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Experimental Investigation of Wear-Resistant Al 7075–SiC/TiC Hybrid Metal Matrix Composites

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Abstract: Aluminium alloy 7075 is extensively used in lightweight structural applications; however, its relatively low wear and corrosion resistance limits performance in demanding environments. To address these limitations, Al 7075 hybrid aluminium matrix composites were fabricated using a two-step stir casting process reinforced with equal proportions of silicon carbide (SiC) and titanium carbide (TiC) particulates at 5, 10, and 15 vol.%. The incorporation of ceramic reinforcements significantly improved the physical, mechanical, tribological, and corrosion properties of the alloy. Density increased with reinforcement content, with the 15 vol.% composite showing a 4.62% increase over the base alloy. Microstructural and phase analyses using XRD, optical microscopy, SEM, and EDAX confirmed uniform dispersion of SiC and TiC particles and the presence of constituent elements. Micro hardness improved progressively by 3.6%, 10.1%, and 18.8% for 5, 10, and 15 vol.% composites, respectively. Tensile strength reached a maximum of 240 MPa for the 10 vol.% composite, while finite element analysis predicted a maximum strength of 561.9 MPa for the 15 vol.% composite. Wear studies revealed reduced wear rate with increasing reinforcement fraction, whereas corrosion testing in 3.5 wt.% NaCl solution showed a substantial decrease in corrosion rate from 3.925 to 0.401 mm/year for the 15 vol.% composite. These results demonstrate that SiC/TiC reinforced Al 7075 hybrid composites are promising candidates for aerospace and other lightweight high-performance engineering applications.

Keywords: Aluminium Matrix Composites, Al 7075, Stir Casting, Silicon Carbide, Titanium Carbide, Micro Hardness, Tensile Strength, Wear Resistance, Corrosion Resistance, Finite Element Analysis.

1. Introduction

Alloys are solid solutions formed by combining metallic and/or non-metallic elements at the atomic scale within their solubility limits. In aluminium alloys, aluminium serves as the base metal and has remained a principal structural material in aerospace applications because of its low density, ease of fabrication, and favorable mechanical properties. Key properties such as hardness, tensile strength, yield strength, compressive strength, wear resistance, and corrosion resistance are critical for advanced engineering applications. These properties are strongly influenced by chemical composition and manufacturing methods, which determine microstructural features such as grain size, grain morphology, recrystallization behavior, and intermetallic phase formation.

The development of composite materials has enabled significant enhancement of these properties to meet specific performance requirements. During World War II, the aerospace sector initiated the development of Organic Matrix Composites (OMCs) with improved specific strength and stiffness, primarily to overcome fatigue and corrosion issues associated with conventional aluminium alloys. Subsequently, glass fiber reinforced plastics gained widespread use in aircraft structures and later expanded into commercial applications due to their improved performance and cost-effectiveness.

Among metal matrix composites, Aluminium Matrix Composites (AMCs) offer superior physical, mechanical, and thermal properties compared to monolithic alloys. Owing to their high strength-to-weight ratio, stiffness, and environmental benefits, AMCs are extensively employed in aerospace and automotive industries to reduce fuel consumption and noise. Their properties can be tailored through appropriate selection of reinforcement materials and fabrication techniques.

Wear is defined as the progressive loss of material from a surface or subsurface due to relative motion between contacting surfaces. It is commonly quantified in terms of weight or volume loss and is often associated with localized plastic deformation and microcrack formation. Wear behavior is influenced by factors such as applied load, sliding velocity, counterface material, surface roughness, lubrication conditions, and operating temperature. Common wear testing methods include pin-on-disc, pin-on-cylinder, and pin-on-flat configurations.Corrosion refers to the gradual or accelerated deterioration of metallic materials due to environmental interactions, affecting both surface integrity and mechanical performance. Although AMCs are highly attractive for lightweight structural applications, corrosion can occur at the matrix–reinforcement interface due to galvanic effects, interfacial phase formation, and defects such as voids or fissures that facilitate corrosive attack. These interfacial regions are often the primary sites for corrosion initiation and propagation.

