Research Article

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Evaluating the Material Performance of AZ91 Reinforced with 3 wt. % of Nano SiC and Micro B_4C Through Stir Casting

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ABSTRACT

This research employs the stir-casting approach to cast magnesium AZ91 with micro boron carbide (μ-B_4C) and nano silicon carbide (n-SiC) ceramics individually at a 3 wt.% concentration, aiming for the successful fabrication of a composite with defect-free production. This approach is chosen because magnesium is valued for its lightweight nature. Still, its weak mechanical properties restrict its broader use. The properties of each sample were tested in different ways, evaluating the integrity of the material by physical characterization, such as density and porosity measurement. A metallurgical assessment was done to investigate the microstructural dispersion of reinforcement in the composite. Mechanical properties, including flexural and impact strength, were analyzed to evaluate their resistance performance subjected to stress conditions. Salt spray tests were performed to assess the performance of the materials in corrosive environments. To investigate how much wear loss has occurred, a pin-on-disc was utilized. These investigations clarify how the composite may be used with various sorts of applications and highlight the promise of uses in engineering sectors that call for lightweight materials with exceptional performance.

Keywords: Magnesium AZ91; Nano SiC; Micro B_4C; Performance; Stir casting.

1. INTRODUCTION

Magnesium metals are becoming a popular choice (Tan and Ramakrishna, 2021). They have been used in all fields for more than twenty years. It is 1.74 kg/m^3 dense, which means it is not as heavy as steel or aluminium. Because of this, magnesium is a good material to use instead of metal and steel in building (Zhang *et al.* 2023). Things that are made of magnesium metal are much lighter but still strong (Rajak and Menon, 2025). By mixing two or more parts with different chemical or physical properties, composite materials are made to have better mechanical qualities (Amalan and Sivaram, 2022). Matrix metal composites, or MMCs, are one kind of material. Magnesium is the core, and other materials are added to improve its strength and performance (Ma *et al.* 2020). They are often made by stir casting, which is also a cheap method. In this process, the base metal is melted, and bits are added to make the mixture stronger. The reinforcement is mixed evenly with the melted metal using a motorized mixer. The metal is then poured into moulds and left to cool (Kumar *et al.* 2018). The AZ91D/ZrB_2 composites in this study performed better than regular cast composites after casting. The voids in them are 31.61% smaller, they're 115 HV hard, they can hold 275 MPa of tension, and they wear down 25.14% faster (0.024 mm^3/m) (Ayyanar *et al.* 2023). AZ31 magnesium alloy metal matrix composites strengthened with different amounts of ZrO_2 reinforcements showed better dynamic properties than the as-cast AZ31 alloy.

However, the composites became less flexible as more ZrO_2 reinforcements were added (Kumar *et al.* 2019). Stir casting in Al_2O_3 makes it stronger and harder, and this study looked at ZX51 metal that was strengthened with Al_2O_3 microparticles. Changes in microstructure, porosity, and general mechanical behaviour are being studied (Rahmany *et al.* 2016). Huang *et al.* (2021) used gravitational melt-stir casting to introduce reinforcements into AZ91, aiming to refine the microstructure, inhibit $Mg_{17}Al_{12}$ formation, and form strengthening phases. The mechanical properties of the composite were evaluated, and microstructural and phase analyses were conducted to understand strengthening mechanisms such as the Orowan effect and shear transfer.

AZ91 magnesium alloy is widely used in engineering industries for its low density and excellent mechanical properties, but it limits high-temperature applications. Enhancing its performance with calcium

and rare earth (RE) elements has been explored, as Ca improves strength while RE elements enhance high-temperature stability. However, excessive Ca can weaken room-temperature properties and increase hot tearing susceptibility, while RE additions may reduce corrosion resistance. Nami *et al.* (2010) examined the combined impact of Ca and RE on the creep behavior of AZ91 *via* the impression creep system. Efe (2024) fabricated a composite from recycled AZ91 magnesium chips reinforced with B_4C using ball milling and sintering. This reduced machining waste and improved hardness and density. Analysis confirmed the presence of B_4C and MgO phase formation. Despite slight porosity and uneven B_4C spread, strong bonding was achieved.

