Research Article

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Evaluating the Mechanical Features of Nano Alumina Reinforced Magnesium Alloy-fly Ash Nanocomposites

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ABSTRACT

In this work, hybrid magnesium nanocomposite (HMNC) was fabricated with ultrasonic cavitation assisted bottom pouring stir casting method. For this, fixed quantity (7.5 wt.%) of fly ash (FA) and varying proportions of nano alumina (nAl_2O_3) (0, 0.5, 1, 1.5, and 2 wt.%) in AZ61 magnesium alloy matrix were used. Microstructural images reveal near homogeneous distribution of reinforcements with nAl_2O_3 available at the grain boundaries. The physical and mechanical properties were determined as per ASTM standards. It is found that the density and porosity tend to rise with increasing nAl_2O_3 content, whereas the porosity of 2 wt.% addition of nAl_2O_3 was very significant. The AZ61 alloy reinforced with 1.5 wt.% nAl_2O_3 and 7.5 wt.% FA exhibited enhanced strength and stiffness, which can be attributed to the Orowan strengthening mechanism and increased dislocation density. The 0.5 and 1 wt.% nAl_2O_3 reinforcement may be insufficient to effectively impede dislocation motion leading to limited improvements in mechanical properties. On the other hand, 2 wt.% nAl_2O_3 reinforcement leads to particle agglomeration and poor dispersion. This in turn, weakens the matrix-reinforcement interface and diminishes mechanical properties.

Keywords: AZ61 alloy; Nano alumina; Fly ash; Ultrasonic cavitation; Stir casting; Orowan strengthening

1. INTRODUCTION

Magnesium alloys are highly sought after in the engineering field for a variety of reasons, including their remarkable machinability, lightweight, and exceptional specific strength for automotive, aerospace, and electronics industries where weight reduction is vital (Carou and Davim, 2018). While aluminium alloys have traditionally dominated lightweight applications, magnesium alloys offer a superior strength-to-weight ratio and better damping capacity, providing a compelling alternative where further weight savings are desired. However, the relatively low mechanical strength and poor wear resistance of monolithic magnesium alloys have driven the development of magnesium-based composites. Compared to aluminium composites, magnesium composites provide a significantly higher strength-to-weight ratio, which is crucial for applications requiring extreme weight reduction without compromising mechanical performance (Dobrzanski *et al*. 2019). When compared to unreinforced magnesium alloys, magnesium matrix composites exhibit superior mechanical properties, including increased hardness, strength, and resilience to wear due to the incorporation of ceramic or nano-scale reinforcements (Luo *et al*. 2024). These reinforcements improve load-bearing capacity, inhibit grain growth, and enhance dislocation density, leading to refined microstructures and improved thermal stability. Overall, magnesium composites strike an effective balance between lightweight characteristics and enhanced performance, making them a more efficient and versatile alternative to both aluminium composites and conventional magnesium alloys (Ashby *et al*. 2018).

Pandian and Vinayagam (2024) examined the wear properties of nano zirconium carbide (50 nm) fortified AZ61 nanocomposite fabricated *via* stir cast method. They identified that the most substantial variable influencing the wear rate is the applied load, whereas sliding distance influences friction coefficient. Sudarsan *et al*. (2024) considered ultrasonic assisted stir casting for casting 3% MoS_2 with varying fractions of SiC (5, 10, and 15%) in LM25. Significant enhancements were seen in the outcomes of mechanical characteristic testing, particularly when 15% nSiC was incorporated as the nSiC is evenly distributed throughout the host metal which strengthens the inter-particle bonding. Saleh *et al*. (2024) fabricated magnesium-based composites strengthened with particles of squid quill ash (SQA) *via* stir casting. Microstructure analysis shows well-distributed SQA particles in matrix, indicating successful reinforcement. When tested against the AZ91 matrix alloy, the manufactured composites had much better mechanical and wear characteristics.

