EXPERIMENTAL INVESTIGATION ON THE MECHANICAL AND MICROSTRUCTURAL CHARACTERISTICS OF LM13 ALUMINIUM ALLOY REINFORCED WITH ZIRCONIUM SILICATE ($ZRSIO_4$) PARTICULATES

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Abstract

Aluminium Metal Matrix Composites (AMMCs) have attracted considerable attention for automotive and aerospace applications because of their high strength-to-weight ratio, improved wear resistance, and excellent mechanical properties. In the present study, LM13 aluminium alloy reinforced with 0, 2, 4, and 6 wt.% zirconium silicate ($ZrSiO_4$) particles was successfully fabricated using the stir casting technique to investigate the effect of reinforcement on mechanical and microstructural properties. The fabricated composites were evaluated through tensile, Charpy impact, and Rockwell hardness tests, followed by optical microscopy and Scanning Electron Microscopy (SEM). The results showed that the mechanical properties improved with increasing $ZrSiO_4$ content. The composite containing 6 wt.% $ZrSiO_4$ exhibited the highest ultimate tensile strength (169.79 MPa), breaking strength (128.75 MPa), impact strength (0.10 N·m/mm²), and hardness (76 HRB). Microstructural analysis revealed grain refinement and improved particle distribution, while SEM confirmed uniform dispersion and good interfacial bonding between the reinforcement and the matrix. These findings demonstrate that $ZrSiO_4$-reinforced LM13 composites are promising materials for lightweight, wear-resistant, and high-strength engineering components in automotive and aerospace industries.

Keywords: Aluminium Metal Matrix Composite (AMMC), LM13 Alloy, Zirconium Silicate ($ZrSiO_4$), Stir Casting, Tensile Strength, Hardness, Scanning Electron Microscopy (SEM).

1. Introduction

Aluminium Matrix Composites (AMMCs) have emerged as promising engineering materials due to their low density, high specific strength, excellent wear resistance, and superior thermal stability. These properties make them suitable for applications in the automotive, aerospace, marine, and defence industries, where lightweight materials with enhanced mechanical performance are required. The incorporation of ceramic reinforcements into aluminium alloys significantly improves their strength, hardness, and wear resistance while maintaining a favourable strength-to-weight ratio.

Among aluminium casting alloys, **LM13** is widely used for manufacturing pistons, cylinder heads, and other engine components because of its excellent castability, corrosion resistance, and high-temperature performance. However, the mechanical properties of unreinforced LM13 are insufficient for applications involving high loads and severe wear conditions. Reinforcing LM13 with ceramic particles is an effective approach to overcome these limitations.

Ceramic reinforcements such as SiC, Al_2O_3, TiB_2, and $ZrSiO_4$ have been extensively used to enhance the mechanical and tribological properties of aluminium alloys. Among them, **zirconium silicate ($ZrSiO_4$)** is an attractive reinforcement owing to its high hardness, excellent wear resistance, low thermal expansion coefficient, and good interfacial bonding with the aluminium matrix. These characteristics promote grain refinement, improve load transfer, and increase the strength and hardness of the composite.

Although several studies have investigated $ZrSiO_4$-reinforced aluminium composites, limited work has focused on the systematic evaluation of LM13 reinforced with different weight percentages of $ZrSiO_4$ using the stir casting process. Furthermore, comprehensive studies correlating mechanical properties with microstructural and SEM analyses are relatively scarce.

The present work aims to fabricate LM13 aluminium matrix composites reinforced with **0, 2, 4, and 6 wt.% $ZrSiO_4$** using the stir casting technique. The fabricated composites were characterized through tensile, Charpy impact, and Rockwell hardness tests, followed by optical microscopy and Scanning Electron Microscopy (SEM) to evaluate the effect of reinforcement on the mechanical behaviour and microstructure of the composites. The experimental results provide insights into the suitability of $ZrSiO_4$-reinforced LM13 composites for lightweight and wear-resistant engineering applications.