Wear analysis revealed that composites with finer SiC particles maintained a more consistent friction coefficient compared to those with coarser particles (Erarslan and Cem, 2015). Mg–fly ash composites with reinforcement levels ranging from 2.5 to 7.5 wt.% were evaluated against pure Mg. The composites demonstrated significant enhancements in tensile strength (up to 42%) and hardness (up to 21%). Higher fly ash content contributed to reduced wear rates and friction coefficients. The SEM analysis revealed strong interfacial bonding, highlighting the composites' suitability for wear-resistant applications (Santhosh *et al.* 2022).

AZ91 magnesium reinforced with SiC enhanced microhardness and lowered wear rate and friction, attributed to the hard particles and refined grains. Wear increased with higher normal loads due to greater plastic deformation, while friction decreased as load and sliding distance increased, likely from smoother surface interactions. At a lower sliding speed (1.39 m/s), wear was dominated by oxidation and delamination, whereas at a higher speed (2.6 m/s), abrasion and adhesion occurred due to higher energy input. Scanning Electron Microscope (SEM) analysis showed significant surface distortion under higher load conditions, suggesting that the material possesses the durability and strength required for demanding applications (Kumar *et al.* 2021).

Limited research exists on AZ91 composites reinforced with n-SiC and µ-B_4C elements. Due to their increased usage, magnesium metal matrix composites were experimented with by reinforcing them with a 3 wt.% of n-SiC and µ-B_4C.

2. EXPERIMENTATION

AZ91 contains aluminum (9%), zinc (1%), magnesium, and minor trace impurities. The exceptional castability of AZ91 renders it one of the most favored magnesium alloys for the production of composites. AZ91 magnesium alloy was purchased from Met Mech Lab in Chennai, ensuring a high level of purity at 99%. The chemical composition of AZ91, as provided by the supplier, aligns with standard specifications. Additionally, the elemental composition of the material was examined to validate its consistency with the requirements, and the SEM image of the base cast alloy is depicted in Fig. 1.

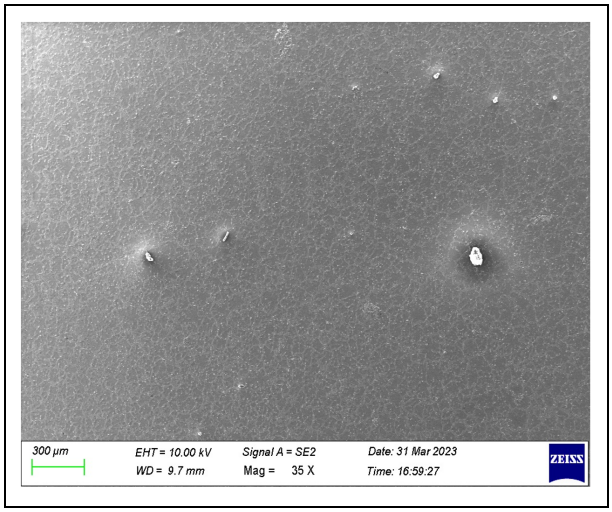


Fig. 1: SEM image of base cast AZ91

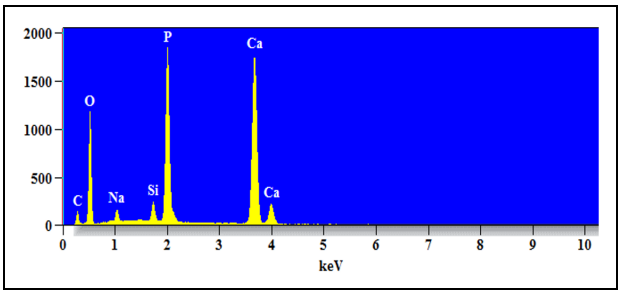


Fig. 2: EDX image of n-SiC

2.1 Composite Preparation

n-SiC (100 nm) and µ-B_4C (100 µm) were selected as reinforcement materials for the synthesis and fabrication of the composite, as these particles work well together since they have many good properties. This makes them a good choice for strengthening MMCs, which leads to higher performance and the ability to develop high-performance parts for a wide range of sectors. The EDX images of n-SiC and µ-B_4C are displayed in Fig. 2 and Fig. 3. The choice of 3 wt.% of n-SiC and µ-B_4C weight percentages was learnt by preceding research works, material property, and preliminary experimental validations engrossed on matching mechanical properties, even dispersal, and lessening brittleness in composites (Huang *et al.* 2023; Murali *et al.* 2023). The main properties of AZ91 that make it well-suited for reinforcement with n-SiC and µ-B_4C are its low density, high strength-to-weight ratio, good castability, and favorable mechanical behavior (Liu *et al.* 2022). When reinforced with these ceramics, AZ91 composites demonstrate improved characteristics and

