al-6061 alloy and reinforcements, either separately or in conjunction with other reinforcements such as SiC [23], Al_2O_3 [24], B_4C [25], CNT [26], TiO_2 [27], and so on. Nevertheless, there is a significant lack of study on the combination of Al-6061 with either CeO_2 or GNPs. Existing studies in this area generally do not surpass concentrations of 2 wt.% for each reinforcement, as indicated by references [28]–[31]. This study aims to fill that gap by investigating the effects of higher concentrations of CeO_2 and GNPs on the mechanical properties of HAMMCs. The present work aims to investigate the mechanical and microstructural characterization of hybrid nano-composites made up of Al-6061, CeO_2, and GNPs [32]–[34], with a particular focus on their possible use as connecting rods in internal combustion engines. This study investigates the use of Al-6061-based HAMMCs with varying weight percentages (ranging from 1 wt.% to 5 wt.%) of CeO_2 and GNPs as reinforcements.

2. Materials and methods

2.1. Matrix and Reinforcements details

The stir-casting approach was employed to make HAMMCs, which involved the incorporation of Al-6061, graphene nanoplatelets (GNPs), and cerium oxide (CeO_2). The procurement of these materials is sourced from NRL, Jamshedpur (India). The supplier has supplied thorough information on the physical parameters of these materials in Table 2.

A total of four stir-cast alloys were produced with GNP and CeO2 concentrations varying between zero and three weight percent. The exact names of substances and compositions are shown in Table 3.

2.2 2-Step Stir-Casting Route

The two-step stir-casting approach was used to fabricate the hybrid aluminum metal matrix composites. The procedure started by subjecting Al-6061 alloy ingots to a temperature of 750°C within a graphite crucible utilizing an electric furnace. After that preheating at 750°C in a muffle furnace of ceria and graphene was done to remove any moisture from the powders used for reinforcement. Once the temperature was raised, the reinforcing particles were mixed with the molten melt prepared by the Al-6061 alloy. To prevent the clumping together of the nanoparticles, a process of constant stirring was carried out. Magnesium was employed as a wetting agent, while tetrachloromethane served as a degassing agent in the casting procedure. The agitation persisted for a duration of 20 minutes before the molten metal being transferred into a mould and waiting for the cooling of the mould. Once the cooling was done, the extraction of the specimens was processed from the casting. The procedure is shown in Figure 1 as a schematic diagram.

2.3. Microstructure and Mechanical Tests

2.3.1 Microstructure Evolution

The microstructure (FESEM) and elemental analysis (EDS) of the two-step stir-cast HAMMCs specimen were carried out using the Sigma 500VP ZEISS microscope. The FESEM and EDS analysis are the part of Sigma 500VP ZEISS microscope. The Microscope is available at the IIC Centre, NIT Jalandhar, India.

2.3.2 Tensile Strength Test

The model UT-04-100 (BISS manufactured) of the Universal Testing Machine was used to analyze the tensile test of stir-cast HAMMCs specimens. The maximum loading capability of 100 kN with 0.5 kN resolution of the machine used IS 1786:2008 to compile the tensile test. Figure 2 shows the specimen details prepared using the ASTM E8 standard.

2.3.3 Flexural Strength Test

In order to assess the bending strength of the samples, a three-point bending test was performed utilising a Universal Testing Machine (UTM). The test followed the guidelines set by IS 1599:1985, using a machine that can handle a maximum load of 100 kN and has a resolution of 0.5 kN. The specimens were constructed following the guidelines of ASTM E290-14 in order to quantify the flexural strength. The experiment was conducted using a 15 mm span with a crosshead velocity of 0.3 mm/min. The specimens were rectangular prisms measuring 32 x 6 x 3 mm (length x width x height). They were meticulously processed and polished to attain a surface roughness of 0.1 µm. In order to guarantee precision, three duplicates of every specimen were examined in order to get an average measurement for each characteristic.

2.3.4 Hardness Test

The Blue Star Limited manufactured digital hardness tester having model no 404 SxV was used for hardness measurements. The tester adhered to ASTM E92 standards, featuring an auto-focus system and automatic readout for ease of use. It supported a loading range from 1 gf to 2 kgf, a dwell time between 5 to 60 seconds, and magnification capabilities ranging from 100x to 400x.

2.3.5 Impact Strength

The impact energy was measured using an Impact Testing Machine, model number JBW-500, manufactured by IE Corporation, a company specializing in testing machinery. The testing followed ASTM E23-12C standards for sample preparation. The samples were prepared with dimensions of 75 x 10 x 10 mm (length x breadth x height).

2.3.6 Grain Size Test

ASTM E1382 was used to measure the grain size of the stir-cast HAMMCs specimens on DeXel-Metallography having a diameter of 12.5 mm and a thickness of 22 mm. The metallograph used micrographs of the materials, delineating 10 lines in the pictures to intersect grain boundaries. The metallograph automatically counted and recorded the grain sizes. The average grain size was estimated by calculating the mean of the three readings obtained for each item.

2.3.7 Fractography Test

Fractography is the process of analysing fracture processes by examining the microscopic morphology of fracture surfaces. The fracture analysis of tensile specimens was conducted using the guidelines outlined in ASTM E139. The Scanning Electron Microscopy (SEM) analysis of the broken tensile specimens was conducted using a JEOL JSM-6390LV model at the Instrumentation Centre (IIC) at NIT Kurukshetra. The purpose of this analysis was to investigate the surface morphology of the specimens.

3. Results Section

3.1 Mechanical Properties

3.1.1. Effect on Ultimate Tensile Strength Effect

Table 4 gives values for the shock, final tensile strengths, and percent elongation in the HAMMCs. According to linear interferometry grain-size measuring mechanisms, the grain-fine size refinement of particles enhances the strength of fabricated composites. The grain size is directly proportional to HAMMC state strength, as determined from total strengthening equations [35] , The strengthened HAMMCs micromechanics are affected by the intermetallic bonding of (GNPs+CeO_2).

The conversion of Al-6061 alloy feedstock to the molten state results in significant increases in densities due to variations in coefficients of thermal expansion between the matrix and the reinforcing particles. The smaller grain size of REP (CeO_2), as indicated by the FESEM images, greatly enhances the homogeneous dispersion when using GNPs as reinforcement. The even distribution and ability to withstand displacement of the reinforcements led to an enhancement in the tensile strength of the HAMMCs.

Figure 3 demonstrates that the tensile strength of the samples rose when the reinforcing levels varied between 1 wt.% and 3 wt.%. The examination of the microstructure of the HAMMCs demonstrates that the mechanical characteristics, such as strength and grain size, are improved due to the uniform dispersion of reinforcements throughout the matrix material. Figure 3 depicts a visual depiction of the tensile strengths of multiple HAMMC samples, each containing varying weight percentages of reinforcements. The investigation suggests that the most effective combination is Al-6061 alloy with 3 weight percent of graphene nanoplatelets (GNPs) and 3 weight percent of cerium oxide (CeO_2), exhibits peak values for Ultimate Tensile Strength (UTS), reaching 105.862 MPa. The present study results are consistent as compared to those of these earlier studies [7], [36]–[39].