2. Literature Review

Several researchers have investigated the influence of ceramic reinforcements on the mechanical performance of aluminium matrix composites. Panwar and Pandey (2013) reported that $ZrSiO_4$-reinforced LM13 composites exhibited improved hardness and wear resistance with increasing reinforcement content. Patel et al. (2015) observed enhanced compressive strength in aluminium composites reinforced with SiC and $ZrSiO_4$ due to improved particle distribution. Okafor and Aigbodion (2010) demonstrated that $ZrSiO_4$ addition increased the hardness and tensile strength of Al–Cu composites up to an optimum reinforcement level. Similarly, Baghchesara and Abdizadeh (2013) found that zircon-based reinforcements significantly enhanced the tensile strength and hardness of Al-A356 composites. Overall, previous studies indicate that ceramic reinforcements improve the mechanical and tribological properties of aluminium alloys. However, limited work has been reported on the combined evaluation of tensile, impact, hardness, microstructural, and SEM characteristics of LM13 reinforced with varying $ZrSiO_4$ contents. Therefore, the present study investigates the effect of **0, 2, 4, and 6 wt.% $ZrSiO_4$** on the mechanical and microstructural behaviour of LM13 composites fabricated by the stir casting process

3. Methodology

3.1 Materials

LM13 aluminium alloy was selected as the matrix material because of its excellent castability, low density, corrosion resistance, and good mechanical properties, making it suitable for automotive engine components such as pistons and cylinder heads. Zirconium silicate ($ZrSiO_4$) was used as the reinforcement owing to its high hardness, superior wear resistance, low thermal expansion coefficient, and good thermal stability. The composites were fabricated with **0, 2, 4, and 6 wt.%** $ZrSiO_4$ to evaluate the influence of reinforcement content on the mechanical and microstructural properties. The chemical composition of LM13 alloy and the properties of $ZrSiO_4$ are presented in **Tables 1 and 2**, respectively

Table 1. Chemical Composition of LM13 Alloy

Element	Si	Cu	Mg	Ni	Fe	Zn	Ti	Pb	Sn	Mn	Al
wt.%	11.8	1.2	0.9	0.9	0.3	0.2	0.02	0.02	0.005	0.4	Balance

Table 2. Mechanical Properties of $ZrSiO_4$

Property	Value
Density	4.5–4.7 g/cm³
Hardness	7.5 (Mohs)
Melting Point	2500 °C
Thermal Expansion	4.5×10^{-6} /K
Crystal Structure	Tetragonal

3.2 Composite Fabrication

The LM13–$ZrSiO_4$ composites were fabricated using the **stir casting process**, which is widely employed for producing aluminium matrix composites because of its simplicity, low cost, and suitability for mass production. LM13 alloy ingots were melted in an electric resistance furnace at approximately **750 °C**. After complete melting, pre-weighed $ZrSiO_4$ particles (0, 2, 4, and 6 wt.%) were gradually added into the molten alloy while mechanical stirring was carried out to ensure uniform particle distribution. A degassing agent (C_2Cl_6) was introduced to remove dissolved gases and minimize porosity. The molten composite was then poured into metallic moulds and allowed to solidify under ambient conditions. The cast specimens were machined according to standard testing dimensions for subsequent characterization.

LM13 Alloy Ingots
▼ Melting (750 °C)
▼ Addition of $ZrSiO_4$ Particles (0, 2, 4 and 6 wt.%)
▼ Mechanical Stirring
▼ Degassing (C_2Cl_6)
▼ Pouring into Metallic Mould
▼ Solidification

▼ Composite Casting

Figure 1. Schematic of Stir Casting Process

3.3 Mechanical Characterization

The fabricated composites were subjected to mechanical characterization to evaluate the effect of $ZrSiO_4$ reinforcement. Tensile tests were performed using a Universal Testing Machine (UTM) to determine the ultimate tensile strength and breaking strength. Charpy impact tests were conducted to measure the energy absorbed during fracture, while Rockwell hardness tests were performed using the HRB scale to assess resistance to indentation. For each composition, multiple specimens were tested and the average values were considered for analysis.