2. Materials And Methods Of Al 7075 Hybrid Composites

In the present study, Al 7075 (Al–Zn alloy) was selected as the matrix material for automotive and aerospace structural applications due to its excellent mechanical strength, wear resistance, and corrosion performance. The properties of the matrix and reinforcement materials are summarized in the corresponding tables.

Table 3.1 Chemical Composition of Al 7075 Alloy

Element	Weight Percentage (wt.%)
Zinc (Zn)	5.5
Magnesium (Mg)	2.5
Copper (Cu)	1.6
Iron (Fe)	0.5
Silicon (Si)	0.4
Manganese (Mn)	0.3
Chromium (Cr)	0.15
Titanium (Ti)	0.2
Aluminium (Al)	Remaining

Table 3.2 Properties of Al 7075, SiC, and TiC Materials

Property	Al 7075	SiC	TiC
Elastic Modulus (GPa)	70–80	410	493
Density (g/cm^3)	2.81	3.21	4.93
Poisson's Ratio	0.33	0.14	0.187
Hardness (HB)	60	2800	3400
Tensile / Compressive Strength (MPa)	220 (T)	3900 (C)	118 (T)

Silicon carbide (SiC) and titanium carbide (TiC) were used as reinforcing particulates for the fabrication of hybrid aluminium matrix composites. SiC is a high-performance ceramic compound of silicon and carbon, widely used in abrasives, refractories, and advanced ceramics because of its low density, high hardness, high strength, high elastic modulus, low thermal expansion, and high thermal conductivity.

TiC is an extremely hard refractory ceramic with a face-centered cubic crystal structure. It is commonly employed in heat-shield coatings for spacecraft re-entry systems and in cermets used for high-speed machining of steel.

The reinforcement particles used in this work possess densities of 3.21 g/cm^3 for SiC and 4.93 g/cm^3 for TiC, with melting points of 2730°C and 3160°C, respectively. Their low reactivity with molten aluminium and relatively low cost make them suitable reinforcement candidates. The incorporation of SiC and TiC significantly enhances the strength, wear resistance, corrosion resistance, and fracture toughness of the Al 7075 hybrid composites.

3. Experimental Procedure

Figure 3.1 illustrates the flowchart of the experimental procedure adopted for the present investigation. The study includes the selection of matrix and reinforcement materials, identification of the composite fabrication process, and characterization of the developed Al 7075 alloy (AST0) and its composites. Detailed investigations were carried out on density, porosity, microstructural features, EDAX analysis, tensile properties, wear behavior, and corrosion performance.