3.1.2. Effect on Flexural Strength

The three-point bending test is essential for assessing the mechanical characteristics of produced HAMMCs. Flexural tests provide important information on the material's capacity to tolerate bending loads, in contrast to tensile and impact testing. This information is crucial for forecasting the performance and durability of the composites under varied loading scenarios. The presence of the node effects caused by GNPs and CeO_2 particles in the composites being manufactured is a reason for choosing flexural tests instead of tensile tests. Also, we need an ultrafine, smooth surface, a rigid structure, and special processing for the components manufacturing for the HAMMCs. High-speed Diamond-coated tools fulfill those requirements in composites processing. The Al-6061 matrix material is reinforced with GNPs and CeO_2 (1wt.%-3 wt.%) by stir-casting techniques. The hybrid composite samples were fabricated in accordance with the specifications described in ASTM E290-14. The produced samples were then evaluated in three-point bending tests in order to obtain a maximum stress bending value. After getting the values of maximum bending loads of the various hybrid samples, the value of load was then converted into flexural strength (MPa). A UTM machine model UTE100 made by BISS was used to perform three-point bend tests at room temperature. Figure 4 displays the graphical representation of the flexural strength values. The findings indicate a rise in flexural strength, with the H3-3C3G samples exhibiting a maximum value of 265 MPa, in contrast to 179 MPa in the base Al-6061 alloy. This enhancement in flexural strength is attributed to the improved interfacial bonds between the matrix and reinforcement particles. The rigidity of the graphene nanoplatelets (GNPs) and the solid nature of cerium oxide particles contribute to this increase, interacting effectively with the Al-6061 matrix. Analysis reveals that the addition of 3 wt.% CeO_2 and 3 wt.% GNPs resulted in a 32.5% improvement in flexural strength compared to the Al-6061 alloy. The present results are consistent with the previous studies [40]–[42].

3.1.3. Effect on Hardness

The Vickers hardness tester was used to assess the hardness of HAMMC specimens. The test results indicated that as the weight percentage of reinforcements increased, the micro-hardness also increased, rising from 96.9 HV to 117.7 HV at 3 wt.% reinforcement. Notably, a 21.47% increase in hardness was observed at a 6 wt.% reinforcement level (3% GNP + 3% CeO_2)

compared to the base matrix material. The enhanced microstructure of the HAMMCs, as shown in FESEM images, demonstrates improved finesse and stronger particle bonding due to the addition of rare earth particles (REPs). This improvement supports better bonding and contributes to increased microhardness and surface density of the samples. Figure 5 provides a graphical representation of the relationship between hardness and different weight percentages of reinforcements. The results from the present study are consistent with those from recent studies [43]–[45].

3.1.4. Effect on Impact Strength

Figure 6 demonstrates the relationship between the weight % of reinforcement and the impact force of HAMMCs. The graph illustrates a positive correlation between reinforcement levels and impact energy. More precisely, the inclusion of 1% CeO_2 and 3% GNPs leads to an impact energy of 10.465 J, while 3% CeO_2 and 3% GNPs produces an impact energy of 13.06 J. When comparing the two materials, the Al-6061 alloy has an impact energy of 7.869 J, whereas the hybrid Al-6061/3% CeO_2/1% GNPs composite has an impact energy of 9.954 J. Visual comparison of fabricated 2-step stir-casted HAMMCs specimen is represented in Figure 6. The impact energy value shown in Figure 6 demonstrates a positive correlation between weight and impact strength.

3.1.5. Effect on Grain Size

The grain size plays a crucial role in defining the properties of hybrid aluminum metal matrix composites (HAMMCs) that are strengthened with reinforcements. Reducing the size of grains often results in enhanced mechanical qualities, such as heightened strength and hardness. This is because smaller grains have a greater number of grain boundaries, which impede the movement of dislocations. Figure 7 displays the average grain sizes of specimens H1-0C0G, H2-3C1G, H3-3C3G, and H4-1C3G in the present investigation. The relationship between grain size and the strength and hardness of the HAMMCs is such that a decrease in grain size increases in strength and hardness. The enhancement may be ascribed to the augmented quantity of grain boundaries and elevated dislocation density, both of which lead to a higher composite strength. In addition, smaller particle sizes enhance the distribution of ceria and graphene into the base Al-6061 matrix alloy. The greater dispersion enhances the connection between the reinforcement particles and the aluminium matrix, leading to higher load transmission and overall improved mechanical characteristics.

3.2 Microstructure Analysis

3.2.1. Microstructure Development of 2-Step Stir Casting HAMMCs

Stir-cast HAMMCs reinforced with various percentages of CeO_2 and GNPs were prepared in sample sizes of 10 x 10 x 4 mm for FESEM analysis. The samples were subjected to an initial polishing process using emery sheets of increasing fineness (ranging from 100 to 2,000 grit). This was followed by the application of 0.5% diamond paste to get a superior level of smoothness and quality. To obtain a mirror-like polish, the samples were further processed using Ion Beam Polishing machines. The microstructure analysis of two-step stir-casted HAMMCs specimens is shown in Figure 8 (a-d). The microstructure analysis of specimen H1-0C0G (base Al-6061 alloy) without reinforcement addition is represented in Figure 8(a). The presence of casting flaws such as pores and voids are shown in Figure 8(b), corresponding to the H2-3C1G specimen, these defects are evident, highlighting the presence of casting imperfections. Figure 8(c) illustrates the H3-3C3G specimen, where increased particle bonding is observed due to the irregular shapes of the rare-earth particles and graphene nanoplatelets, leading to enhanced tensile strength. The superfine reinforcement structures are visible in this image, showing the effective distribution of matrix and reinforcements, and making it difficult to pull reinforcements out of the matrix, which contributes to the increased strength of the HAMMCs. Figure 8(d) depicts the H4-1C3G specimen, where the clustering of reinforcement particles is evident.

Aggregation of GNPs and CeO_2 within the matrix decreases surface smoothness as well as the strength of composite samples as shown in figure 8 (d) [46]. The presence of dendritic elements at the surface of the composite also decreases its strength of the composite. The cause for these dendritic structures is an incorrect rate of solidification and cooling of the composite samples. The FESEM image of H3-3C3G specimen further described the smooth dispersion phases achieved through a reaction between GNPs and CeO_2 particles and 6061 aluminium alloy. The addition of REPs decreases the agglomeration level and helps in improving matrix grain refinement on the HAMMCs, as can be seen in microstructure images of the FESEM. The formation of defects such as pores and cracks in the surface of the composite is also reduced by adding GNPs as a strengthening agent, which also increases the strength of the produced HAMMCs. Uniform dispersion and refinement of the grains lead to an improvement of HAMMCs mechanical properties as shown in figure 8 (c). Similar results are observed in various studies, mentioned below; uniform distributions are observed in aluminium alloy matrixes, where small nanoparticle reinforcements Y_2O_3 are added to reinforce it [47]. The present work takes into account evidences obtained by the FESEM images, i.e. The better defended the matrix-reinforcement fiber interface, the better will be the ability to resist forces and load transport in the composite. The addition of GNPs and REPs as reinforcements to

Al6061 matrix improved mechanical properties of fabricated components in the HAMMC. [48]–[50].

