Enhancement of Magnesium Alloy Composite Behaviour Featuring Alumina and Silicon Carbide Nanoparticles

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**Abstract:** This study investigates the effects of silicon carbide and alumina nanoparticle reinforcements on the mechanical and structural properties of AZ91 magnesium alloy, utilising a semi solid stir casting technique to improve dispersion and bonding of the composites and then five distinct composite formulations were developed by varying the SiC concentration from 2.5 weight % to 7.5 weight % while maintaining a constant AlO loading of 3 weight %. To evaluate the impact of dual-phase reinforcement, the resulting composites were systematically analysed for density, porosity, tensile strength and Vickers microhardness. The composite containing 3 weight % AlO₃ and 5 weight % SiC exhibited the optimal combination of high strength, low porosity and exceptional hardness among the assessed samples signifying effective load transfer and a uniform microstructure and these findings illustrate its exceptional suitability for sports cycle frame applications where great performance and long term reliability hinge on the integration of lightweight characteristics, mechanical strength and durability.

# Introduction

The tradition of magnesium alloys AZ91 in particular in the manufacturing of lightweight components is increasing due to its low density and high specific strength and they need to be improved for structural applications because of their moderate tensile strength, low hardness and comparatively poor resistance to wear and is now possible to improve mechanical qualities and structural dependability by reinforcing nanoparticles with ceramic fillers like silicon carbide and alumina [1-2].

SiC enhances wear resistance and load bearing capability due to its high modulus and hardness while AlO₃ enhances thermal stability and acts as a grain refiner. Researchers [3-5] studied the wettability and uniform spreading of reinforcement particles have a direct impact on the tensile properties of Al MMCs. Researchers [6-7]investigated the AZ61 alloy reinforced with hybrid particles and stir cast highlighting the improvements in mechanical strength caused by fine-grained microstructures. The process parameters for AZ91D/AlO₃/SiC nanocomposites were optimized by Researchers [8-10] using friction stir processing and they observed better mechanical responses by employing multi response optimization techniques.

Researchers [9]shown that the AZ91D alloy enhanced with CNTs and SiC nanoparticles produced by semisolid stir casting had greater microstructural homogeneity and toughness. [5] demonstrates hybrid reinforcing systems significantly improve yield and tensile strengths especially in alloys belonging to the AZ class. In their investigation of TiO₂ and WC as reinforcements in aluminium MMCs, Researchers [10-12] found notable improvements in hardness and wear resistance.

Researchers [13] conducted a comprehensive investigation of hybrid Al/SiC/Al₂O₃ nanocomposites and found that synergistic reinforcement effects led to notable gains in ductility and strength. Researchers [14-17] investigated CeO₂ reinforced Mg composites and found that proper filler dispersion enhances wear resistance and load-bearing capability. In their magnesium nanocomposites investigation, Researchers [18] examined wettability nanoparticle aggregation and interfacial reactivity.

They found that hybrid hard-soft particle combinations improve microstructural refinement and strength in AZ91 alloy reinforced with Ni Al₂O₃ particles. Researchers [19-20] examined nano enhanced phase reinforced magnesium composites emphasising matrix reinforcement interface design advances that allow property tailoring. Researchers [21-22] found that adding AlO₃ and ZrO₂ nanoparticles to AZ91 matrix produces fine microstructures and higher tensile strength suggesting dual ceramic reinforcements.

Researchers [23] showed that SiC-reinforced AZ91D nanocomposites produced by liquid-state processing significantly improved in hardness and wear resistance. By adding ultrasonic treatment to the AZ91 stir casting method Ponhan [14] significantly improved characteristics by increasing matrix bonding and nanoparticle dispersion and shear deformation during asymmetric rolling enhances mechanical performance and refines grain structure in AZ31B sheets according to research [24-26] on the impacts of rolling induced deformation. By using classic stir casting to generate AZ91D/SiCp composites, Researchers [27] found that a larger SiC percentage improved the overall hardness, wear resistance and structural integrity.

The semi solid stir casting technique allows for the effective absorption and uniform dispersion of these reinforcements into the magnesium matrix which has benefits over conventional liquid casting techniques, such as enhanced particle wetting and reduced porosity.

# Materials and Methods

## Materials

Ingots of the magnesium alloy AZ91 were used as the main matrix material in the production of the AZ91 based nanocomposites. Alumina (AlO₃) and silicon carbide (SiC) nanoparticles were used as reinforcements they were heated beforehand to remove surface moisture and improve their wettability with the molten alloy. To enhance reinforcement dispersion and reduce oxidation the AZ91 melt was kept in a semi-solid condition during the semi solid stir casting process which was carried out at about 600°C. To ensure even mixing, the nanoparticles were added to the melt and mechanically agitated for ten minutes at 500 rpm.