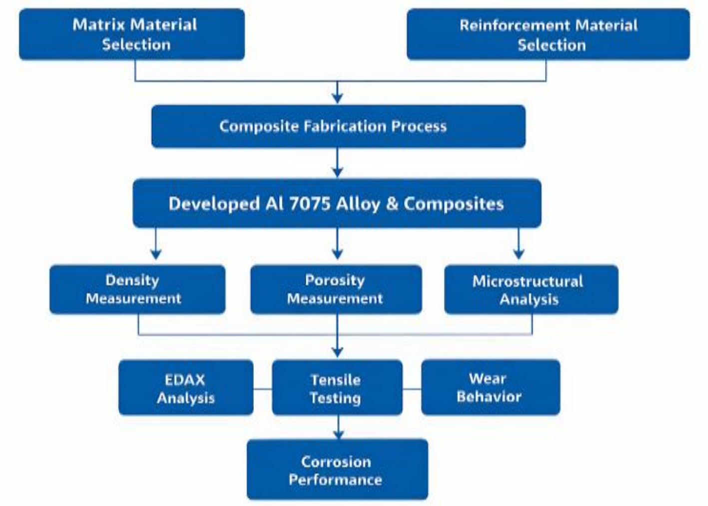


Figure 3.1 Experimental study process flowchart

3.1 Fabrication of AMCs and Sample Preparation: Al 7075–SiC/TiC hybrid aluminium matrix composites were fabricated using the **two-step stir casting method**, a simple and widely adopted liquid metallurgy route for composite preparation. In conventional casting, poor wettability between the molten aluminium alloy and ceramic reinforcements often leads to particle flotation due to the presence of surface gas layers around the particulates. The two-step stir casting technique overcomes this limitation by first removing the gas layer and subsequently improving the uniform dispersion of reinforcement particles within the molten matrix. The composites were prepared by adding **0, 5, 10, and 15 vol.%** of SiC and TiC reinforcements into the Al 7075 matrix based on calculated volume fractions. Melting of the alloy was carried out in a **muffle furnace**, and mechanical stirring was performed using a fire-resistant motorized stirrer equipped with a speed regulator to ensure homogeneous mixing of the reinforcement particles.

3.2 Sample Preparation: Density and Porosity Measurement:Density is an important physical parameter used to characterize the quality of the fabricated composites. Theoretical density was calculated using the **rule of mixtures**, based on the volume fractions of the matrix and reinforcement phases. Experimental density was determined using **Archimedes' principle**, in which the composite specimen was immersed in distilled water and its displaced weight was measured.

The porosity of the composite was then estimated from the difference between the theoretical and actual density values, providing an indication of internal voids and casting defects in the fabricated samples.

4. RESULTS AND DISCUSSIONS

4.1 Density, Porosity, and Microstructural Characterization:4.2 Density and Porosity: The theoretical densities of AST0 and its composites (AST5, AST10, and AST15) were calculated using the **rule of mixtures**, assuming homogeneous distribution of SiC and TiC particles and complete wettability between the matrix and reinforcements. Since the densities of SiC (3.21 g/cm^3) and TiC (4.93 g/cm^3) are higher than that of Al 7075 (2.81 g/cm^3), the overall density of the composites increased with increasing reinforcement content.Porosity was determined from the difference between theoretical and experimentally measured densities. The porosity increased with increasing reinforcement fraction due to particle agglomeration, clustering, and the formation of air pockets around the reinforcement particles during stir casting. However, the use of die casting reduced solidification time, improved particle distribution, refined grain structure, and minimized void formation compared to conventional sand casting.

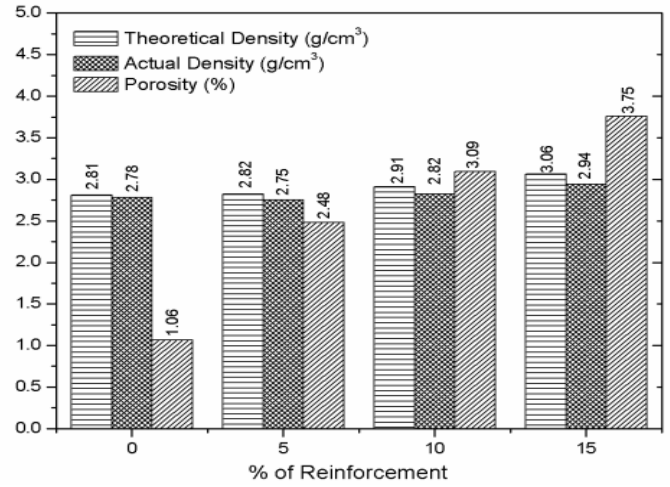


Figure 4.1 Densities and porosity of Al 7075 composites

The measured porosity values were **1.067%, 2.482%, 3.092%, and 3.758%** for AST0, AST5, AST10, and AST15, respectively. Although porosity increased with reinforcement addition, the values remained below 4%, which is generally considered acceptable for cast aluminium matrix composites.