Current studies have followed similar tendencies and found that the improvements in the mechanical properties such as hardness, strength, and stiffness qualify the components for use in electronics, automotive, aerospace, and defense sectors. The finer grain texture and uniform distribution are responsible for microstructure enhancement. The addition of reinforcements also provides a structure without dendrites.

3.2.2. Stir Casting Effect on EDS Analysis

Figures 9 (a, b, c, and d) show the EDS analysis of the samples of produced HAMMCs. The presence of Al as matrix aluminum material, reinforcements; Ce as ceria and C as graphene nanoparticles, and wetting agent magnesium (Mg) followed by different peaks is visible in Figure 10.

The HAMMCs are also reinforced by oxides, indicating the presence of oxygen in the samples. For the best metal bonding structures, the selection of various spectrums was analyzed. Uniform grain polishing and scattering of the reinforcing particles showed smooth surfaces for HAMMCs. The possibility for a harmful reaction to occur there may arise from using oxides as reinforcement. To avoid such reactions, we used ccl_6 agents, and because of that, there were no harmful reactions observed at the sample surface of the HAMMC. The EDS plots also clearly showed Mg peaks in the spectra, which were included for the wet agents during the preparation of 2-step stir-casting HAMMCs specimens, which enhances the strengthening mechanism and bonding between the reinforcing particles. The phenomenon was visualized in the EDS spectrum with the presence of all the elements that were added during casting and the same is also affected by the stirrer speed and stirring duration during the preparation of HAMMCs specimens.

3.2.3. Fracture Analysis of Tensile Specimens

The fractography analysis of fractured HAMMCs specimens after tensile tests using SEM micrographs are shown in Figure 10 (a, b, c, and d).

Figure 10a depicts the fracture surface of the Al-6061 alloy in its original, unaltered state. The surface has uneven planes and significant indentations, which suggest a fracture pattern resembling cleavage. This fracture type is linked to reduced mechanical characteristics as a result of insufficient reinforcing. Figures 10 (b, c, and d) show the fractured HAMMCs specimens after tensile tests having different proportions of ceria and graphene. Figure 10b shows the fracture surface of the H2-3C1G sample, which displays a combination of ductile and brittle fracture characteristics. Notable surface defects, including particle clustering, cracks, and matrix-reinforced particle disintegration, are visible. These defects contribute to reduced mechanical strength compared to other HAMMCs samples. Figure 10c depicts the fracture surface of the H3-3C3G sample, which shows an improved distribution of reinforcing particles within the matrix and smaller cracks. This enhanced distribution correlates with higher tensile strength, flexural strength, impact strength, and hardness, as well as smaller grain sizes, as observed in Figure 3 to Figure 7. In Figure 10d, the H4-1C3G specimen is shown with increased grain size and additional defects such as pores. These issues lead to decreased strength and increased porosity in the HAMMCs samples.

4. Discussion Section

In recent years, hybrid aluminum metal matrix composites (HAMMCs) have gained significant attention due to their enhanced mechanical and metallurgical properties, which make them suitable for advanced industrial applications such as automotive, aerospace, and defense. In this study, cerium oxide (CeO_2) and graphene nanoplatelets (GNPs) were used as reinforcements in the Al-6061 matrix. Cerium oxide, a rare earth particulate, is known for improving hardness, thermal stability, and wear resistance, while graphene nanoplatelets provide exceptional strength and electrical conductivity due to their unique two-dimensional structure. The combination of these materials aims to offer a balance of mechanical properties, making the HAMMCs more versatile and durable.

4.1 Advantages of the study

- ❖ **Novel Material Combination**: The study investigates a hybrid composite using graphene nanoplatelets (GNPs) and cerium oxide (CeO_2) as reinforcements in Al-6061 alloy, which is relatively unexplored. This combination shows promise in enhancing mechanical properties compared to conventional composites.
- ❖ **Improved Mechanical Properties**: The HAMMCs fabricated with GNPs and CeO_2 reinforcement demonstrate significant improvements in tensile strength, hardness, flexural strength, and impact resistance compared to the base alloy. These findings support the potential for industrial applications where high-performance materials are required.
- ❖ **Successful Fabrication Method**: Stir casting, a relatively simple and cost-effective method, was successfully used to incorporate GNPs and CeO_2 into the aluminum matrix. The study shows that this technique can achieve good particle dispersion and interfacial bonding.

- **Comprehensive Characterization**: The study offers an extensive characterization of the composites, including mechanical tests, microstructural analysis (FESEM and EDS), and fracture analysis, providing a thorough understanding of the material's behavior.
- **Potential for Automotive and Aerospace Applications**: The enhanced mechanical properties and ability to withstand higher stresses make the fabricated HAMMCs a suitable candidate for components in high-performance industries like automotive and aerospace.

4.2 Disadvantages of the study

- **Particle Agglomeration**: The study notes some particle agglomeration, especially at higher wt.% of CeO_2 and GNPs, which can lead to uneven properties across the material. This suggests the need for more precise control over the distribution of reinforcement particles.
- **Narrow Range of Reinforcement Percentages**: Only a limited range of reinforcement percentages (1 wt.% to 3 wt.%) were studied. This limits the understanding of the full potential of these reinforcements at different concentrations.
- **Limited Focus on Other Properties**: The study focuses primarily on mechanical properties and neglects other important factors such as thermal and electrical conductivity, wear resistance, and corrosion behavior, which are crucial for real-world applications.
- **Scalability Concerns**: While the stir casting method is effective for small-scale laboratory production, there may be challenges in scaling up the process for industrial applications, especially in maintaining uniform particle dispersion and consistent properties.

4.3 Limitations of the study

- **Absence of Long-Term Performance Data**: The study does not explore long-term properties such as fatigue, corrosion resistance, or thermal cycling behavior, which are critical for the durability of materials in practical applications.
- **Limited Range of Reinforcement Compositions**: The study only investigates specific wt.% values of GNPs and CeO_2. Exploring a wider range of compositions might reveal more optimized reinforcement levels and provide insights into performance at varying concentrations.
- **Unexplored Environmental Factors**: The effect of extreme environmental conditions, such as high-temperature or corrosive environments, on the HAMMCs was not investigated. This limits the understanding of how the material would perform in real-world settings.
- **Lack of Comparative Analysis**: The study does not provide a comparative analysis between the fabricated HAMMCs and other conventional composites, such as those

reinforced with SiC or B_4C, which would offer a clearer understanding of the relative advantages of using GNPs and CeO_2.