refined grain structure, all while maintaining reasonable ductility (Karthik *et al.* 2023).

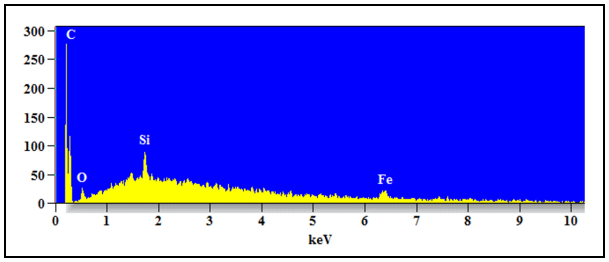


Fig. 3: EDX image of µ-B_4C

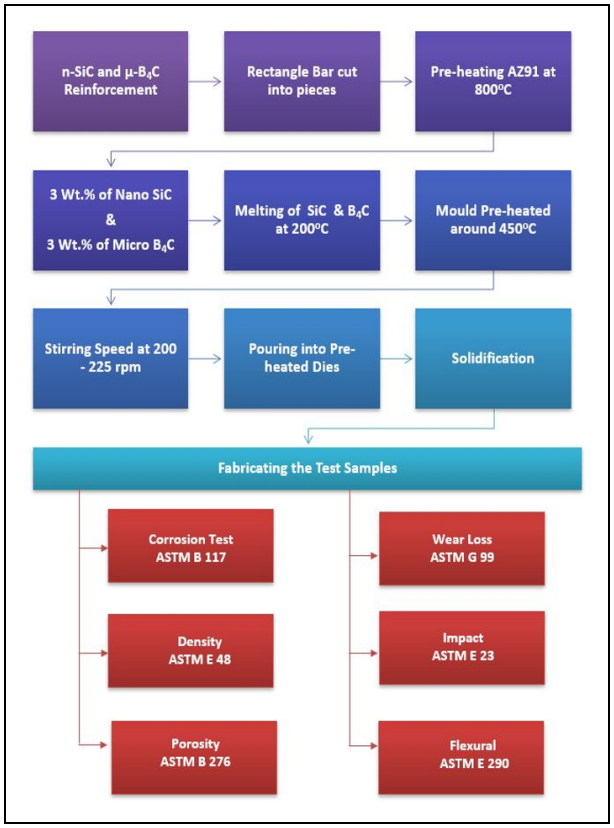


Fig. 4: Schematic of production and testing of n-SiC and µ-B_4C infused AZ91 composites

The AZ91 alloy was heated in a steel crucible within an electric furnace at approximately 800°C. To enhance castability and eliminate moisture and residual stresses, the mold was preheated to around 450°C, while the n-SiC and µ-B_4C particles were heated to 200°C (Jeffrey *et al.* 2022a) with the feed rate range of 1 g/s. A single stage steel stirrer for controlled vortex stirring was employed with stirrer angle (30°) to achieve a stirring speed of 200–225 RPM for a duration of 10 minutes, ensuring uniform dispersion of the reinforcement particles within the molten metal. The location of steel stirrer was made lesser than 30% of the height from base of used crucible to evade accumulation of n-SiC and µ-B_4C at the bottom of the crucible. The molten slurry was poured into the mould and then allowed to solidify as the mixture is homogenized, to obtain the desired composite (Jeffrey *et al.* 2022b), and the steps for preparation and experimental setup are shown in Fig. 4 and 5with the ASTM standards used for testing.