Table: Density and Porosity of Al 7075 Hybrid Composites

Composition	Theoretical Density (g/cm³)	Actual Density (g/cm³)	Porosity (%)
AST0	2.81	2.78	1.067
AST5	2.82	2.75	2.482
AST10	2.91	2.82	3.092
AST15	3.06	2.94	3.758

4.3 XRD Analysis

X-ray diffraction (XRD) was performed to identify the phases present in the Al 7075 hybrid composites and to study interfacial reactions between the matrix and ceramic reinforcements. The diffraction patterns confirmed the presence of **Al 7075, SiC, and TiC phases**, along with intermetallic compounds such as **$Al_{12}Mg_{17}$** and **Al_3Ti**.A significant observation from the XRD results was the **absence of the Al_4C_3 phase**, which indicates good interfacial stability and proper dispersion of SiC particles within the aluminium matrix. This is particularly beneficial because Al_4C_3 formation is generally undesirable due to its detrimental effects on mechanical properties and corrosion resistance.

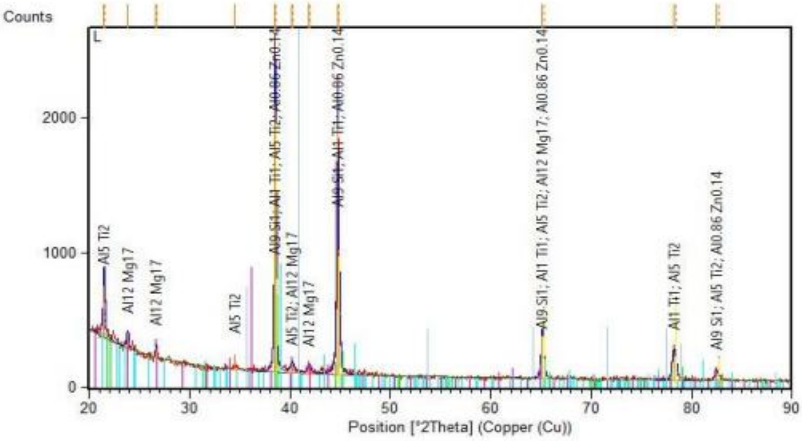


Figure 4.2 Intermetallic peaks identified

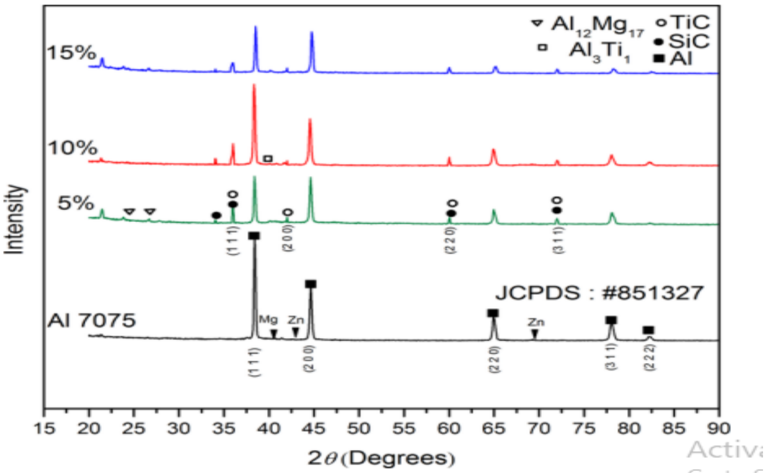


Figure 4.3 XRD image of SiC and TiC reinforced aluminium 7075 composites

The formation of intermetallic phases was influenced by alloying elements, reinforcement content, preheating conditions, and casting parameters, all of which contributed to improved composite properties.

4.4 Optical Microstructure Analysis: Optical microstructural examination was used to assess the quality of the fabricated composites and the effectiveness of the two-step stir casting technique. The as-cast Al 7075 base alloy exhibited a **dendritic grain structure**, whereas the reinforced composites showed a more refined microstructure with **uniformly distributed SiC and TiC particles** throughout the matrix.