4.4 Future Scopes

- **Exploration of Different Reinforcement Combinations**: Future research can explore the use of different combinations of reinforcements such as carbon nanotubes (CNTs), silicon carbide (SiC), or titanium dioxide (TiO_2) alongside cerium oxide (CeO_2) and graphene nanoplatelets (GNPs). This could further enhance the mechanical and thermal properties of hybrid composites.
- **Optimization of Stir Casting Parameters**: The stir casting process could be optimized by varying parameters like stirring speed, time, and temperature control, to improve the distribution of reinforcement particles and reduce defects such as porosity or clustering.
- **Advanced Characterization Techniques**: The use of more advanced characterization techniques, such as Transmission Electron Microscopy (TEM) or X-ray diffraction (XRD), could provide deeper insights into the material's microstructural behavior, helping to better understand the effects of reinforcement at the atomic level.
- **Performance in Extreme Conditions**: Testing the hybrid composites under extreme conditions such as high temperatures, corrosion environments, and fatigue testing would provide valuable information about their reliability and durability for aerospace or automotive applications.
- **Scaling for Industrial Applications**: Future work could focus on scaling the production of HAMMCs for industrial use. Investigating cost-effective manufacturing methods that retain the material's improved mechanical properties will be crucial for practical applications.
- **Finite Element Analysis (FEA)**: Simulation and modeling techniques like Finite Element Analysis could be used to predict the behavior of HAMMCs under different loading conditions, which would aid in optimizing material design for specific applications.
- **Bio-compatible HAMMCs**: Research could be directed toward the development of bio-compatible HAMMCs for medical applications, such as implants, where strength, wear resistance, and biocompatibility are required.

5. Conclusions

This study used stir casting for the production of HAMMCs in addition to graphene and ceria. Mechanical and metallurgical tests showed that the composites outperformed the Al-6061 alloy base material. The findings show that GNP and CeO_2 reinforcements can improve high-performance HAMMCs for internal combustion engine connecting rods. The following research provides insights into optimizing composite materials for advanced engineering applications:

1. An aluminum metal matrix composite was effectively fabricated utilizing the stir casting technique. The composite material was enhanced using nanographene and nanoceria particles, with weight percentages varying between 1% and 3%.
2. The successful incorporation of GNPs and CeO_2 into the Al-6061 matrix was confirmed through Energy-Dispersive Spectroscopy (EDS) testing. The composite materials have been revealed to include graphene, ceria, and Al-6061.
3. Significant enhancements in mechanical properties were observed when 1 wt.% GNPs and 3 wt.% CeO_2 were incorporated into the Al-6061 matrix. The hardness experienced a significant increase of 21.47%, while the tensile strength showed a remarkable improvement of 66.76% when compared to the base alloy. The impact and flexural strengths were significantly increased, with a 66% improvement in impact strength and a 48% improvement in flexural strength.
4. The fracture surface analysis of the H3-3C3G specimen showed small dimples, suggesting improved mechanical properties of the HAMMCs.
5. The FESEM images clearly illustrate the strong interfacial bonding between the GNPs, CeO_2 particles, and the Al-6061 matrix. The bonding plays a vital role in the observed enhancements in the microstructural behavior of the HAMMCs.
6. The effectiveness of the stir casting technique in blending GNPs and CeO_2 with the Al-6061 matrix is highlighted by the successful incorporation of these reinforcements, as confirmed by EDS testing.
7. The observed enhancements in hardness and tensile strength can be ascribed to the reinforcing effects of GNPs and CeO_2. The significant enhancements in impact and flexural strengths serve as clear evidence of the advantages of these reinforcements in improving the mechanical properties of the HAMMCs.
8. The fracture surface of the H3-3C3G specimen displays narrow-sized dimples, indicating that the reinforcements have played a significant role in enhancing toughness and mechanical performance. This underscores the efficacy of the reinforcement strategy.

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Table 1: Previous research carried out on the Al-6061 alloy and reinforcements

S. No	Composite	Properties	Ref.
1	Carbon- CeO_2	Enhance the mechanical properties/ implement these materials in sensors	[51]

2	AA2024 CeO_2-Al_2O_3	The hybrid matrix was found to possess remarkable barrier ability which was preserved even after prolonged exposure to the coatings to a model corrosive medium of 0.05 M NaCl.	[52]
3	AA2024-Glu-CeO_2	The increment in inhibition efficiency was observed from 40.5 to 85.4% for 0.05 mm Glu + 0.30 mm CeO_2.	[53]
4	Al6063- CeO_2-Graphite	A reduction in grain size was observed from 25 µm to 21.8 µm. The maximum stress and hardness were 325 MPa and 325 MPa, respectively.	[54]
5	CeO_2/ZrO_2	Maintained good corrosion resistance and high flux (34411.9 Lm^{-2} h^{-1})	[55]
6	CeO_2/BC	Improvement in wear and corrosion resistance	[56]
7	CeO_2 coated Graphene oxide reinforced Al7075	The ultimate tensile strength was increased by 69.4% with the addition of CeO_2. The decrement of grain size was also seen as 100.8 µm to 38.5 µm.	[57]
8	$CeAlO_3$@rGO nanocomposite	Enhancement of corrosion resistance via electrochemical characterization	[58]
9	CeO_2 and Al_2O_3	Improvement in tensile strength and Young's modulus	[59]

Table 2: Reinforcement Particulates Detailed specification

Reinforcement	Purity (%)	Density (g/cm^3)	Melting Point (°C)	Average Particle Size (nm)
Cerium Oxide (CeO_2)	99.5	7.2	2350	20-25
Graphene Nanoplatelets (GNPs)	99.9	2.3	3500	3-5

Table 3: Composition and designation of prepared samples

Sample Number	Composition	
H1-0C0G	Base Alloy	
H2-3C1G	CeO_2 3%	GNPs 1%
H3-3C3G	CeO_2 3%	GNPs 3%
H4-1C3G	CeO_2 1%	GNPs 3%

Table 4: Properties of the Tensile Tested Specimens

Sample Nomenclature	Tensile Strength (MPa)	Load (kN)	Strain	% Elongation	Yield Strength (MPa)	Elastic Modulus (GPa)
H1-0C0G	63.481	9.776	0.845	1.202	52.761	17.787
H2-3C1G	72.141	11.110	1.013	2.158	57.246	17.336
H3-3C3G	88.822	13.679	1.611	2.790	61.066	17.368
H4-1C3G	105.862	16.303	1.657	2.806	73.238	16.322