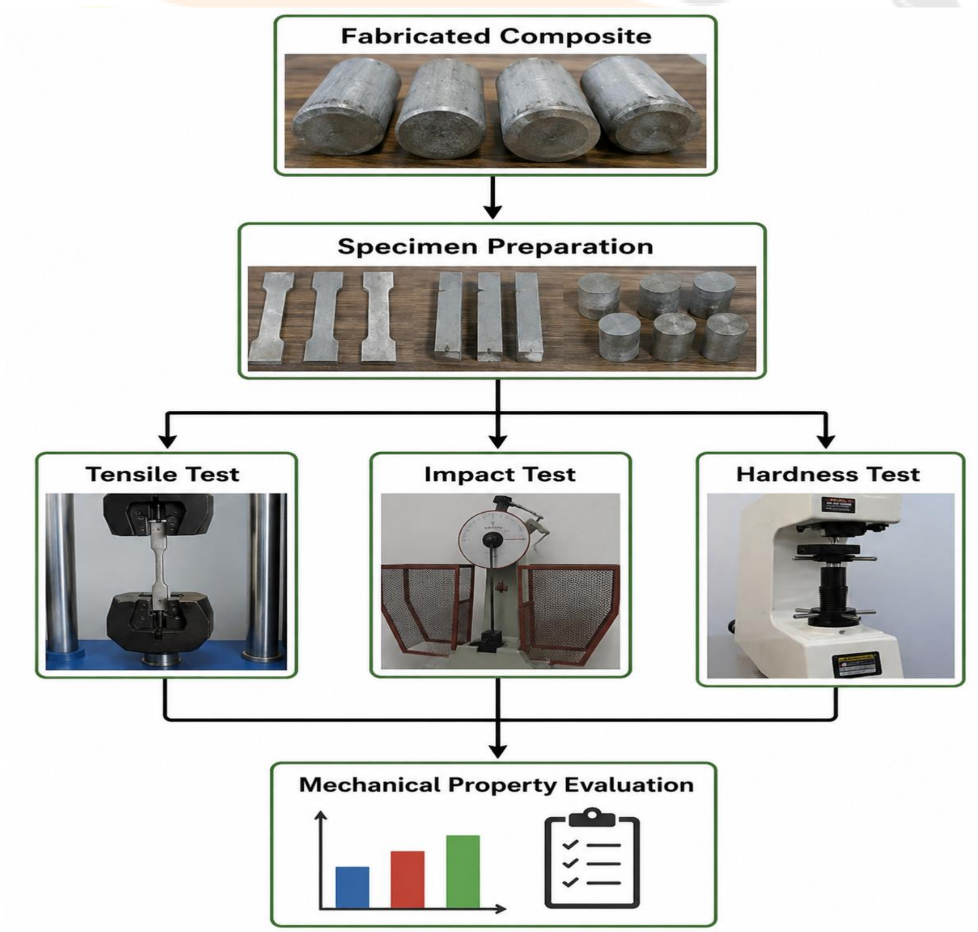

Figure 2. Mechanical Testing Procedure

3.4 Microstructural and SEM Analysis

Microstructural examination was carried out using an optical metallurgical microscope after polishing and chemical etching of the specimens. The analysis was performed to study grain morphology, dendritic structure, and reinforcement distribution. Scanning Electron Microscopy (SEM) was further employed to examine the dispersion of $ZrSiO_4$ particles and the interfacial bonding between the reinforcement and the LM13 matrix. These observations were correlated with the measured mechanical properties to understand the strengthening mechanisms of the composites.

4. Results and Discussion

The mechanical and microstructural properties of LM13 aluminium alloy reinforced with varying weight percentages (0, 2, 4, and 6 wt.%) of zirconium silicate ($ZrSiO_4$) were investigated to evaluate the influence of ceramic reinforcement on composite performance. Tensile strength, impact strength, Rockwell hardness, optical microstructure, and Scanning Electron Microscopy (SEM) analyses were carried out. The results indicate that the addition of $ZrSiO_4$ significantly improved the mechanical properties owing to effective load transfer, grain refinement, and uniform particle distribution within the aluminium matrix.