**TABLE 1.** Mechanical Composite Formulations Table

|  |  |
| --- | --- |
| **Sample** | **Description** |
| S1 | AZ91 (Unreinforced) |
| S2 | AZ91 + 3 wt% Al₂O₃ |
| S3 | AZ91 + 3 wt% Al₂O₃ + 2.5 wt% SiC |
| S4 | AZ91 + 3 wt% Al₂O₃ + 5 wt% SiC |
| S5 | AZ91 + 3 wt% Al₂O₃ + 7.5 wt% SiC |

The composite slurry was then put into steel molds that had been heated in order to harden it. The impact of hybrid ceramic reinforcements was investigated by preparing 5 distinct composites. Sample 2 has 3 weight % AlO₃, while Sample 1 was the unreinforced baseline. Samples 3 through 5 included a fixed 3 weight % AlO₃ with different concentrations of SiC at 2.5 weight %, 5 weight % and 7.5 weight %, respectively and to assess the physical and mechanical performance of these composites, standard characterization techniques were employed. Density and porosity were measured using Archimedes' principle to determine material compactness and internal voids [28-30]. Tensile testing was accompanied with ASTM E8 standards to calculate strength and ductility and micro Vickers hardness testing was used to assess surface hardness and resistance to localized deformation.

# Results and Discussion

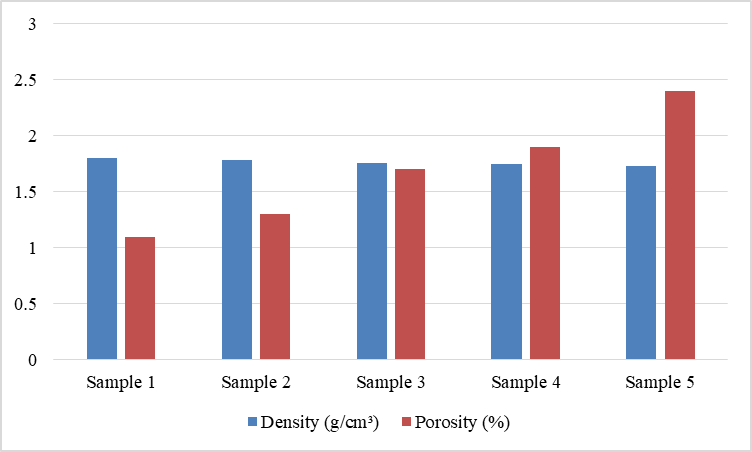
## Density and Porosity

The measured density and porosity values of the AZ91 based composites indicate a progressive reduction in density with increasing nanoparticle loading, as shown in the table below:

**TABLE 2.** Density and Porosity

|  |  |  |
| --- | --- | --- |
| **Sample** | Density (g/cm³) | Porosity (%) |
| S1 | 1.8 | 1.1 |
| S2 | 1.78 | 1.3 |
| S3 | 1.76 | 1.7 |
| S4 | 1.75 | 1.9 |
| S5 | 1.73 | 2.4 |

Because SiC and AlO₃ have lower densities than the underlying AZ91 alloy, there was a noticeable decrease in density as the filler content increased. For lightweight applications especially in the transportation industry this density reduction is advantageous. Porosity levels increases in Sample 5 most likely as a result of air entrapment and nanoparticle agglomeration during mixing. These flaws may result in gaps that break the continuity which will negatively affect the mechanical properties [31-35].

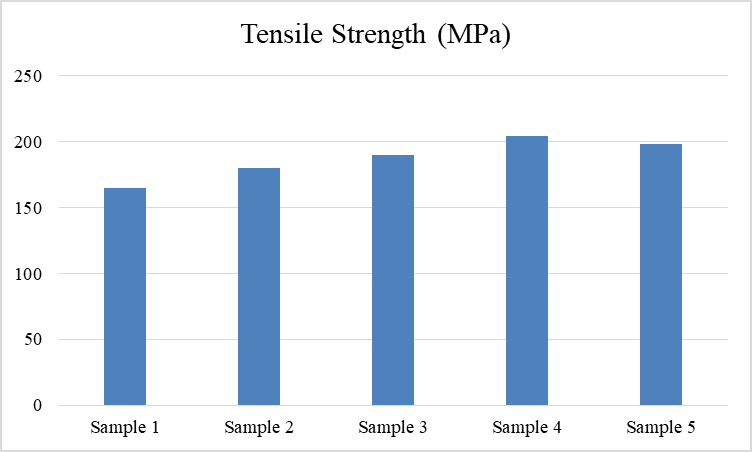
  
**Figure 1.** Density and Porosity

## Tensile Strength

**TABLE 3.** Tensile Strength

|  |  |
| --- | --- |
| **Sample** | **Tensile Strength (MPa)** |
| S1 | 165 |
| S2 | 180 |
| S3 | 190 |
| S4 | 204 |
| S5 | 198 |

The tensile strength results demonstrates improvement in mechanical performance due to reinforcement with Al₂O₃ and SiC