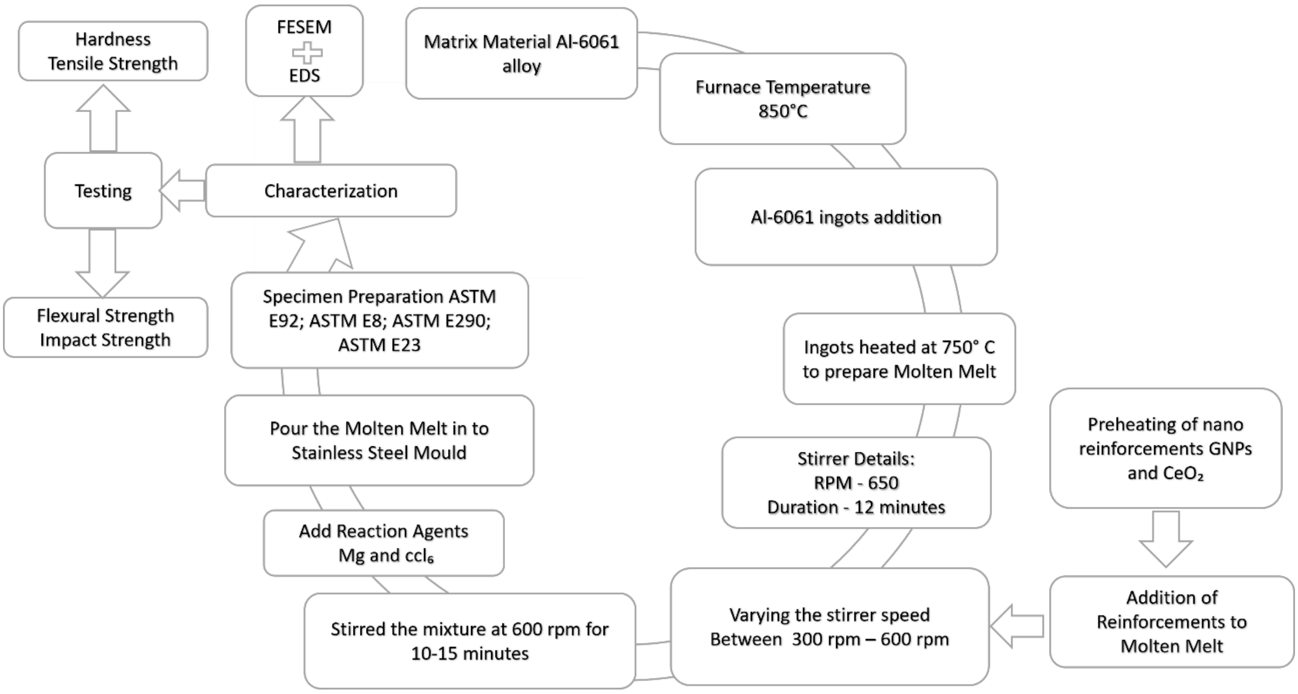

Figure 1: Schematic representation of stir-casting setup.