Kumar *et al*. (2023) incorporated Al_2O_3 into an AZ91 matrix by stir casting in conjunction with ultrasonication. Microhardness, energy absorption, and indentation fracture toughness were all improved at the same time when Al_2O_3 particles were added. An improvement in durability against wear was attributed to the uniform dispersion of small particles brought about by the ultrasonic agitations. Titarmare *et al*. (2025) utilized ultrasonic-aided stir casting method to reinforce nB_4C particles at different weight % (0.5, 1.0, 1.5 and 2 %) in AZ31 matrix. Optical microscopy showed the presence of α-Mg and β-$Mg_{17}Al_{12}$, while SEM showed that B_4C particles were evenly distributed throughout the magnesium matrix. The micro hardness of the developed composites was higher than that of the AZ31 alloy. When compared to base alloy, the composite had a much higher density. The wettability and bonding capacity of the composites were improved by adding CNTs to the matrix. Magnesium matrix composites supplemented with Al_2O_3 were superior in terms of wear resistance compared to those reinforced with CNTs. Wear and creep endurance were improved in SiC-particle strengthened magnesium MMCs as compared to their Al_2O_3 counterparts. When incorporated to a magnesium matrix, B_4C increases the flexural strength and interfacial bonding strength of hybrid composites (Arora *et al*. 2022). The effect of hafnium carbide, a ceramic reinforcement that can withstand very high temperatures, on the dry sliding wear behaviour of AZ91D composite was studied (Surendran *et al*. 2022; Gnanavelbabu *et al*. 2022). While the wear rates of both materials increased with an increase in normal load, the composite exhibited superior wear characteristics. Conversely, when sliding speed increased, wear rates dropped. The wear rate increased dramatically at 150°C when subjected to high temperatures. When exposed to high temperatures, the most common forms of wear were oxidation, abrasion, plastic yield and delamination.

Fly ash (FA), a waste product from coal combustion processes, has gained attention as a cost-effective and sustainable filler material in magnesium matrix composites. When merged into the magnesium matrix, FA particles improve the overall mechanical properties of the composite viz, resilience to wear, hardness and compressive strength (Wei *et al*. 2021). This enhancement is primarily attributed to the good dispersion of FA particles, which act as barriers to dislocation motion and reinforce the matrix. Additionally, the low density of FA contributes to the lightweight nature of the composite, makes it ideal for use in the aviation and automotive sectors where weight reduction is important. Moreover, using FA helps in waste utilization, thereby offering environmental and economic benefits (Harshit *et al*. 2024). From an environmental standpoint, employing FA aids mitigate waste dumping problems and reduces the ecological footprint and minimizing greenhouse gas emissions associated with cement and metal production (Virendra *et al*. 2024). The AZ91 composites containing fly ash cenospheres were successfully manufactured (Nagarajan *et al*. 2025). The cenospheres and the liquid magnesium alloy reacted to produce Mg_2Si and MgO. Composite densities were found to be much lower when cenospheres were introduced to AZ91 magnesium alloy. Saranu *et al*. (2021) fabricated the AZ91E hybrid composite with SiC and FA supplemented using the stir casting method. The results demonstrated that the particles were evenly distributed throughout the matrix. Reinforcement particles reduced elongation and fracture toughness in magnesium composites by refining the grains. With the use of powder metallurgy and microwave sintering, lightweight AZ61/FA synthetic microsphere foams were effectively produced (Akinwekomi *et al*. 2019). The microstructural analysis of the syntactic foams showed that the FA microspheres were evenly dispersed throughout the matrix. The synthesis of FA showed no risks of alterations in chemistry, porosity, castability, bonding and reinforcement (Samvatsar and Dave, 2021).

