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INFLUENCE OF TIC AND GRAPHITE REINFORCEMENTS ON THE MECHANICAL AND MICROSTRUCTURAL BEHAVIOR OF AL 7075 COMPOSITES

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ABSTRACT

This study aimed at fabricating Al 7075-based metal matrix composites (MMCs) reinforced with 3 wt.% Titanium Carbide (TiC) and varying proportions of graphite (1 wt.%, 3 wt.%, and 5 wt.%) using the stir casting technique. The synthesized composites were systematically characterized through mechanical testing, including tensile and hardness evaluations, as well as detailed microstructural analysis using Scanning Electron Microscopy (SEM). The TiC particles were found to be uniformly dispersed within the ductile Al 7075 aluminium matrix, exhibiting strong interfacial bonding between the reinforcement and matrix. This homogeneous distribution, coupled with effective particle-matrix interaction, led to notable improvements in mechanical and *surface properties over the unreinforced Al 7075 alloy. Among the tested specimens, the composite with an optimal reinforcement combination achieved superior tensile performance, recording an ultimate tensile strength (UTS) of 113.7 MPa, yield strength of 100.1 MPa, elongation of 2.4%, and a Rockwell hardness of 223 HRC.*

Keywords: Al 7075 Alloy, Metal Matrix Composites (MMCs), Titanium Carbide (TiC) Reinforcement, Graphite Additions, Stir Casting Process, Mechanical Properties.

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1. Introduction

The rapid advancement of engineering applications particularly in the aerospace, automotive, and defence sectors has created a strong demand for advanced lightweight materials that offer superior strength, toughness, and durability. This demand has led to significant interest in metal matrix composites (MMCs), which are engineered by reinforcing ductile metal matrices with hard ceramic particles to achieve a balanced combination of mechanical and physical properties [1]. While ceramic particles inherently possess high hardness, excellent creep resistance, and superior Young's modulus, their brittle nature restricts their application in load-bearing structural components, especially under dynamic or impact conditions [2]. Conversely, metallic materials though highly ductile and tough often lack the required strength and stiffness for high-performance applications [3]. To bridge this gap, MMCs have emerged as a promising class of hybrid materials, designed to combine the benefits of ceramics and metals. These composites feature uniformly dispersed hard ceramic reinforcements within a ductile metal matrix, resulting in enhanced mechanical strength, wear resistance, and thermal stability [4]. Among various MMC systems, aluminium matrix composites (AMCs) have garnered considerable attention due to aluminium's low density, excellent castability, and favorable mechanical characteristics [5]. AMCs are widely used in industries where the strength-to-weight and stiffness-to-weight ratios are critical, and they offer additional advantages such as high thermal conductivity, corrosion resistance, and cost-effectiveness [6–8]. Numerous reinforcement materials such as alumina (Al_2O_3), silicon carbide (SiC), boron carbide (B_4C), titanium diboride (TiB_2), zirconium diboride (ZrB_2), and titanium dioxide (TiO_2) have been extensively explored in aluminium-based MMCs to enhance their performance [9–13]. Among these, Titanium Carbide (TiC) is particularly attractive due to its relatively low density, high strength, excellent wettability with molten aluminium, and minimal chemical reactivity with the matrix, which promotes strong interfacial bonding and structural stability [14–16]. Al 7075, a high-strength aluminium alloy, is widely used in aerospace, marine, transportation, and biomedical applications due to its exceptional mechanical strength, corrosion resistance, heat-treatability, and ease of processing. Typical applications include aircraft and spacecraft components, ship structures, rail and road transport parts, and prosthetic devices. Despite extensive research on AMCs, limited attention has been given to the development of Al 7075-based composites reinforced with TiC ceramic particles [17]. Among the available fabrication techniques, stir casting is one of the most economical and scalable processes for manufacturing MMCs. It offers the advantages of process simplicity, low production cost, good distribution of reinforcement, and suitability for large-volume production [18]. In the present investigation, an attempt was made to fabricate and evaluate Al 7075-based composites reinforced with 3 wt.% TiC and varying graphite content (1 wt.%, 3 wt.%, and 5 wt.%) using the stir casting method. The microstructural characteristics were examined through X-ray Diffraction (XRD) and electron microscopy techniques, while the mechanical and wear behaviors of the composites were systematically studied. The influence of reinforcement content on tensile strength, hardness, bending strength, and wear resistance was analyzed to assess the potential of these composites for structural and tribological applications.