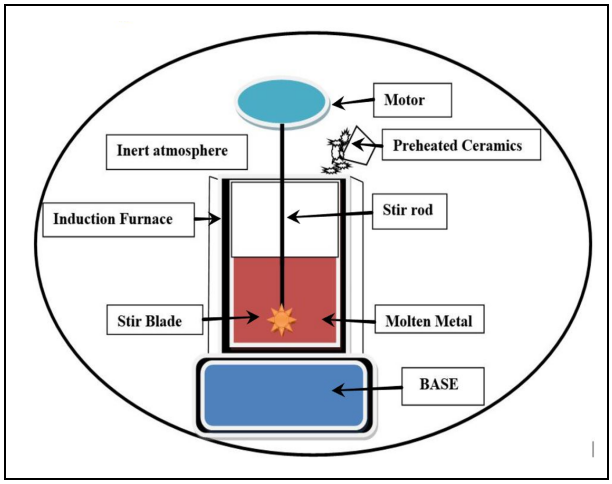


Fig. 5: Schematic of stir casting setup for preparing composites

2.2 Experimental Testing

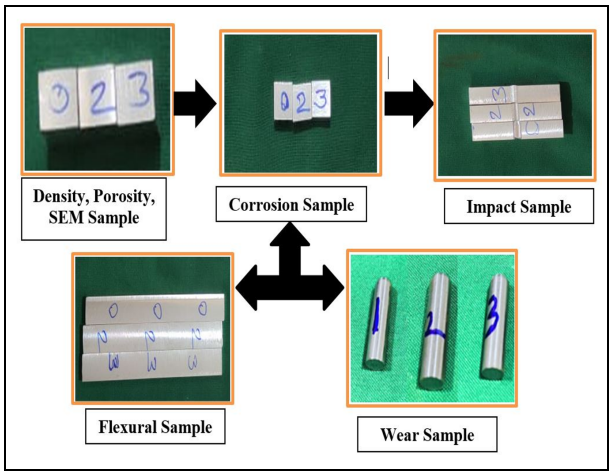


Fig. 6: Prepared samples for evaluation and testing

Three point bending tests were conducted to measure the flexural strength using the computerized universal testing machine Corrosion testing is essential for figuring out how well a material can withstand damage in certain types of conditions. The salt spray approach attempts to replicate corrosive real-world scenarios, providing valuable insights into the material's lifespan and its potential applications over extended periods. Prepared samples were placed in a controlled chamber and subjected to a fine mist of a saline solution, usually 5% sodium chloride (NaCl) dissolved in water. The salt solution's pH was regulated, and the chamber was kept at a steady temperature, around 33°C. The salty mist simulates a corrosive environment by continuously settling on the sample surfaces throughout the test.

Composites were exposed to salt spray for about 48 hrs. after taking initial weight.

The DUCOM pin-on-disc device was utilized to assess the wear attributes. The counter disk was fabricated from EN31 steel. Pin samples and disc surfaces were dressed with acetone before the commencement of the investigation to eliminate any residues after each experiment. The test was conducted without any lubrication at room temperature. The total wear loss was determined by measuring the pins' weight before and after the testing. Fig. 6 depicts the samples of various tests utilized for the study. The morphology of the specimens was studied using scanning electron microscopy (SEM). Specimens were polished with a disc polisher and a fine emery sheet. Picral reagent was used for etching the specimens.