4.1 Tensile Properties

The tensile test results for LM13–$ZrSiO_4$ composites are presented in Table 4. The ultimate tensile strength (UTS) increased steadily with increasing reinforcement content. The unreinforced LM13 alloy exhibited a UTS of **56.6 MPa**, whereas the composite reinforced with **6 wt.% $ZrSiO_4$** attained the highest tensile strength of **169.79 MPa**, representing nearly a three-fold improvement. Similarly, the breaking strength increased from **28.29 MPa** for the base alloy to **128.75 MPa** for the 6 wt.% composite.

The improvement in tensile strength is primarily attributed to the uniform distribution of hard zirconium silicate particles within the aluminium matrix. The ceramic particles act as effective barriers to dislocation movement and facilitate load transfer from the ductile matrix to the reinforcement. In addition, the presence of $ZrSiO_4$ promotes grain refinement during solidification, resulting in a stronger microstructure.

Table 4. Tensile Test Results

$ZrSiO_4$ (wt.%)	Ultimate Tensile Strength (MPa)	Breaking Strength (MPa)
0	56.60	28.29
2	89.14	42.49
4	113.19	56.65
6	169.79	128.75

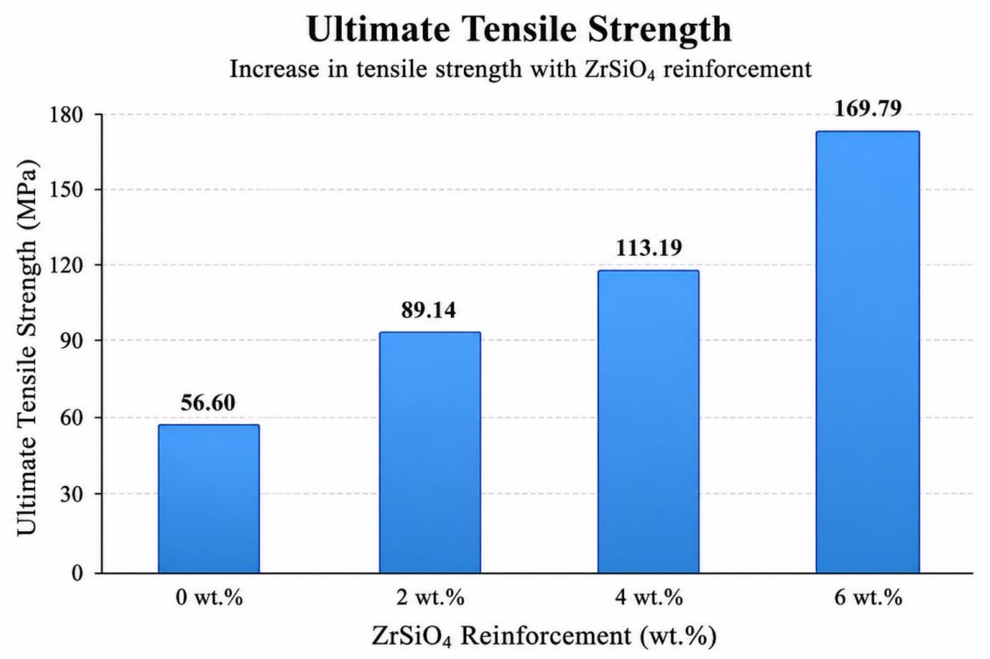

Figure 3. Ultimate Tensile Strength of LM13–$ZrSiO_4$ Composites

4.2 Impact Properties

The Charpy impact test was performed to evaluate the toughness of the fabricated composites. As shown in Table 5, the impact strength increased continuously with reinforcement content, reaching **0.10 N·m/mm²** for the composite containing **6 wt.% $ZrSiO_4$**. The increase in absorbed impact energy suggests improved resistance to crack propagation due to effective particle reinforcement and better matrix–particle bonding.