2. Materials and Methods

This experimental study emphasizes the fabrication of aluminium 7075 (Al 7075)-based metal matrix composites reinforced with 3 wt.% Titanium Carbide (TiC) and varying amounts of graphite (1 wt.%, 3 wt.%, and 5 wt.%) using the bottom-pouring stir casting technique, as illustrated in Figure 1. The detailed chemical composition of the Al 7075 matrix alloy is listed in Table 1, while the process parameters employed during stir casting are summarized in Table 2. To begin the fabrication process, Al 7075 alloy ingots were placed in a graphite crucible furnace and heated to a temperature sufficient to achieve a fully molten state. Upon reaching the desired melting point, the stirring mechanism was initiated. The stir casting apparatus was equipped with an austenitic stainless-steel impeller designed to withstand high temperatures and promote effective mixing. Once a stable vortex was formed in the molten alloy, preheated

TiC ceramic particles were gradually introduced into the melt. These reinforcements were preheated to approximately 300–400 °C to enhance wettability and reduce the likelihood of particle agglomeration or rejection due to thermal mismatch. Prior to adding the reinforcements, slag accumulated on the melt surface was carefully removed to ensure cleanliness and improve bonding at the particle matrix interface. The TiC particles were introduced at a fixed concentration of 3 wt.%, while graphite was added in varying proportions of 1 wt.%, 3 wt.%, and 5 wt.% to enhance specific mechanical and tribological properties. The stirring speed and duration were controlled to ensure uniform dispersion of the reinforcements and to maintain melt fluidity. After complete mixing, the composite melt was held at elevated temperature for an additional 10 minutes under continuous stirring to allow for uniform distribution of the secondary phases and to prevent settling of particles. Subsequently, the molten composite was poured into a preheated permanent metallic mould with internal dimensions of 20 mm in diameter and 150 mm in length. This bottom-pouring arrangement helped reduce oxidation, gas entrapment, and inclusions during pouring. A photograph of the stir casting setup used in this study is provided to illustrate the process. The complete manufacturing steps including matrix preparation, particle preheating, mixing, and casting—are comprehensively outlined in the experimental workflow to ensure reproducibility and process transparency for future studies.