3. RESULTS AND DISCUSSIONS

3.1 Composite Physical Properties

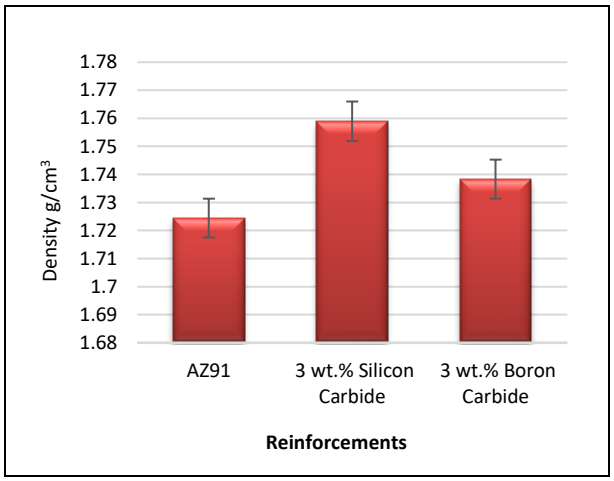


Fig. 7: Results of composite density

The density of distributed n-SiC and µ-B_4C exceeds that of the pure materials. The rule of mixtures and Archimedes' principle were used to ascertain the disparity in density values. The density of µ-B_4C particle composite is inferior to that of n-SiC composite and superior to that of as cast AZ91. The presence of scattered particles results in an increased density of the final composite. Fig. 7 displays the experimental results. The incorporation of high-hardness reinforcing particles and their uniform distribution slightly increased the composite's density (Pooja *et al.* 2025). The n-SiC inside the particles aids in filling the micro-voids during stir casting, hence increasing the density of the composites. The disparity in the thermal coefficient between AZ91 and the reinforcing particles results in low porosity readings, as in Table 1, indicate that porosity is uniformly distributed over the structures. Consistent with previous research, the findings show that densities of composites tend to rise as reinforcement content rises, owing to efficient processing enhancing mechanical characteristics (Kumar *et al.* 2020).

Table 1. Porosity in percentage

Compositions	Porosity Percentage
AZ91	0.138
3 wt.% n-SiC	0.152
3 wt.% µ-B_4C	0.165

3.2 Composite Impact and Flexural Properties

Adding hard reinforcement particles improved the impact strength, as shown in Fig. 8. The observed increase was caused by more energy being directed towards plastic deformation. When n-SiC and µ-B_4C reinforcements are added, materials require more energy to break because the reinforcing particles used are inherently harder. The improvements in AZ91 composites come from finer grains, evenly spread ceramic particles, and strong bonding between the AZ91 and reinforcements. These helps to absorb impact energy, reduces the start and growth of cracks, and makes it easier for the load to be shared between the n-SiC and µ-B_4C and the AZ91 (Baraniraj *et al.* 2023).

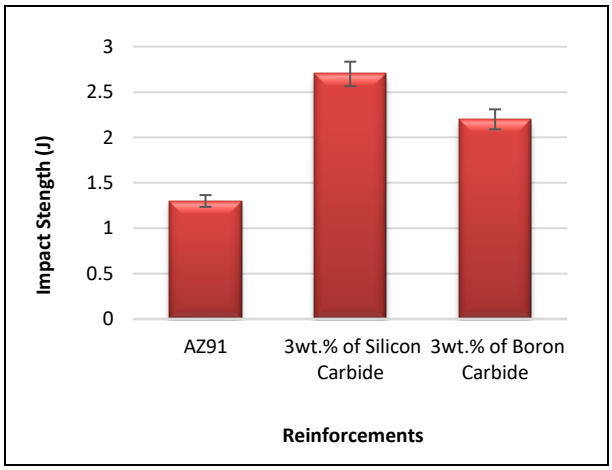


Fig. 8: Results of composite impact strength

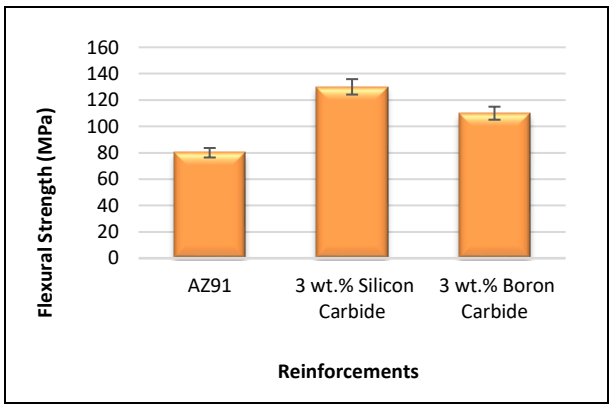


Fig. 9: Results of composite flexural strength

The flexural strength of synthesized n-SiC and μ-B_4C composites increases when the reinforcements are evenly distributed as shown in Fig. 9. This makes it easier for AZ91 to stick to the particles. The primary cause of the increased strength was the reduction in grain size. When the particles are small, the space between them becomes smaller. The nanoparticles prevent the plastic from bending. In the end, this approach makes the modulus bigger.