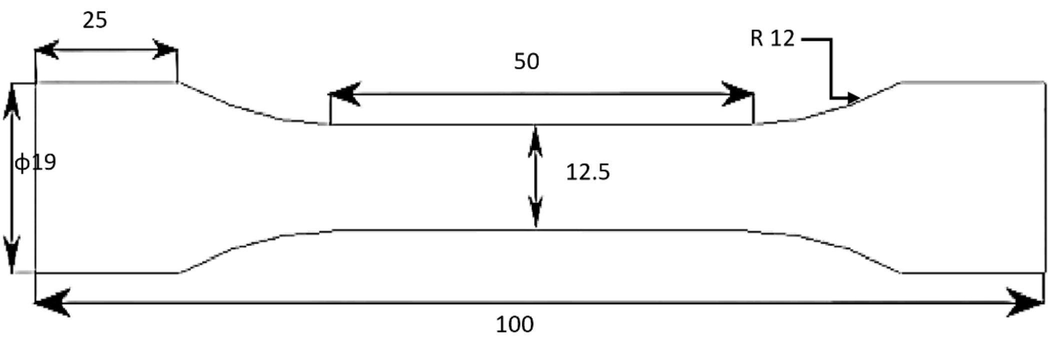

Figure 2: Tensile test specimen following ASTM E8

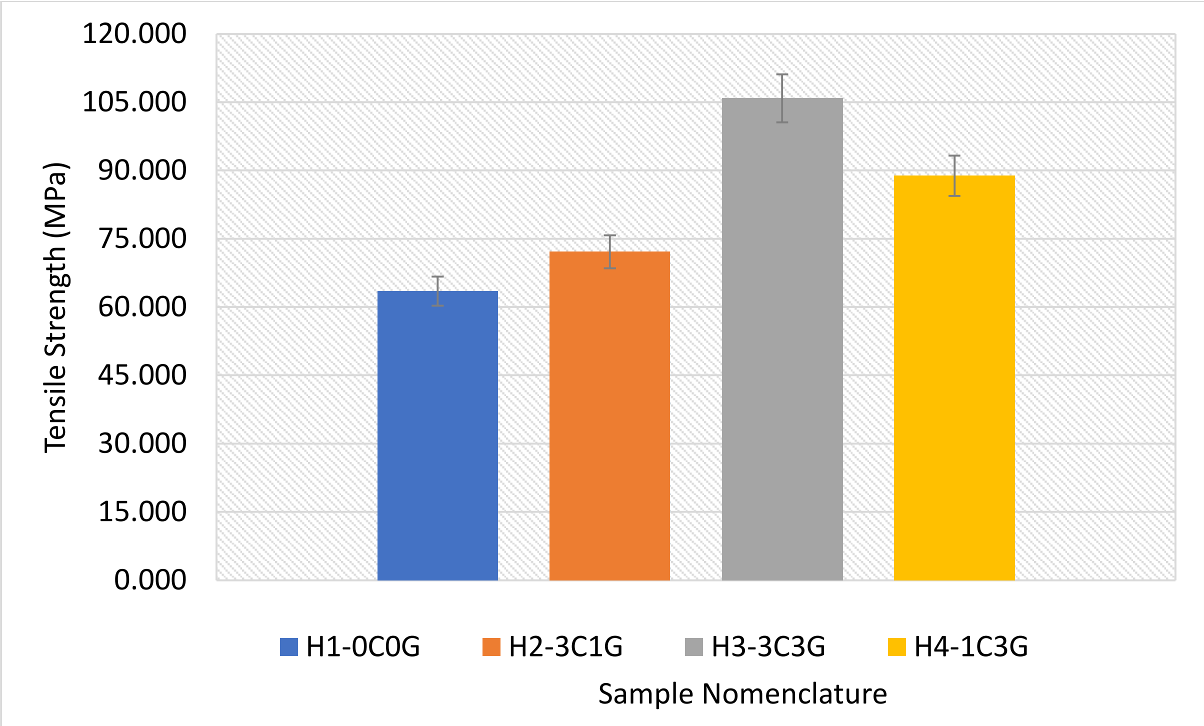

Figure 3: Tensile Strength for different tested specimens

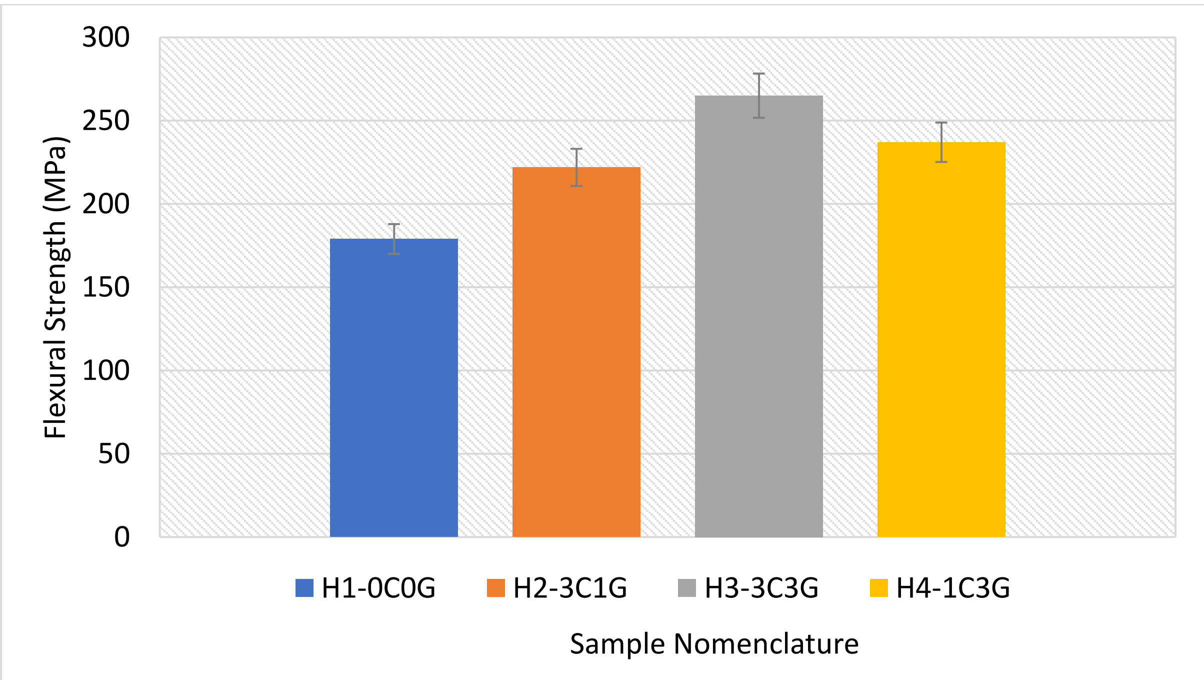

Figure 4: Flexural Strength for different tested specimens

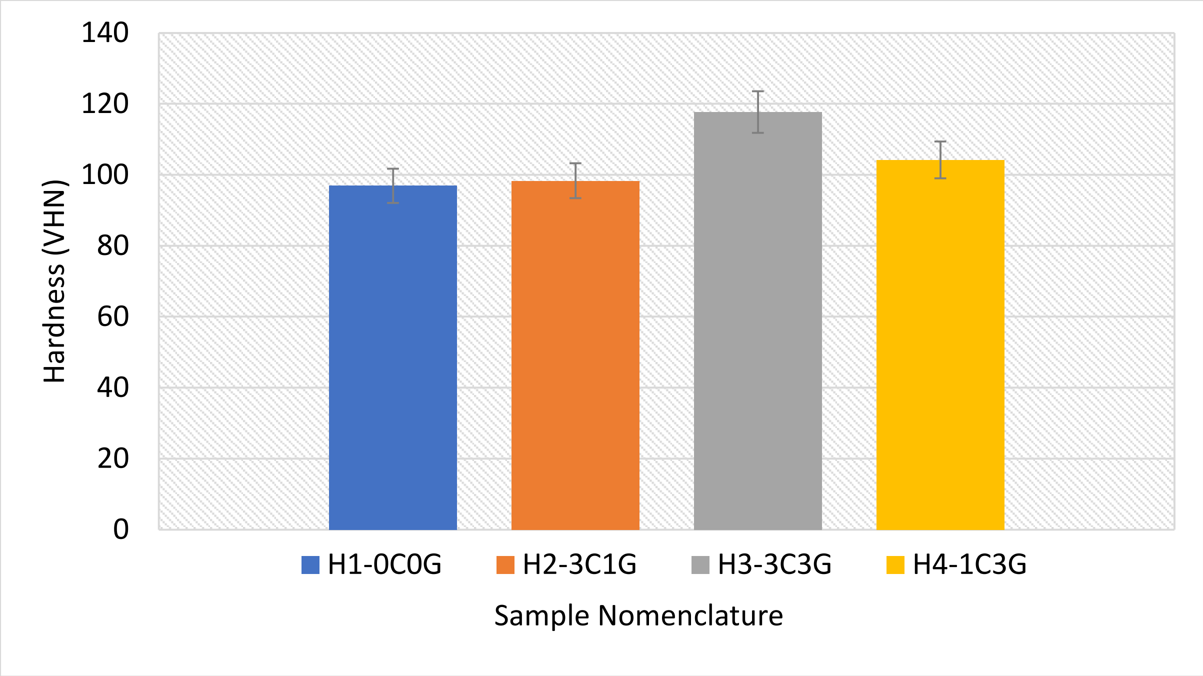