Nano-sized reinforcements have been found to significantly improve the overall performance of magnesium composites compared to traditional micron-sized ceramic reinforcements (Nie *et al*. 2021). Due to their ultrafine size and high surface area-to-volume ratio, nanoparticles offer more uniform distribution within the magnesium matrix, leading to more effective load transfer and enhanced interfacial bonding (Singhal *et al*. 2025). Mechanically, they contribute to superior strength and the process of hardening by grain refining, Orowan strengthening, and increased dislocation density, which are more pronounced at the nanoscale (Anbukarasi *et al*. 2025). The refined microstructure and homogeneous dispersion of nanoparticles reduce friction and wear rates by promoting the formation of stable tribo-layers and minimizing surface damage. Additionally, nano-reinforcements improve corrosion resistance by creating a more compact and less porous microstructure, reducing galvanic coupling sites and hindering the penetration of corrosive media (Muresan *et al*. 2023). Furthermore, hybrid magnesium composites reinforced with a combination of ceramic particles and secondary reinforcements like fly ash or carbon-based materials enable a synergistic improvement in mechanical, tribological, and thermal properties, while also promoting cost-effectiveness and sustainability (Sagar *et al*. 2024). As a result, nano-hybrid magnesium composites are emerging as a promising class of materials for next-generation lightweight structural components. Moreover, hybrid reinforcement allows for better control over cost and density, especially when using industrial waste materials like fly ash as a partial reinforcement (Khatkar *et al*. 2023; Osunmakinde *et al*. 2024).

The identified literature gap in the mechanical characterization of AZ61 alloy strengthened with FA and

varying proportions of nAl_2O_3 using an ultrasonic-assisted stir casting setup lies in the limited exploration of the synergistic effects of hybrid reinforcements on the microstructural refinement and mechanical performance of the composite. While previous studies have separately investigated the use of FA or nAl_2O_3 ceramic particles in magnesium-based composites, comprehensive research that systematically examines the combined influence of these reinforcements particularly at varying nAl_2O_3 proportions on key mechanical properties remains scarce. Furthermore, the role of ultrasonic vibration in enhancing the dispersion of nano-sized particles and improving interfacial bonding has not been thoroughly quantified in the context of such hybrid composites. This gap highlights the need for detailed investigations into process-structure-property relationships, considering both the reinforcement ratio and processing parameters, to optimize the performance of AZ61-based hybrid composites.

2. MATERIALS AND METHODS

2.1 Magnesium Alloy and Reinforcements

AZ61 is a magnesium alloy containing approximately 6% aluminium and 1% zinc, known for its excellent combination of lightweight characteristics and good mechanical performance. It exhibits a low density of about 1.8 g/cm^3, making it significantly lighter than aluminium alloys, which is ideal for weight-sensitive applications. AZ61 is widely used in applications such as automotive components (e.g., transmission housings, brackets), aerospace structures, portable electronic devices, and sporting goods (Dziubinska *et al.* 2021). nAl_2O_3 is a high-performance ceramic material with a low density of about 3.95 g/cm^3 and excellent thermal stability. It is capable of withstanding high temperatures without degradation. Its high surface area and nanoscale dimensions facilitate better dispersion and stronger interfacial bonding in composites, leading to improved load transfer and resistance to plastic deformation. Additionally, nAl_2O_3 exhibits excellent wear resistance, chemical inertness, and corrosion resistance (Mohanty *et al*. 2015). Fly ash is a fine, powdery byproduct generated from pulverized coal combustion in power plants and is predominantly composed of alumina, silica, and iron oxides (Alterary *et al*. 2021). It typically has a low density of 2.4 g/cm^3 with spherical morphology. Incorporation of FA into metal matrices improves wear resistance, dimensional stability, and stiffness due to its rigid nature and good thermal stability (Anandaraj *et al*. 2024).