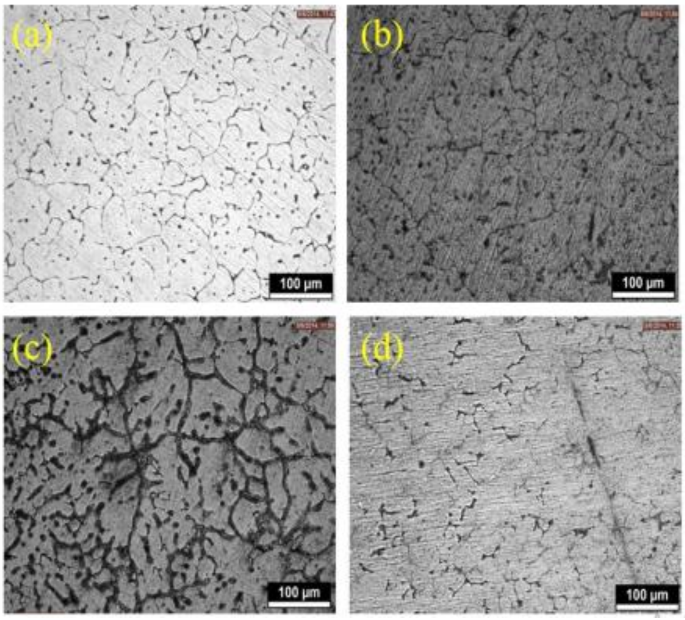


Figure 4.4 Optical microstructure of (a) AST0, (b) AST5, (c) AST10 and (d) AST15

As the reinforcement content increased from 5 to 15 vol.%, the presence of particles became more prominent. In addition, intermetallic phases such as **Al–Si** and **Al_3Ti** formed during solidification and appeared as fine granular phases uniformly dispersed within the matrix, contributing to improved mechanical performance.

4.5 SEM Analysis:Scanning electron microscopy (SEM) further confirmed the effectiveness of the two-step stir casting route. The SEM images revealed **uniform distribution of SiC and TiC particles** in the Al 7075 matrix with minimal clustering.The micrographs also showed **irregular spherical reinforcement particles**, dendritic solidification features, and a thin discontinuous interfacial compound layer surrounding the particulates.

In SEM contrast imaging, the aluminium-rich matrix regions appeared darker, while regions containing alloying elements and reinforcements such as **Zn, Cu, Cr, Mg, Si, Ti, and Fe** appeared brighter due to differences in atomic number.

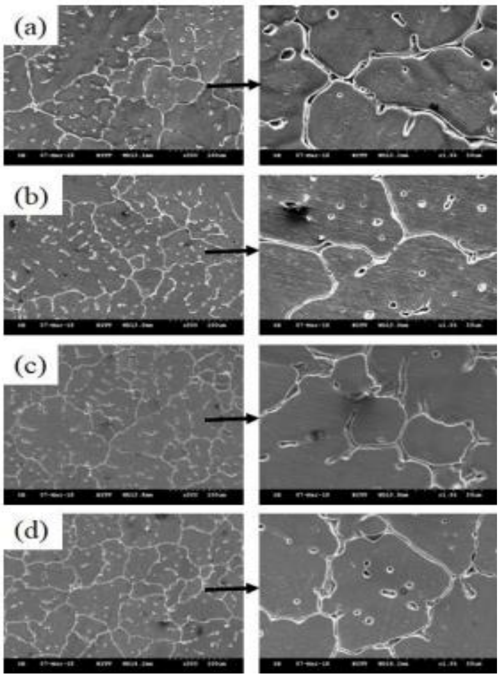
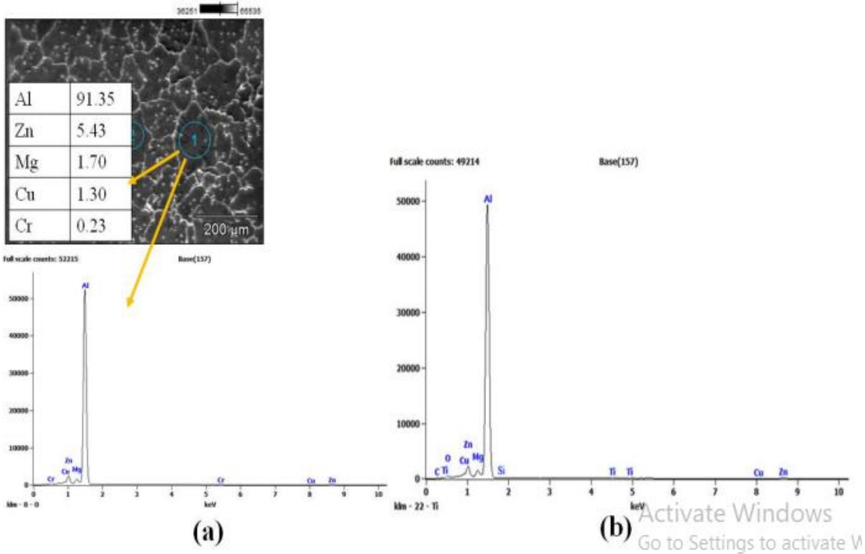