Figure 5: Hardness for different tested specimens

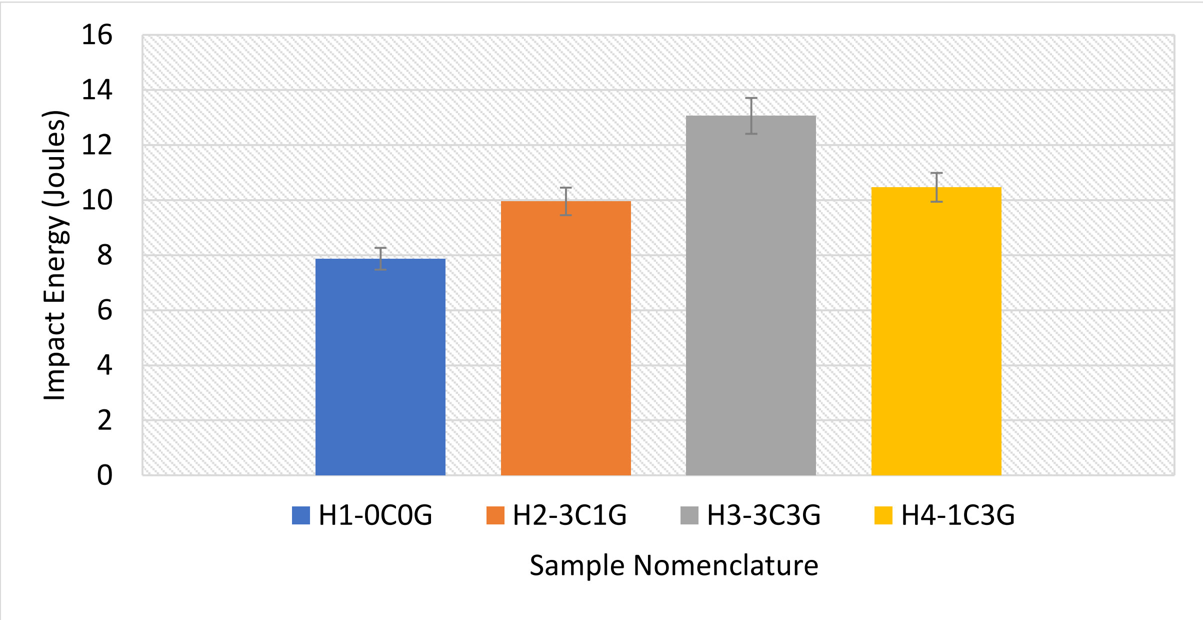

Figure 6: Graphical representation of Impact Strength for different specimens

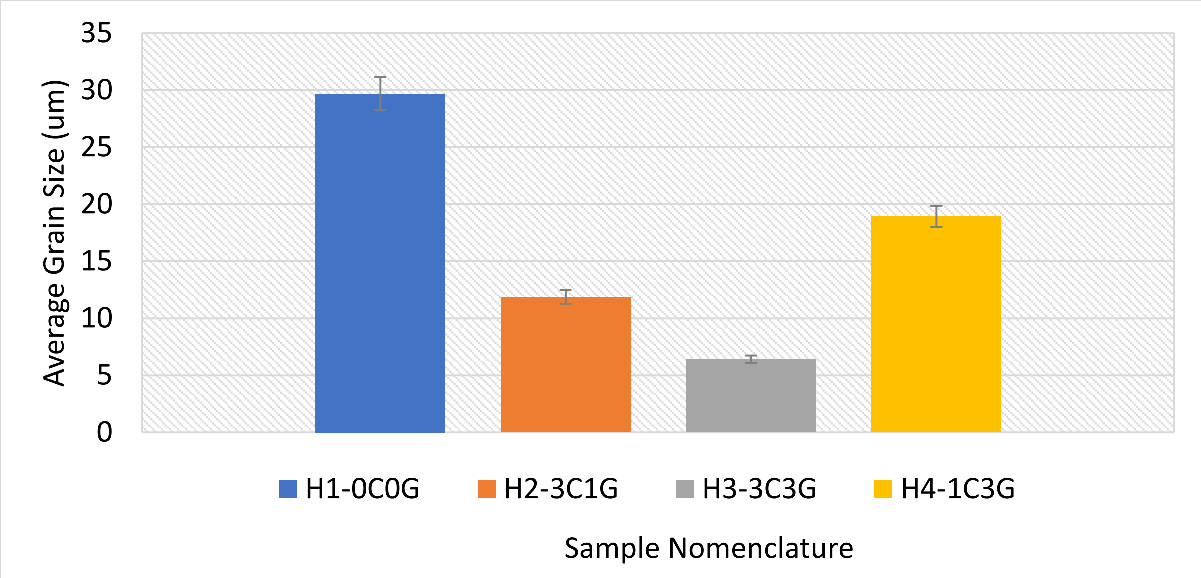

Figure 7: Graphical representation of Grain size for different specimens

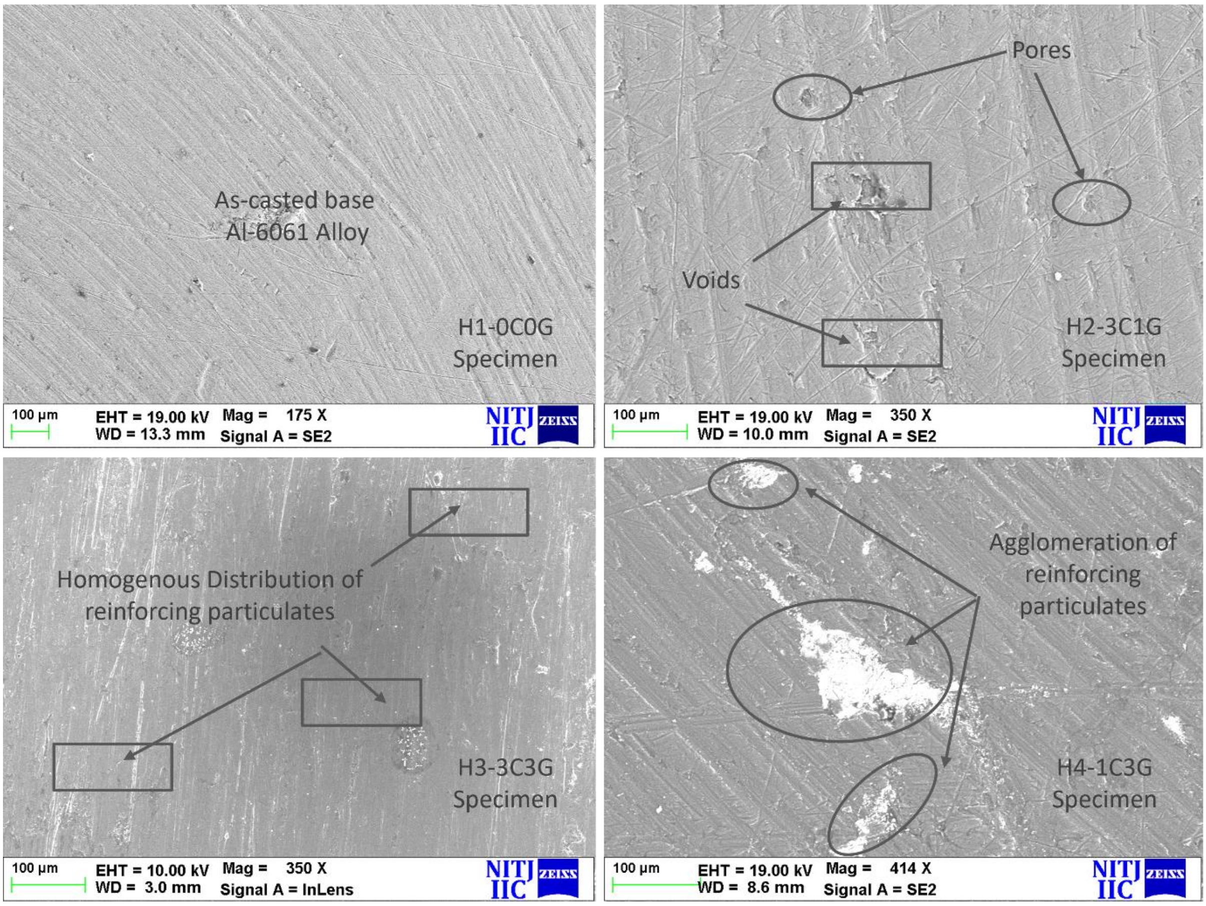

Figure 8: Microstructures of base alloy and HAMMCs samples