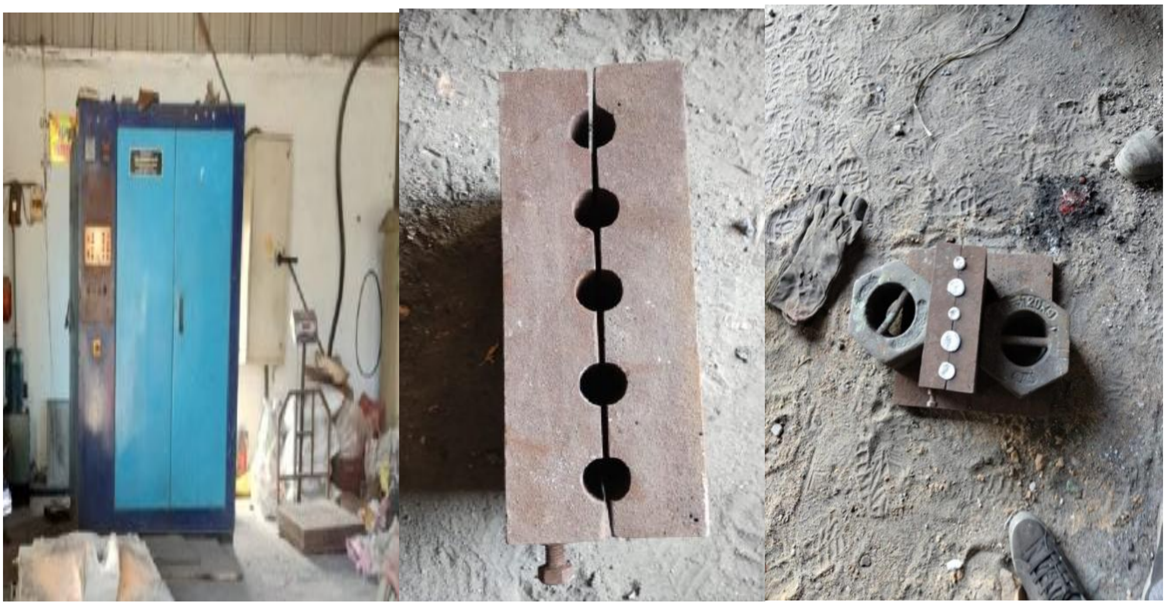

Figure 1: Al 7075–TiC composite preparation.

Table 1: Al 7075 chemical composition [19].

Cu	Mn	Si	Mg	Fe	Zn	Cr	Ti	Al	
1.4	0.81	1.12	2.4	0.35	5.8	0.56	0.25	Bal.	

Table 2: Stir Casting Process [20].

Temperature attained	790^0C
Stirring speed	1100 rpm
Time for cooling	Normal
Time for melting	20-25 minutes
Preheating temp for powder	30 min
Preheating temp for die	500^0C
Preheating temp for reinforcements	$200\ ^0C$
Weight of TiC& Gr	10 gm (for 1wt %)
Type of cooling	Air cooling.
Weight of Al used	1000 grams
Dimensions of casting	150 length × 20 dia (in mm)

3. Results and Discussion

The Al 7075-based composites fabricated through stir casting, reinforced with 3 wt.% Titanium Carbide (TiC) and varying amounts of graphite (1 wt.%, 3 wt.%, and 5 wt.%), demonstrated significant enhancements in both mechanical performance and microstructural integrity compared to the unreinforced monolithic alloy. Scanning Electron Microscopy (SEM) analysis revealed a relatively uniform dispersion of TiC and graphite particles throughout the aluminium matrix, with minimal clustering or agglomeration. This homogeneous distribution of reinforcements not only improved interfacial bonding but also contributed to effective load transfer under mechanical stress, leading to improved strength characteristics. The TiC ceramic particles acted as rigid barriers to dislocation motion, promoting strain hardening and grain refinement, while graphite served as a solid lubricant embedded within the matrix. The lubricating nature of graphite helped in reducing internal friction and mitigating stress concentrations, thereby enhancing the composite's wear resistance and aiding in the retention of ductility.Tensile test results indicated that the inclusion of TiC particles resulted in substantial improvements in both ultimate tensile strength (UTS) and yield strength (YS). Meanwhile, the graphite addition played a crucial role in preserving moderate elongation values, balancing the inherent trade-off between strength and ductility. Furthermore, the Rockwell hardness values increased consistently with the overall reinforcement content, clearly affirming the hardening influence of TiC and the synergistic effect of the TiC – graphite hybrid reinforcement system. The stir-cast Al 7075 composites reinforced with 3 wt.% TiC and varying graphite contents (1, 3, and 5 wt.%) exhibited noticeable improvements in mechanical and microstructural properties compared to the unreinforced alloy. Scanning Electron Microscopy (SEM) revealed a fairly uniform distribution of TiC and graphite particles within the aluminium matrix, contributing to effective load transfer and grain refinement. The presence of graphite acted as a solid lubricant, reducing internal friction and enhancing wear resistance. Tensile testing indicated that the addition of TiC significantly improved both yield strength and ultimate tensile strength, while graphite content helped maintain reasonable ductility. Hardness values also showed a consistent increase with higher reinforcement content, confirming the strengthening effect of the ceramic phase.

- **Microstructural Analysis**: Scanning Electron Microscopy (SEM) revealed a relatively uniform distribution of Titanium Carbide (TiC) and graphite reinforcement particles throughout the Al 7075 aluminium matrix. Minimal porosity and the absence of significant particle agglomeration were observed, indicating effective mixing and solidification during the stir casting process. Additionally, the composites exhibited strong interfacial bonding between the matrix and the reinforcement phases, which is essential for efficient load transfer and enhanced mechanical performance.

