

"EXPERIMENTAL EVALUATION OF MECHANICAL AND TRIBOLOGICAL PROPERTIES OF HYBRID B₄C–TiB₂ REINFORCED AL7075 ALUMINUM COMPOSITES FABRICATED BY STIR CASTING"

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ABSTRACT

The present study focuses on the development and characterization of hybrid metal matrix composites (MMCs) based on aerospace-grade aluminium alloy Al-7075 reinforced with ceramic and nano-scale particulates. Boron carbide (B₄C), silicon carbide (SiC), titanium diboride (TiB₂), and graphene nanoplatelets were selected as reinforcements to enhance the mechanical, tribological, and functional properties of the base alloy. Five material systems were fabricated: pure Al-7075 as the baseline and four hybrid composite compositions with varying reinforcement contents, namely: (i) pure Al-7075, (ii) 93% Al-7075 + 2% B₄C + 2% SiC + 2% TiB₂ + 1% graphene, (iii) 91% Al-7075 + 3% B₄C + 3% SiC + 2% TiB₂ + 1% graphene, and (iv) 89% Al-7075 + 4% B₄C + 4% SiC + 2% TiB₂ + 1% graphene, all expressed in weight percentages.

The hybrid composites were fabricated using the stir casting technique combined with ultrasonic assistance to achieve uniform dispersion of reinforcements and improved interfacial bonding between the matrix and particles. The fabricated specimens were subjected to comprehensive experimental investigations, including tensile, compressive, flexural, hardness, impact, and wear tests using a pin-on-disc tribometer. Comparative analysis between the baseline alloy and reinforced composites was carried out to evaluate the influence of incremental ceramic and graphene additions on mechanical strength, hardness, wear resistance, ductility, and overall performance.

The results demonstrate that the incorporation of B₄C, SiC, TiB₂, and graphene significantly enhances the mechanical and tribological properties of Al-7075, while also revealing a trade-off between strength and ductility with increasing reinforcement content. The study provides valuable insights into the synergistic effects of hybrid reinforcements and establishes the potential of Al-7075 hybrid MMCs for advanced aerospace and high-performance engineering applications where high specific strength, wear resistance, and multifunctional properties are essential.

1 INTRODUCTION

1.1 INTRODUCTION OF AL7075

Aluminium Alloy 7075 (AL7075) is a high-strength aluminium alloy primarily alloyed with zinc, magnesium, and copper. It is one of the strongest aluminium alloys available and is widely used in aerospace, automotive, and structural applications where high strength-to-weight ratio is required. AL7075 exhibits excellent mechanical properties, good fatigue resistance, and moderate corrosion resistance. Due to its superior performance, it is often considered an alternative to steel in lightweight structural components.

1.2 OVERVIEW OF COMPOSITES:

People have been making composites for many thousands of years. One early example is mud bricks. Mud can be dried out into a brick shape to give a building material. It is strong if you try to

squash it (it has good compressive strength) but it breaks quite easily if you try to bend it (it has poor tensile strength). Straw seems very strong if you try to stretch it, but you can crumple it up easily. By mixing mud and straw together it is possible to make bricks that are resistant to both squeezing and tearing and make excellent building blocks. Another ancient composite is concrete.

1.3 CLASSIFICATION OF COMPOSITES:

Composites are classified based on the types of matrix and reinforcements. Matrix is the base material in the composite. Reinforcements are usually added to the matrix (base metal) to improve its properties like strength, stiffness, conductivity, wear and corrosive resistance etc. Reinforcements increase the properties of matrix by transferring the strength to the matrix constituent.

Composites are manmade materials consisting of one or more discontinuous phases

having intimate contact with each other, with are cognizable interface between them. These are multifunctional materials systems that provide characteristics not obtainable from individual phases. Further, composites are tailor made to cost effective, property effective and application oriented.

1.4 TYPES OF COMPOSITES:-

In general, composites are classified according to the type of matrix material and then nature of reinforcement at two distinct levels. The first classification includes ceramic matrix composites (CMCs), organic matrix composites (OMCs) and metal matrix composites (MMCs). The term organic-matrix composite is generally assumed to include polymer Matrix composites (PMCs) and carbon matrix composites. The second classification refers to the reinforcement form; particulate reinforcements, whiskers, continuous fiber, laminated composites and woven composites.