Table 5. Charpy Impact Test Results

$ZrSiO_4$ (wt.%)	Impact Strength (N·m/mm²)
0	0.02
2	0.04
4	0.06
6	0.10

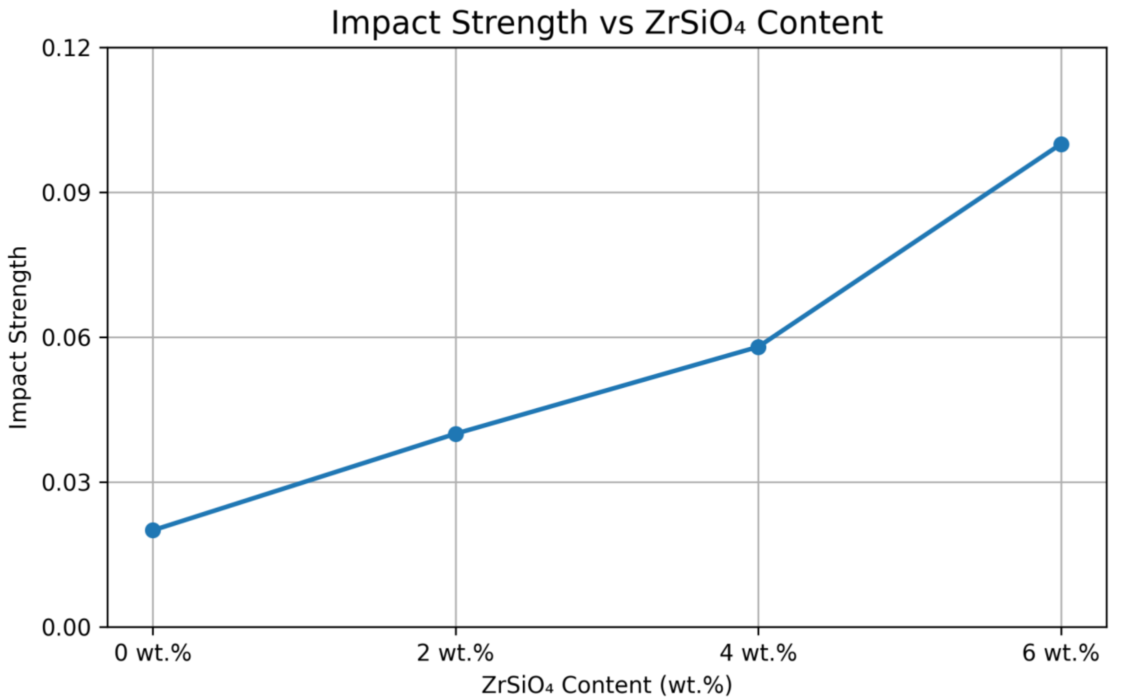

Figure 4. Variation of Impact Strength

4.3 Hardness

Rockwell hardness measurements indicate a significant improvement in surface hardness with increasing reinforcement content. The average hardness increased from **44.66 HRB** for the unreinforced alloy to **76 HRB** for the 6 wt.% reinforced composite. The enhancement is attributed to the presence of hard $ZrSiO_4$ particles, which resist localized plastic deformation and improve resistance to indentation.