2.2 Fabrication Method

Initially, the AZ61 magnesium alloy was charged into a crucible made of graphite and using electric furnace the alloy was melted under argon gas to prevent oxidation. Meanwhile, the reinforcements nAl_2O_3 and fly ash particles were preheated separately at 400°C for an hour to remove moisture and enhance wettability (Uday *et al.* 2022; Grilo *et al*. 2021). Once the alloy reached the desired molten state (750°C), mechanical stirring was initiated using a graphite-coated impeller at a controlled speed (600 rpm) to create a vortex. Preheated reinforcements were gradually introduced into the vortex zone, and simultaneous ultrasonic cavitation was applied using an ultrasonic probe immersed in the melt (Akash *et al.* 2025). After sufficient mixing and cavitation (10 minutes), the homogeneously mixed slurry was bottom-poured into a preheated metal mould to solidify under controlled cooling conditions. This process yielded a dense, well-bonded hybrid composite with enhanced mechanical and microstructural properties due to the uniform distribution of nano and micro-scale reinforcements.

2.3 Characterization Methods

The microscopic features of the composites were investigated using a scanning electron microscope (Zeiss) (SEM). Specimens were prepared according to the metallographic methods before examining under a microscope. SiC abrasive sheet of different grit sizes (240/400/600/1000) and diamond paste were used for polishing with etchant as Keller reagent. Vickers micro hardness testing was performed on the cast specimens in line with ASTM E384 (Kociubczyk *et al*. 2023), and a tensile test was conducted in line with ASTM-E8. ASTM-E23 was followed for impact testing (Karakoc *et al*. 2023). Flexural test was carried out following ASTM-D790 (Ostolaza *et al*. 2023). Densities and porosity percentages were used to assess the physical qualities of the cast composites. By using the law of mixtures (Eq. (1)), the theoretical density of composites was obtained. The Archimedes principle was used to calculate the experimental density (Sagar *et al*. 2022). A precision balance was used to measure the weight of the composites, and the percentage of porosity was determined using Eq. (2) (Jones *et al*. 2022).

$$\rho_{com} = \rho_{AZ61} V_{AZ61} + \rho_{nAl_2O_3} V_{nAl_2O_3} + \rho_{FA} V_{FA} \quad \ldots (1)$$