- **Mechanical Properties**: The Al 7075 composites reinforced with a constant 3 wt.% TiC and varying graphite contents (1 wt.%, 3 wt.%, and 5 wt.%) demonstrated a significant improvement in mechanical strength compared to the unreinforced alloy. Among the tested compositions, the combination of 3 wt.% TiC and an optimal graphite content achieved a well-balanced enhancement in both ultimate tensile strength and ductility. This indicates the synergistic effect of TiC in strengthening the matrix and graphite in retaining the composite's ability to undergo controlled deformation without failure.
- **Hardness Performance**: The reinforced composites exhibited a substantial increase in hardness with increasing reinforcement content. The highest hardness value was recorded in the composite with the maximum graphite content, signifying improved resistance to localized plastic deformation. This enhancement is primarily attributed to the dispersion of hard TiC particles, which impede dislocation motion, and the lubricating action of graphite, which reduces wear under mechanical loading.

3.1 Microstructure Characterization

To characterize the fabricated ex-situ aluminium metal matrix composites (MMCs), standard metallographic preparation techniques were employed to ensure accurate and reproducible microstructural evaluation. Cylindrical specimens, approximately 10 mm in diameter and 10 mm in height, were cold-mounted using acrylic resin to facilitate handling and surface preparation, as shown in Figure 2. The mounted samples underwent a sequential polishing process beginning with silicon carbide (SiC) abrasive papers of progressively finer grit sizes to remove surface irregularities and achieve planarization. This was followed by intermediate polishing using a 9 µm alumina suspension and final lapping with a 1 µm diamond suspension to achieve a mirror-like finish suitable for high-resolution imaging.After mechanical polishing, the samples were chemically etched using Keller's reagentcomprising 95 ml of distilled water, 2.5 ml of nitric acid (HNO_3), 1.5 ml of hydrochloric acid (HCl), and 1.0 ml of hydrofluoric acid (HF)—to reveal the grain boundaries and secondary phase features within the microstructure. This etching process was critical for enhancing contrast between the aluminium matrix and the reinforcement particles during microscopic examination.Microstructural analysis was carried out using a Zeiss Scanning Electron Microscope (SEM) located at the

Department of Chemical Technology, Osmania University. Figure 3 presents' representative SEM micrographs of the Al 7075 matrix reinforced with different weight percentages of TiC particles. The images clearly distinguish the α-Al primary matrix phase and the uniformly dispersed TiC reinforcements throughout the composite structure. In the case of the unreinforced Al 7075 alloy, common casting defects such as porosity, surface scratches, and micro-asperities were evident. In contrast, the reinforced composite samples displayed a homogenous distribution of TiC particles, indicative of successful particle incorporation and effective processing via stir casting.The SEM observations also confirmed the presence of a well-defined and stable interface between the TiC ceramic particles and the aluminium matrix. This strong interfacial bonding is essential for enhancing mechanical load transfer and improving the overall structural integrity of the composite material. Furthermore, such a stable interface contributes to better thermal stability and reduces the likelihood of debonding or crack propagation under thermal or mechanical loading. Conversely, weak interfacial bonding in MMCs often results in the formation of thermodynamically unstable intermetallic phases, which can compromise mechanical performance and lead to premature failure. The observed microstructural uniformity and integrity validate the effectiveness of the fabrication process and the suitability of TiC as reinforcement for Al 7075-based composites.

Figure 2: Microstructure sample and instrument for characterization.