**Figure 2.**Tensile Strength

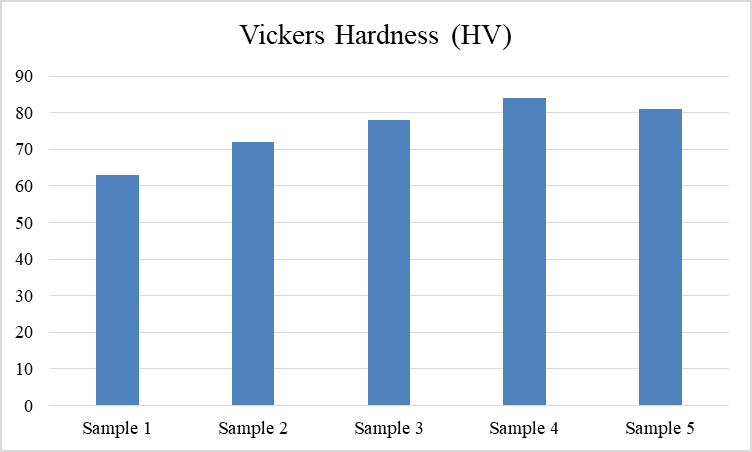
The baseline tensile strength of the unreinforced AZ91 alloy was 165 MPa. This was raised to 180 MPa by adding 3 weight percent AlO₃ and it was further raised by adding 2.5–5 weight percent SiC because of efficient dispersion strengthening and grain refining. Sample 4 had the highest strength (204 MPa) suggesting that AlO₃ and SiC work well together. However, a little decline was observed in Sample 5 which may have been brought on by localized stress accumulation inadequate filler dispersion and particle agglomeration all of which serve as sites for the onset of cracks under tensile loading [36-40].

## Vickers Hardness

The surface hardness of the composites followed a trend similar to that of tensile strength:

**TABLE 4.** Vickers Hardness

|  |  |
| --- | --- |
| **Sample** | **Vickers Hardness (HV)** |
| S1 | 63 |
| S2 | 72 |
| S3 | 78 |
| S4 | 84 |
| S5 | 81 |



**Figure 3.** Vickers Hardness

The Vickers hardness of the base alloy was 63 HV and it gradually rose as reinforcements were added. Sample 4 had the maximum hardness (84 HV) indicating that evenly spaced ceramic particles improved resistance to indentation by acting as barriers to dislocation movement [41-45]. Particle clustering which can produce weak interfacial areas and diminish effective load transmission was blamed for the little drop in Sample 5 (81 HV).

# Application in Automotive Interior Trims

As is typical of unreinforced magnesium alloys with poor resistance to surface wear and indentation the base AZ91 alloy has a comparatively low Vickers hardness value of 63 HV. Sample 2's hardness rose to 72 HV when 3 weight percent alumina was added showing that even a single phase ceramic reinforcement greatly enhances surface rigidity. The use of silicon carbide nanoparticles resulted in further improvement. Hardness values increased to 78 HV and 84 HV in Samples 3 and 4 respectively when the SiC concentration was raised to 2.5 weight % and 5 weight %. Dual phase ceramic impact is responsible for this enhancement which successfully limits dislocation movement prevents grain boundary sliding and enhances the composite's resistance to localized plastic deformation under mechanical loading [46-49].

The sample with the highest hardness Sample 4 had the ideal ratio of AlO₃ to SiC resulting in homogeneous dispersion and a strong interfacial connection with the AZ91 matrix. Sample 5's hardness marginally dropped to 81 HV when the SiC concentration was raised to 7.5 weight percent. Higher filler concentrations cause nanoparticle agglomeration, which results in an uneven distribution and the development of weak spots or microstructural flaws, which is probably the cause of this marginal reduction. These flaws may serve as stress concentrators, reducing load transfer efficiency and partially offsetting the ceramic fillers hardening effect. Even though adding ceramic nanoparticles greatly increases hardness, excessive loading without adequate dispersion control may negatively impact the composite's homogeneity and overall mechanical response [50-54].

# Conclusion

# Noteworthy enhancements in mechanical properties were shown by the hybrid nano reinforcement of AZ91 magnesium alloy utilizing silicon carbide and alumina nanoparticles employing the semi-solid stir casting technique. With a tensile strength of 204 MPa and a Vickers hardness of 84 HV the formulation with 3 weight % AlO₃ and 5 weight % SiC is best among the different compositions evaluated and also maintained minimal porosity and ensured high structural integrity. These enhancements are mostly ascribed to the dual ceramic strengthening mechanisms which include enhanced load transfer efficiency dislocation pinning and grain refining.The semi solid stir casting hybrid nano reinforcement of AZ91 magnesium alloy with silicon carbide and alumina nanoparticles improves mechanical characteristics. The composition with 3 weight % AlO₃ and 5 weight % SiC showed the best performance, with a tensile strength of 204 MPa and a Vickers hardness of 84 HV ensuring structural integrity and minimising porosity. Improvements in grain refinement, dislocation pinning and load transfer efficiency are due to the dual ceramic strengthening mechanisms.

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