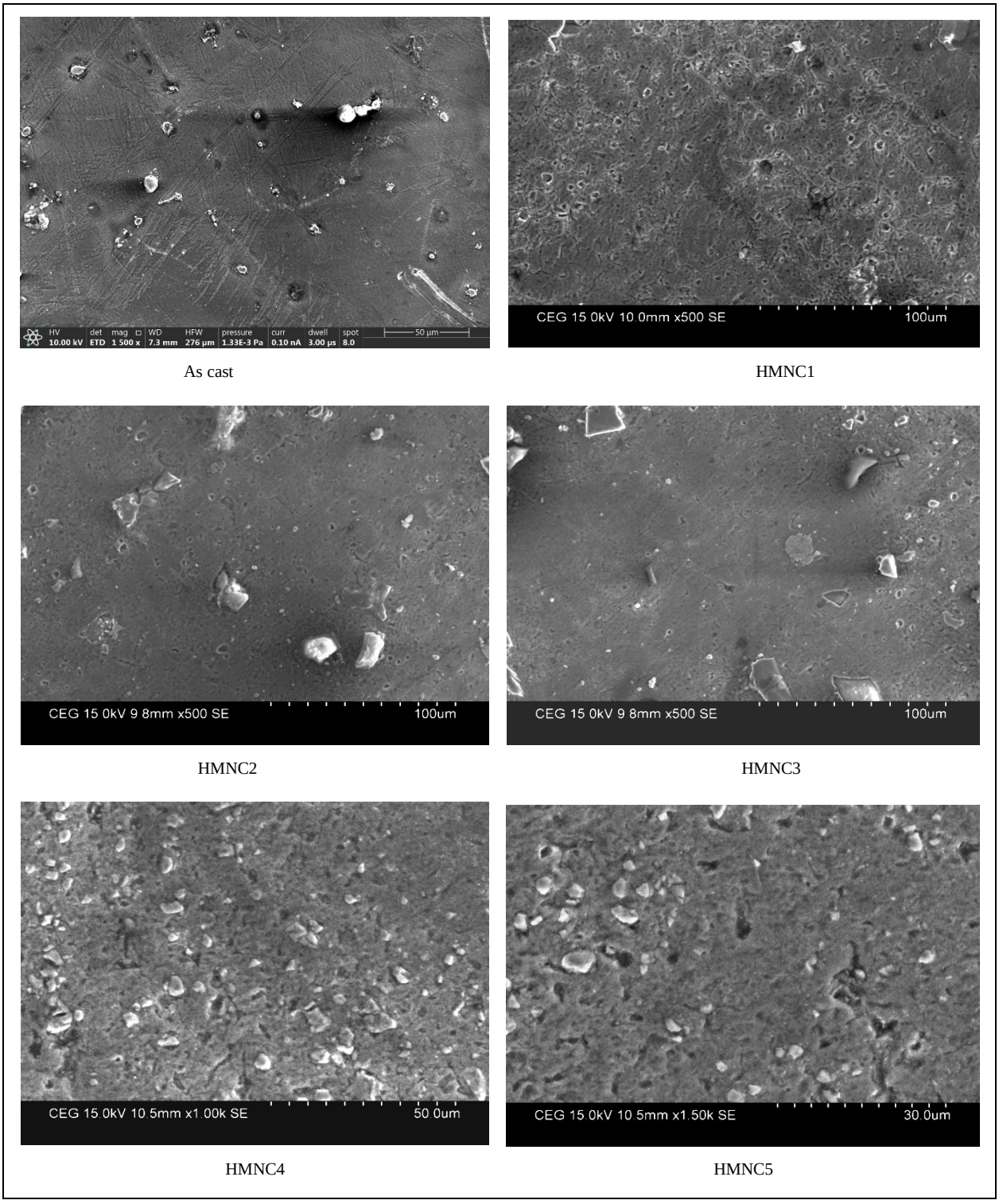
$$Porosity\ \% = \frac{\rho_{Th} - \rho_{Exp}}{\rho_{Th}} \times 100 \quad \ldots (2)$$

where ρ_{com}, ρ_{AZ61}, $\rho(nAl_2O_3)$, ρ_{FA}, ρ_{Th} and ρ_{Exp} are the densities related to AZ61, nAl_2O_3, FA, theoretical and experimental.

3. RESULTS AND DISCUSSION

After formulating the composites, metallographic investigation on the samples was done using SEM. Fig. 1 shows that the reinforced FA is clearly

visible on the matrix material. With inclusion of varying proportion of nAl_2O_3, grain refinement occurs (Kanth *et al*. 2019; Gnanavelbabu *et al*. 2020). No visible surface defects and voids were seen until 1.5 wt.% of nAl_2O_3. Particles were well-dispersed within the matrix, effectively impeding dislocation motion and improving load transfer, while the FA particles helped in grain refinement and weight reduction.



As cast HMNC1

HMNC2 HMNC3

HMNC4 HMNC5

Fig. 1: SEM images of casted samples

The microstructure appears dense, with minimal porosity and better interfacial connection among matrix and reinforcements (Ahmadian *et al*. 2024). However, beyond 1.5 wt.% of nAl_2O_3, the SEM images often reveal signs of agglomeration of nAl_2O_3 and increased porosity. These microstructural flaws lead to stress concentration points and weak bonding zones, which adversely affect the mechanical properties. The deterioration is thus attributed to particle clustering and poor distribution, which compromise the composite's structural integrity.