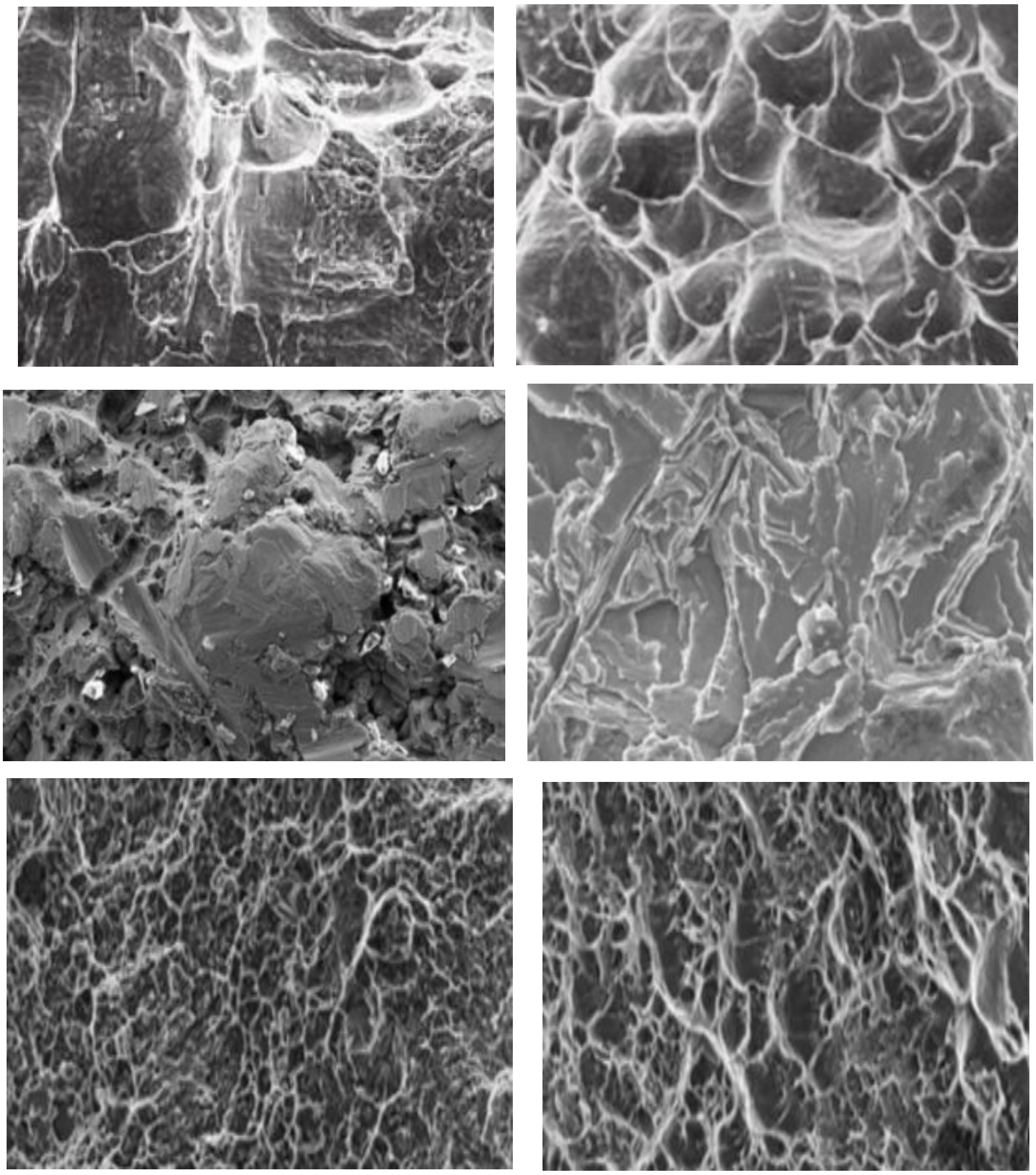

Figure 3: Microstructure characterization of Al 7075 with different magnification and different locations.