Figure 4.5 SEM images of (a) AST0, (b) AST5, (c) AST10 and (d) AST15



Al	91.35
Zn	5.43
Mg	1.70
Cu	1.30
Cr	0.23

Figure 4.6 EDAX of (a) AST0 and (b) AST15

Overall, the SEM observations confirmed good reinforcement dispersion and strong interfacial bonding, which are essential for enhanced mechanical, wear, and corrosion properties.

4.6 Fractography: The fracture behavior of the tensile-tested specimens was examined using scanning electron microscopy (SEM) to understand the failure mechanism of AST0 and its hybrid composites. The mechanical strength of the composites is strongly influenced by microstructural features such as grain size and secondary dendritic arm spacing.

SEM fractographs of the fractured tensile surfaces revealed predominantly **brittle fracture characteristics** in the Al 7075–(SiC/TiC) hybrid composites. The fracture surfaces exhibited **dimples and matrix cracking**, indicating localized deformation followed by crack propagation. In the reinforced composites, especially at higher reinforcement content, cracks were observed adjacent to the SiC and TiC particles, along with limited plastic deformation of the matrix.

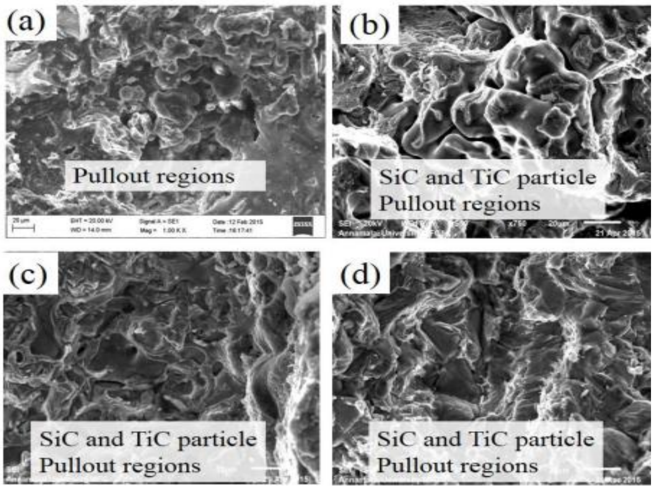


Figure 4.7 SEM micrographs of tensile fracture surface (a) AST0, (b) AST5, (c) AST10 and (d) AST 15

For AST15, a reduction in ultimate tensile strength was observed, which is attributed to increased dendritic arm spacing and higher reinforcement content leading to stress concentration sites and crack initiation around the ceramic particles.

Conclusions

This chapter presents the detailed characterization of AST0 and its hybrid composites AST5, AST10, and AST15. Density and porosity analysis showed that the addition of hard ceramic reinforcements increased both density and porosity of the Al 7075 alloy. XRD analysis confirmed the phases present in the composites, while optical microscopy and SEM studies verified the uniform distribution of SiC and TiC particles within the matrix.

The microhardness of the reinforced composites was found to be significantly higher than that of AST0 due to the superior hardness of SiC and TiC. Among all compositions, AST10 exhibited the highest tensile strength compared to the base alloy and other composite variants. Fractographic analysis further provided insight into the tensile failure mechanism and fracture morphology of the developed hybrid composites.

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