3.3 Composite Corrosion in mm/yr and Weight Loss

The AZ91 subjected to NaCl corrosive media exhibits an increased rate of corrosion, as displayed in Fig. 10.

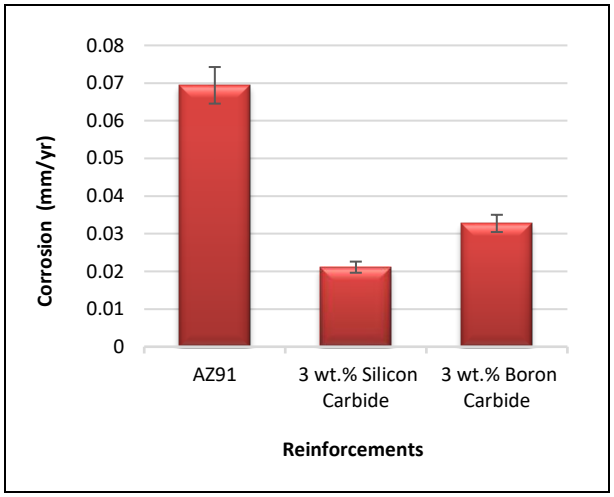


Fig. 10: Results of composite corrosion rate

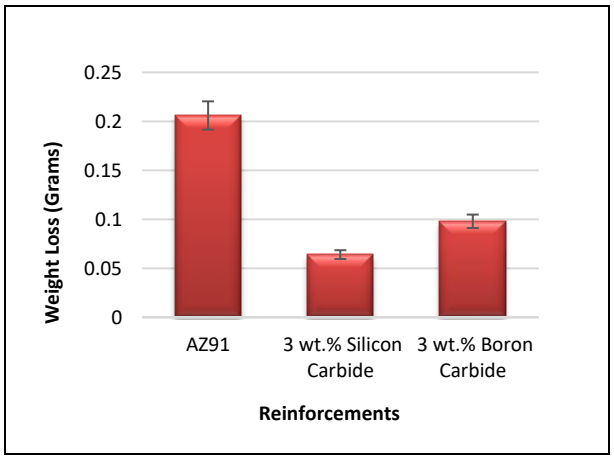


Fig. 11: Results of composite weight loss

The corrosion percentage reduced in the 3 wt.% reinforced composites, as the reinforcement acts as a genuine barrier to the initiation and progression of corrosion pits and alters the microstructure of the AZ91 matrix. The reinforcing particles are inert and hence do not react with the AZ91. The characteristics of the interfacial connection are crucial in the corrosion process. The creation of composites demonstrated enhanced mechanical characteristics, indicating that the contact between AZ91 and the particle is much stronger. The enhancement in corrosion resistance of all composites may result from a strong bond between the matrix and the reinforcing particles (Rajkumar *et al.* 2022). This characteristic may have impacted the enhancement of corrosion resistance in the synthesized composites, regardless of size, and the weight loss (Fig. 11).

3.4 Composite Wear Loss

Adding a small amount of strengthening at 3 wt.% significantly reduced the wear loss compared to the AZ91 cast alloy. The way AZ91 interacts with particles at the interface is crucial for making it more resistant to wear and tear while losing less of it. Harder materials exhibit less plastic deformation, resulting in a smaller contact area between the sample and the disc. This means less wear loss. When compared to pure Mg AZ91, AZ91 composites demonstrate less wear loss. The inclusion of reinforcing particles and the stronger material made it more resistant to wear, as shown in the graph in Fig. 12. Similar findings were obtained by Alam *et al.* (2024).