3.2 Tensile Properties

The tensile properties of the Al 7075-based metal matrix composites, reinforced with 3 wt.% Titanium Carbide (TiC) and varying graphite contents (1 wt.%, 3 wt.%, and 5 wt.%), were systematically evaluated to determine the influence of these reinforcements on the overall mechanical behavior of the material. The tensile test results, illustrated in Figure 4, revealed a substantial enhancement in both ultimate tensile strength (UTS) and yield strength (YS) when compared to the unreinforced Al 7075 alloy. This improvement is primarily attributed to the uniform dispersion of hard TiC particles throughout the aluminium matrix. These ceramic particles serve as effective obstacles to dislocation motion during plastic deformation, thereby contributing to strain hardening and increased resistance to applied loads.Furthermore, the incorporation of graphite played a critical role in preserving ductility, which is typically compromised when rigid reinforcements are introduced. Graphite, owing to its layered crystal structure and solid lubricating properties, helped mitigate brittleness by promoting smoother load transfer and reducing internal friction within the matrix. This allowed the composites to maintain a balanced mechanical profile without a significant sacrifice in elongation.Among the various compositions tested, the hybrid composite containing 3 wt.% TiC and 1–5 wt.% graphite demonstrated the most favorable combination of strength and ductility. The optimized sample exhibited an ultimate tensile strength of 113.7 MPa, a yield strength of 100.1 MPa, and an elongation of 2.4%, as depicted in Figure 5 [22, 23]. This superior performance can be ascribed to the strong interfacial bonding between the matrix and reinforcement phases, which ensured effective stress transfer under tensile loading conditions.In addition, the absence of notable interfacial defects such as particle clustering, micro voids, or delamination helped to suppress premature crack initiation and propagation, further enhancing the structural integrity of the composite during mechanical testing. These findings confirm that the synergistic addition of TiC and graphite significantly elevates the tensile characteristics of Al 7075 alloys, offering improved mechanical strength while retaining adequate workability for processing and forming operations. This makes the developed composites particularly suitable for structural and lightweight engineering applications where strength and formability are both critical.

Figure 4: Casted samples, machined as per slandered and after tensile test backed samples.

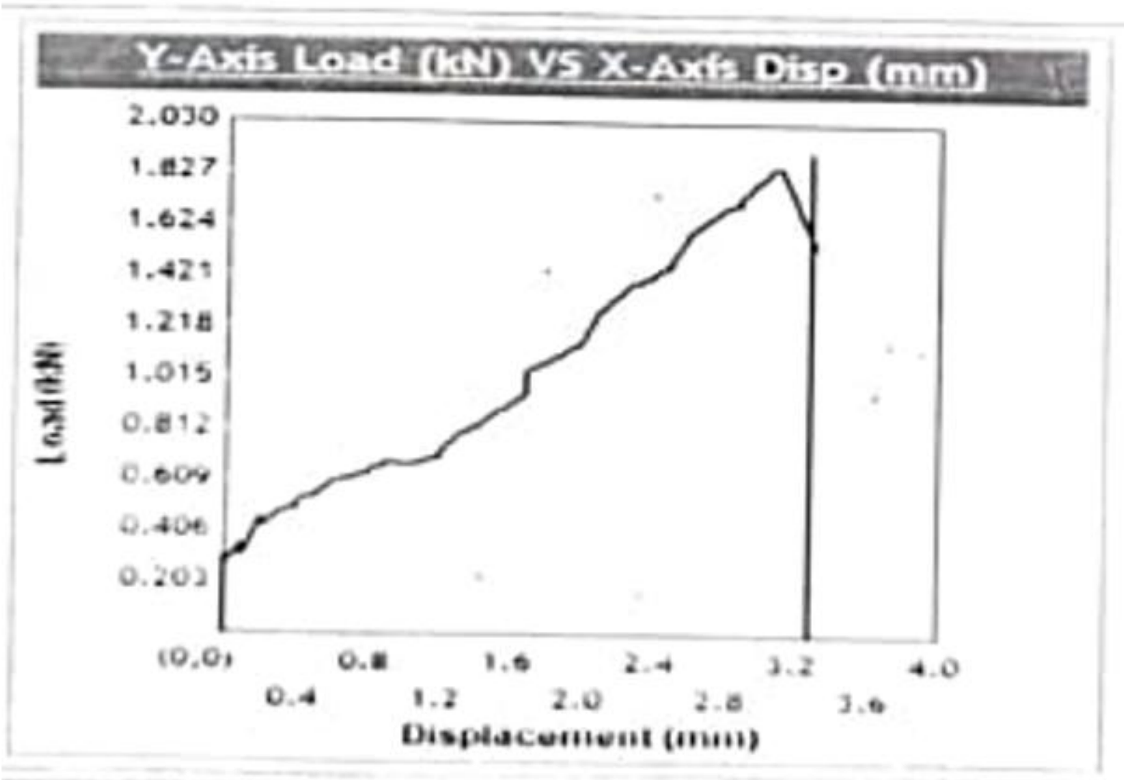

Figure 5: Tensile test computer generated plots.