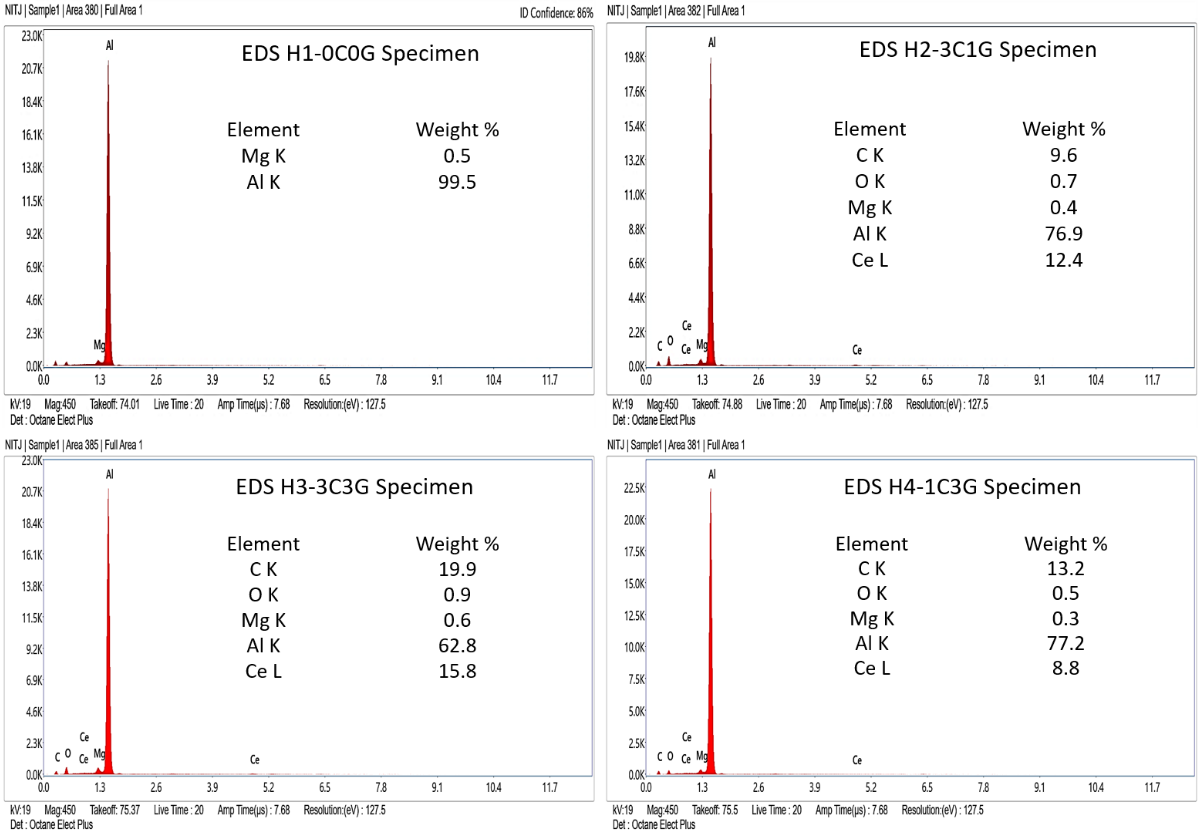

Figure 9: EDS analysis of HAMMCs samples; Al-6061 base alloy (H1-0C0G), H2-3C1G specimens, H3-3C3G specimens, and H4-1C3G specimens

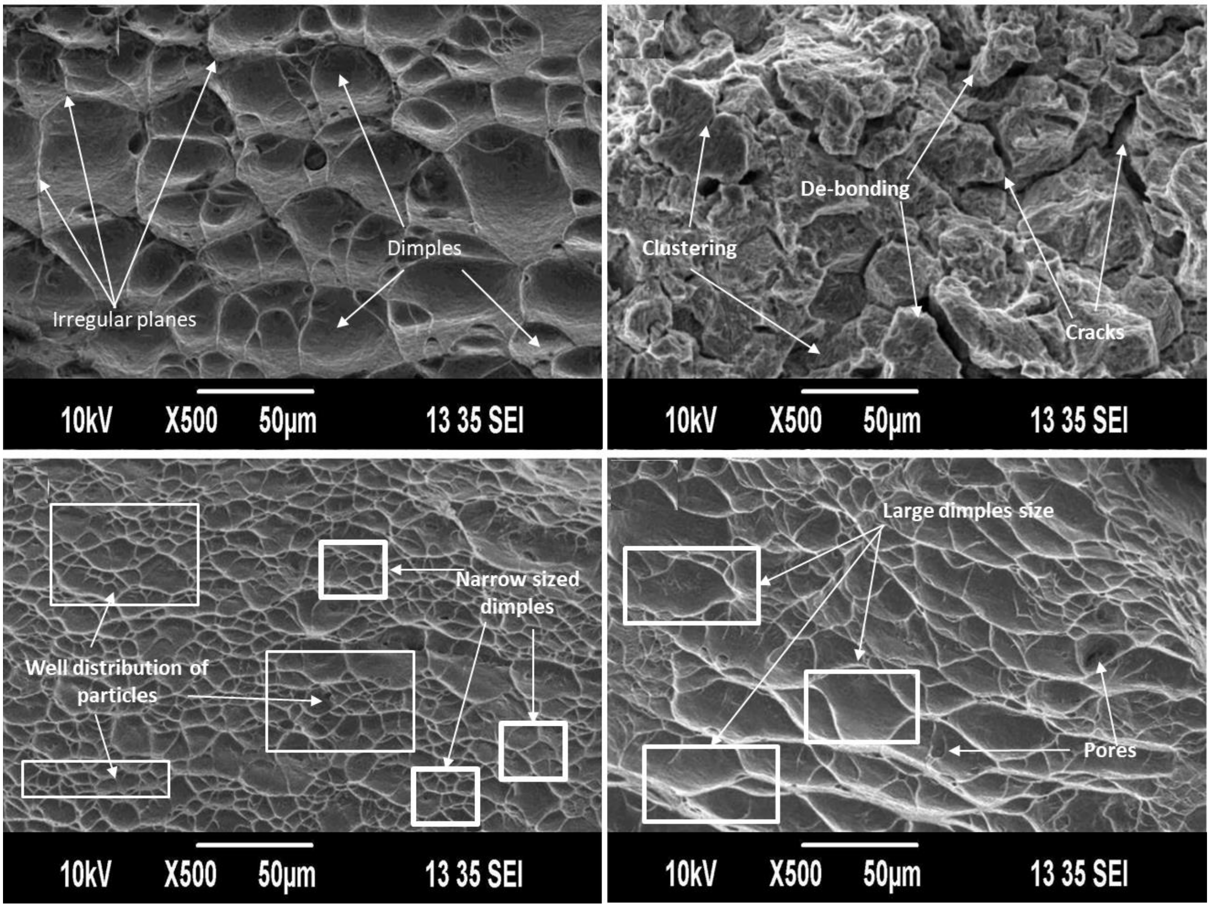

Figure 10: Fractography of tensile tested specimens; Al-6061 base alloy (H1-0C0G), H2-3C1G specimens, H3-3C3G specimens, and H4-1C3G specimens