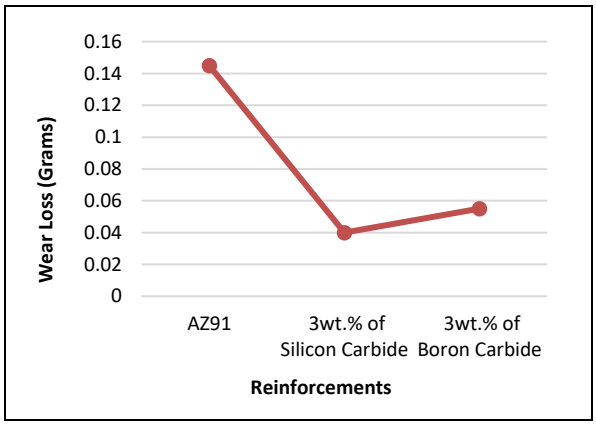


Fig. 12: Results of composite wear loss

3.5 Composite Microstructural Examinations

To make metallographic specimens, the cut specimens were polished using different grit silicon carbide and alumina paste combined with distilled water. The study found that the AZ91 reinforcements were evenly spread out and did not clump together, which was the main reason for the better chemical bonding. Fig. 13 and 14 show that there are no fractures. The fact that composite materials have very little porosity shows that the proper synthesis settings were used. The SEM tests show that all composites contain n-SiC and μ-B_4C particles. Further, it is found that the reinforcements are evenly distributed and that there are no voids or microcracks. This means that the composites are completely dense. Also, there were no signs of heat

damage in the matrix which is depicted similarly as in previous research findings (Sharma *et al.* 2025). The presence of nanoparticles caused them to stick better to the Mg alloy composite in the debonded area. As reinforcing particles are added, the grain boundary becomes finer, and the nanoparticle turns into a rigid secondary phase of the alloys. During the solidification phase of the composite, most of the particles moved to the spaces between the developing grains (Ahmadian *et al.* 2024). This kind of behavior might be due to the proper process parameters used in the casting process.

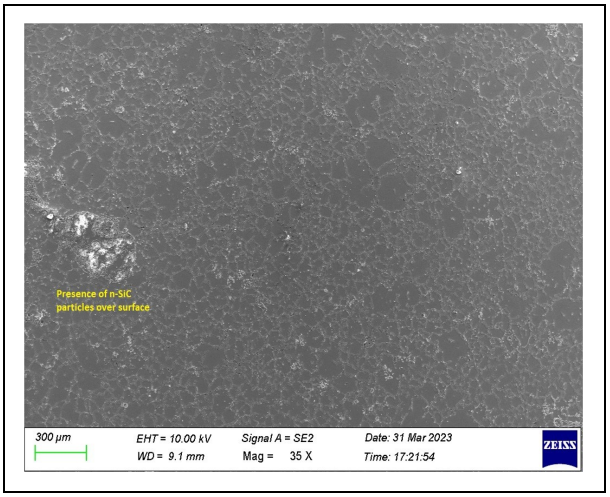


Fig. 13: SEM of AZ91/ n-SiC

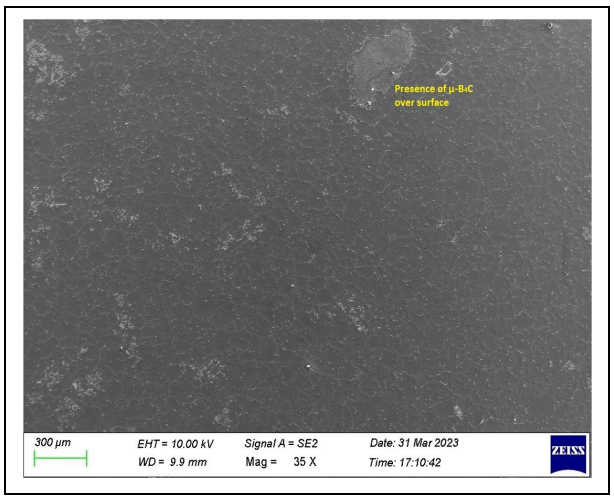


Fig. 14: SEM of AZ91/ µ-B_4C

4. CONCLUSIONS

AZ91 composites reinforced with 3 wt.% n-SiC and µ-B_4C were successfully fabricated using stir casting, and their mechanical, wear, and corrosion properties were evaluated. The addition of both reinforcements improved density while reducing porosity, wear loss, and corrosion rate compared to the base alloy. Significant enhancements in flexural strength and impact resistance were also observed. These improvements are attributed to effective load transfer, grain refinement, strong interfacial bonding, and the barrier effect of inert reinforcements against corrosive media. In conclusion, n-SiC and µ-B_4C reinforcements markedly enhanced the performance of AZ91, making these composites suitable for automotive and aerospace structural applications.

DATA AVAILABILITY STATEMENTS

All the data required are available within the manuscript.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

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