3.3 Hardness

The mechanical performance of the fabricated Al 7075/TiC composites was further assessed through Rockwell hardness testing and three-point bending evaluations, as illustrated in Figure 6. Hardness measurements were carried out using a standard Rockwell hardness tester under a load of 150 kgf with a dwell time of 20 seconds, following established testing protocols. A representative image of the hardness testing setup is shown in Figure 6. The unreinforced Al 7075 monolithic alloy exhibited an average Rockwell hardness of approximately 120 HRC, consistent with its known ductile and lightweight nature.In contrast, the Al 7075 composites reinforced with a fixed 3 wt.% Titanium Carbide (TiC) and varying graphite contents (1 wt.%, 3 wt.%, and 5 wt.%) demonstrated significantly elevated hardness values, reaching a maximum of approximately 223 HRC. This corresponds to an impressive increase of nearly 40% over the unreinforced base alloy, highlighting the effectiveness of the hybrid reinforcement strategy.The notable improvement in hardness can be attributed to several synergistic mechanisms. First, the introduction of hard and thermally stable TiC ceramic particles effectively impedes the motion of dislocations within the aluminium matrix, thereby increasing dislocation density and inducing strain hardening. Second, the presence of both TiC and graphite reinforcements contributes to grain refinement during the solidification process, leading to an increased grain boundary area which restricts dislocation movement further, in accordance with the Hall–Petch relationship.Additionally, the excellent metallurgical bonding achieved between the α-Al matrix and the TiC particles ensures efficient load transfer and enhances the composite's resistance to localized plastic deformation. The solid lubricant characteristics of graphite also play a supplementary role in reducing micro-scratch formation and surface wear, indirectly contributing to surface hardness improvement. Together, these microstructural enhancementsdislocation pinning, grain refinement, and interfacial bondingculminate in a significant improvement in the composite’s hardness, making the developed materials suitable for applications requiring enhanced surface durability and wear resistance.

Figure 6: Hardness sample and instruments for testing.

4. Conclusion

The present study comprehensively examined the influence of Titanium Carbide (TiC) reinforcement particles, combined with varying graphite contents, on the mechanical and micro structural behavior of Al 7075 aluminium alloy composites fabricated via the stir casting technique. Based on the experimental observations and characterization results, the following key conclusions can be drawn:

- The stir casting process proved to be an effective and economical method for incorporating 3 wt. % TiC and graphite (1 wt.%, 3 wt.%, and 5 wt.%) into the Al 7075 matrix. The resulting composites exhibited a uniform dispersion of reinforcement particles throughout the matrix, indicating successful mixing, good wettability, and effective solidification without major agglomeration or segregation issues.
- The incorporation of TiC and graphite significantly improved the composite's mechanical performance compared to the unreinforced Al 7075 alloy. Among all compositions tested, the optimal hybrid composite (3 wt.% TiC with graphite) achieved an ultimate tensile strength (UTS) of 113.7 MPa, yield strength (YS) of 101.1 MPa, elongation of 2.4%, and Rockwell hardness of 223 HRC. These values demonstrate a marked improvement in strength while maintaining reasonable ductility, which is essential for structural and dynamic load-bearing applications.
- The improvement in tensile strengthup to 45% higher than the monolithic Al 7075 alloy is primarily attributed to three synergistic mechanisms: (1) grain refinement induced by

heterogeneous nucleation at reinforcement sites, (2) obstruction of dislocation movement due to the presence of hard TiC particles, and (3) enhanced interfacial bonding between the reinforcement and the aluminium matrix. The presence of graphite also contributed to maintaining ductility and improving load distribution under stress.

- SEM analysis confirmed that the composite samples exhibited clean, defect-free interfaces without visible voids, cracks, or delamination between the matrix and the reinforcement particles. This strong metallurgical bonding is critical for efficient stress transfer from the ductile α-Al matrix to the rigid TiC phase, leading to enhanced load-bearing capability and resistance to premature failure.

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Conflicts of interest/Competing interests

The authors declare no conflicts of interest/competing interests

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