Table 6. Rockwell Hardness Results

$ZrSiO_4$ (wt.%)	Hardness (HRB)
0	44.66
2	54.66
4	60.33
6	76.00

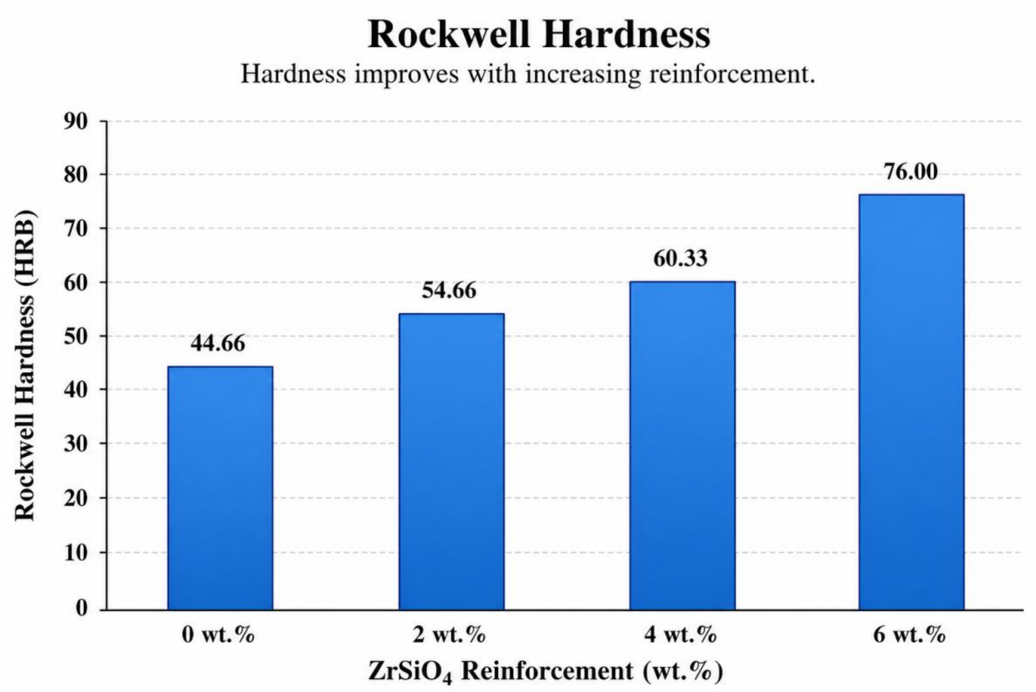

Figure 6. Hardness Variation

4.4 Microstructural Analysis

Optical micrographs revealed noticeable changes in the microstructure with increasing $ZrSiO_4$ content. The unreinforced LM13 alloy exhibited coarse dendritic grains, whereas the reinforced composites showed progressively finer grain structures. The composite containing **6 wt% $ZrSiO_4$** displayed the finest dendritic morphology, indicating effective grain refinement during solidification. The refinement of grains contributed directly to the observed increase in tensile strength and hardness by restricting dislocation movement.

4.5 Scanning Electron Microscopy (SEM)

SEM analysis confirmed that zirconium silicate particles were distributed uniformly within the aluminium matrix, particularly in the 6 wt.% reinforced composite. The micrographs showed good interfacial bonding with minimal particle agglomeration and no significant interfacial cracks. The improved particle distribution enhanced load transfer between the matrix and reinforcement, resulting in superior tensile strength, hardness, and impact resistance.

The results demonstrate that increasing the $ZrSiO_4$ content from **0 to 6 wt%** significantly enhances the mechanical performance of LM13 aluminium composites. The improvements are attributed to grain refinement, dispersion strengthening, efficient load transfer, and strong matrix–particle bonding. Among the compositions investigated, the **6 wt.% $ZrSiO_4$** composite exhibited the best combination of tensile strength, impact strength, hardness, and microstructural characteristics, making it a suitable candidate for lightweight, wear-resistant components in automotive and aerospace applications.

5. Conclusions

LM13 aluminium matrix composites reinforced with varying weight percentages of zirconium silicate ($ZrSiO_4$) were successfully fabricated using the stir casting technique, and their mechanical and microstructural properties were systematically evaluated. Based on the experimental investigation, the following conclusions can be drawn:

1. The stir casting process successfully produced LM13–$ZrSiO_4$ composites with satisfactory particle distribution and minimal casting defects.
2. The addition of $ZrSiO_4$ significantly improved the mechanical properties of LM13 alloy. The composite reinforced with **6 wt% $ZrSiO_4$** exhibited the highest ultimate tensile strength (**169.79 MPa**) and breaking strength (**128.75 MPa**), indicating superior load-bearing capability.
3. Charpy impact strength increased from **0.02 N·m/mm²** for the unreinforced alloy to **0.10 N·m/mm²** for the 6 wt.% reinforced composite, demonstrating enhanced toughness.
4. Rockwell hardness increased from **44.66 HRB** to **76 HRB** with increasing $ZrSiO_4$ content due to the presence of hard ceramic particles and improved resistance to plastic deformation.
5. Optical microstructural analysis revealed finer dendritic structures with increasing reinforcement content, indicating grain refinement and improved microstructural stability.
6. SEM analysis confirmed a relatively uniform distribution of $ZrSiO_4$ particles and good interfacial bonding between the reinforcement and the LM13 matrix, which contributed to the enhanced mechanical performance.
7. Among the compositions investigated, **LM13 reinforced with 6 wt% $ZrSiO_4$** exhibited the best combination of tensile strength, hardness, impact resistance, and microstructural characteristics, making it a promising material for lightweight and wear-resistant automotive and aerospace components.

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