Fig. 2 shows the experimental density and percentage porosity of AZ61 magnesium alloy composites reinforced with 7.5 wt.% FA and nAl_2O_3. The results indicate that the FA reinforced composite maintains a relatively high and consistent experimental density with low porosity throughout the samples. In contrast, the nAl_2O_3 reinforced composite displays significantly lower density values and a steady increase in porosity (Du *et al*. 2020). The elevated porosity in the nAl_2O_3 composite can be attributed to several factors. First, due to their ultrafine size and high surface area, nAl_2O_3 particles tend to agglomerate, making uniform distribution challenging during the fabrication process. These agglomerates can trap gases and hinder proper compaction, resulting in micro-voids (Ivanov *et al*. 2018). Additionally, the poor wettability of nAl_2O_3 by molten magnesium can cause incomplete infiltration and poor bonding at the matrix–reinforcement interface, further contributing to porosity. In contrast, FA, being coarser and more stable, disperses more uniformly and integrates better into the matrix, reducing void formation and improving density. This increase in porosity not only lowers the overall density of the composite but also deteriorates its mechanical properties by acting as crack initiation sites and weakening the load transfer capability (Senthilkumar *et al*. 2025).

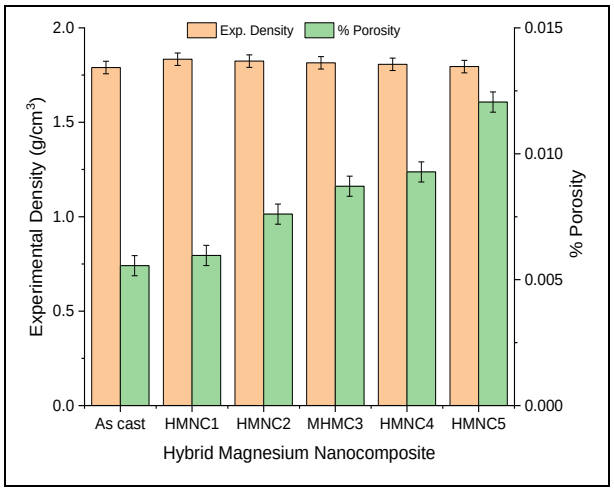


Fig. 2: Density and porosity of MHNCs

Fig. 3 illustrates the tensile strength and elongation % of MHNCs reinforced with 7.5 wt.% FA and nAl_2O_3 particles. It shows that the composite reinforced with FA exhibits lower tensile strength compared to that of hybrid composites reinforced with nAl_2O_3 (Shahabaz *et al*. 2023). However, the % elongation (a measure of ductility) decreases as the reinforcement changes from FA to nAl_2O_3. The increased tensile strength in the FA reinforced composite can be attributed to several strengthening mechanisms, such as the impact of load transfer, Orowan strengthening, and grain refining. Fly ash particles due to their relatively larger size and hard nature, act as obstacles to dislocation motion and contribute to better stress transfer between matrix and reinforcement (Chelladurai *et al*. 2025). Conversely, the nAl_2O_3 particles offer strength through similar mechanisms and agglomerate due to their high surface energy, leading to stress concentrations and microstructural defects. This explains the relatively lower tensile strength and reduced ductility observed in the nAl_2O_3 reinforced composites. Failure mechanisms in these composites are likely due to particle-matrix debonding, crack initiation at the reinforcement sites, and propagation through brittle phases. In the case of nAl_2O_3, the agglomeration and resultant porosity serve as stress raisers, accelerating failure under tensile loading (Ferguson *et al*. 2012; El-Saeid *et al.* 2003).

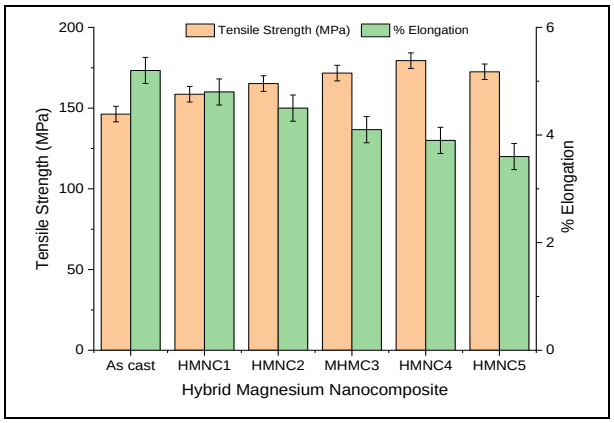


Fig. 3: Tensile strength and % elongation of MHNCs

The stress-strain behaviour of the AZ61 alloy reinforced with 7.5 wt.% FA and varying amounts of nAl_2O_3 exhibits a characteristic enhancement in mechanical properties, particularly in tensile strength and stiffness, due to the synergistic reinforcement effects, as seen in Fig. 4. Initially, all the composites display a steep linear region, indicating elastic deformation (Elajjani *et al*. 2025). As the nAl_2O_3 content increases from HMNC1 to HMNC4, both the ultimate tensile and yield strength enhance progressively, peaking with HMNC4. This is attributed to the uniform dispersion of hard nAl_2O_3 particles, which act as barriers to dislocation motion, thereby strengthening the matrix. The HMNC4 composite shows the highest stress value before necking, signifying optimal particle-matrix bonding and load transfer (Geng *et al*. 2020). Beyond the peak, a sudden drop in stress denotes necking and eventual fracture. Interestingly, HMNC5 exhibits a slight reduction in

tensile strength compared to HMNC4, likely due to nanoparticle agglomeration at higher concentrations, which could introduce stress concentrators and reduce ductility. Overall, the addition of nAl_2O_3 significantly enhances the mechanical response of the composite, though it comes with a cost of reduced elongation due to increased stiffness and brittleness (Ghazanfari *et al.* 2013).

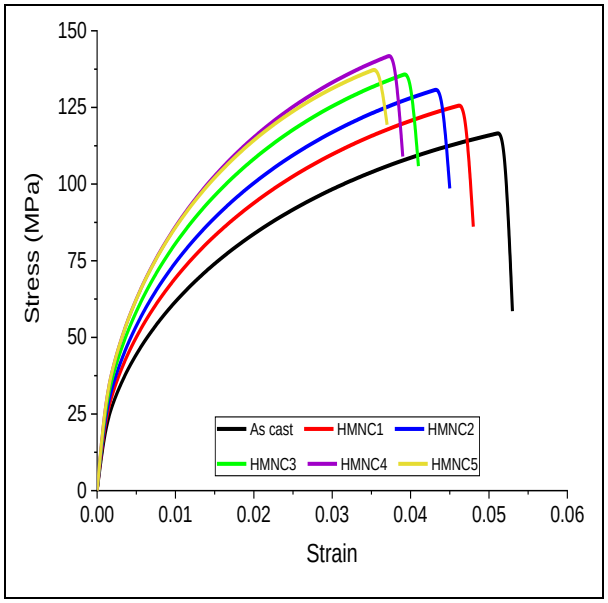


Fig. 4: Stress-strain curve for developed HMNCs

Fig. 5 presents the impact strength and flexural strength of AZ61 composites reinforced with 7.5 wt.% FA and nAl_2O_3. It reveals that the nAl_2O_3 reinforced composite consistently exhibits higher values for both impact and flexural strength compared to the FA reinforced counterpart (Narendran *et al.* 2024). The enhanced impact strength in the nAl_2O_3 composite can be attributed to the uniform dispersion and nanoscale size of the reinforcement, which improves energy absorption during sudden loading. These fine particles help in deflecting and blunting cracks, increasing the composite's resistance to impact failure. Additionally, the nAl_2O_3 particles refine the microstructure and hinder crack propagation, leading to better toughness (Ali *et al.* 2023). In terms of flexural strength, the improvement observed in nAl_2O_3composites is likely due to effective load transfer from the matrix to the well-dispersed, high-surface-area nanoparticles. The nAl_2O_3 bridges microcracks and delays their growth under bending stress. Moreover, the refined grain structure and strong interfacial bonding promote better stress distribution and resistance to flexural deformation (Ren *et al.* 2024). In contrast, while FA improves strength to some extent due to its hardness and ability to carry loads, its larger size and possible interfacial debonding reduce its effectiveness in resisting dynamic and flexural stress (Shishehbor *et al.* 2022). Thus, nAl_2O_3 demonstrates superior performance through refined microstructure and enhanced reinforcement-matrix interactions (Isitan *et al.* 2024).

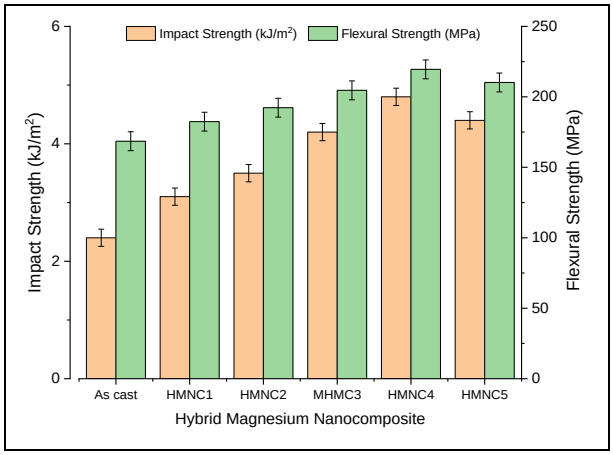


Fig. 5: Impact and flexural strength of MHNCs

In the AZ61 magnesium alloy composite reinforced with 7.5 wt.% FA and varying contents of nAl_2O_3, the mechanical strength and overall performance peak with the addition of 1.5 wt.% nAl_2O_3. This optimal performance can be attributed to the balanced synergy between micro-scale FA and nAl_2O_3 reinforcements. At 1.5 wt.%, the nAl_2O_3 is sufficiently dispersed within the matrix to effectively hinder dislocation motion, enhance load transfer, and refine the grain structure without causing significant agglomeration. This results in improved tensile, impact, and flexural strengths. At lower additions (0, 0.5, and 1 wt.%), the reinforcement effect is limited due to insufficient quantity of nAl_2O_3 to significantly impact the matrix structure. At higher additions (2 wt.%), excessive nAl_2O_3 tend to agglomerate due to their high surface energy, leading to poor dispersion, increased porosity, and stress concentration sites, which deteriorate the mechanical properties. Thus, 1.5 wt.% nAl_2O_3 represents an ideal concentration where strengthening mechanisms are maximized while avoiding the drawbacks of particle clustering and processing defects.

4. CONCLUSION

This study investigates the mechanical characterization of AZ61+fly ash+nAl_2O_3 prepared by ultrasonic assisted stir casting approach. The findings show that the reinforced FA are clearly visible on the matrix material. With inclusion of varying proportion of nAl_2O_3, grain refinement occurs. The microstructure appears dense with minimal porosity and better bonding at interfaces of matrix and reinforcements. Higher nAl_2O_3 (2 wt.%) reveal signs of agglomeration of nAl_2O_3 and increased porosity. The nAl_2O_3 reinforced composite displays significantly lower density values and a steady increase in porosity. The elevated porosity is due to their ultrafine size and high surface area, higher nAl_2O_3 particles tend to agglomerate. The composite reinforced

with FA exhibits higher tensile strength compared to that with nAl_2O_3. However, the ductility decreases as the reinforcement changes from FA to nAl_2O_3. The increased tensile strength is due to Orowan strengthening, refinement of grain and the impact of load transfer. The nAl_2O_3 reinforced composite consistently exhibits higher values for both impact and flexural strength attributed to the uniform dispersion and nanoscale size of the reinforcement, which improves energy absorption during sudden loading. The nAl_2O_3 bridges microcracks and delays their growth under bending stress.

AUTHORS CONTRIBUTION

S. Sundaraselvan: Conceptualization, Methodology, Writing - Original Draft; DVSSSV Prasad: Project administration, Supervision; Dinesh. N: Resources, Data Curation; Marxim Rahula Bharathi B: Review & Editing, Supervision.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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