1.4.1 - CERAMIC MATRIX COMPOSITES (CMCS) :-

Contain ceramic matrix reinforced with short fibers or whiskers such as those made from B4C AND SiC etc. Low conductivity, high temperature resistance, high rigidity, chemically stable and crystalline or amorphous structures are the salient features of ceramic matrix composites. These composites found to be suitable for high temperature applications such as thermal coatings, exhausts etc.,

Composite	Components	Benefits
Al- B4C (p)	Piston	Reduced weight, high strength
	Brake rotor, caliper, linear	High wear resistance and Reduced weight
	Propeller shaft	Reduction of weight and high Specific stiffness
Al- B4C (w)	Connecting rod	Reduced reciprocating mass, high specific strength, stiffness
Al- B4C(p)	Sprockets, pulleys, covers	Reduced weight
Al- Al2O3(sf)	Piston ring	Wear resistance and running Temperature
	Piston crown	Reduced reciprocating mass, high creep and fatigue
Al- Al2O3(lf)	Connecting rod	Resistance Reduced reciprocating mass, improved strength
Cu-graphite	Electrical contact strips,	Low friction and wear lowCTE
Al- graphite	Cylinder, linear piston bearing	Gall resistance reduced friction, Wear and weight
Al- TiC(p)	Connecting	Reduced weight and wear

Table 1: MMCs components and their applications :-

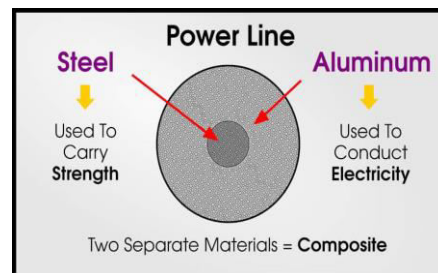
1.5 ALLOY:

An alloy is a material formed by combining two or more metallic elements (or a metal with a non-metal) by melting them together to improve properties such as strength, hardness, corrosion resistance, and ductility. In alloys, the elements are mixed at the atomic level and form a single homogeneous material. Examples include steel

(iron + carbon), brass (copper + zinc), and Al-7075 (aluminum + zinc, magnesium, copper).

1.6 COMPOSITE:

A composite is a material made by combining two or more different materials (matrix and reinforcement) that remain physically distinct but work together to provide enhanced mechanical and functional properties. The matrix binds the reinforcement, while the reinforcement provides strength, stiffness, or wear resistance. Composites are usually heterogeneous and not mixed at the atomic level. Examples include fiberglass (glass fiber + resin), carbon fiber reinforced polymer, and Al-7075 reinforced with SiC, B4C, TiB2, or graphene.



Classification based on Matrices

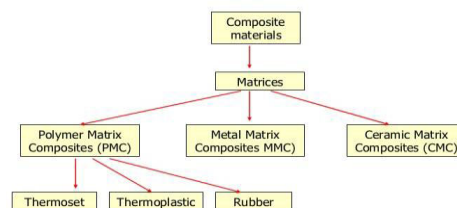


Figure 1 Classification based on Matrices

1.7 - WHY USE COMPOSITES?

Weight saving is one of the main reasons for using composite materials rather than conventional materials for components. While composites are lighter they can also be stronger than other materials, for example, reinforced carbon-fiber can be up to five times stronger than 1020 grade steel and only one fifth of the weight, making it perfect for structural purposes.

1.8 - ADVANTAGES OF COMPOSITE MATERIALS:-

- Low costs compared to metals
- Design flexibility
- Resistance to a wide range of chemical agents
- Low weight
- Durability
- Electric insulation
- High Impact strength

1.9 - MATERIALS USED :-

1. ALUMINIUM 7075
2. BORON CARBIDE (B4C)
3. SILICON CARBIDE
4. TITANIUM DIBORIDE (TiB₂)
5. GRAPHENE

1.9.1 - ALUMINIUM 7075 :-

7075 aluminum, originally known as “Alloy 61s”, was one of the first to be developed (in 1935), and is one of the most commonly available heat-treatable aluminum alloys for commercial use. The 7075 alloy is primarily composed of aluminum, magnesium and silicon. Its other metallic elements include iron, copper, chromium, zinc, manganese and titanium, in descending order of quantity. Alloy 7075 set the standard for a medium-to-high strength, lightweight, economical material. Earlier alloys had been susceptible to stress-corrosion cracking, but the addition of a small amount of Chromium made this alloy highly resistant to corrosion.



1.9.2 - Mechanical properties of Al 7075

Properties	Metric	Imperial
Tensile strength	310 MPa	45000 psi
Yield strength	276 MPa	40000 psi
Shear strength	207 MPa	30000 psi
Fatigue strength	96.5 MPa	14000 psi
Elastic modulus	68.9 GPa	10000 ksi
Poisson's ratio	0.33	0.33
Elongation	12-17%	12-17%
Hardness, Brinell	95	95

FIGURE 2 Properties of al 7075

processing of al7075 matrix composites primary processing for manufacturing of AMCs can be classified into two main groups.

- a) Liquid state process includes stir casting, squeeze castings, and ultrasonic assisted castings,
- b) Solid state process includes powder blending followed by consolidation (Powder metallurgy), high energy ball milling, and friction stir process.

1.9.3 - Boron carbide :-

Boron carbide (chemical formula approximately B₄C) is an extremely hard boron-carbon ceramic and covalent material used in tank armor, bulletproof vests, engine sabotage powders, as well as numerous industrial applications. With a Vickers hardness of >30 GPa, it is one of the hardest known materials, behind cubic boron nitride and diamond



1.9.4 - MECHANICAL PROPERTIES OF BORON CARBIDE

Property	Value
Density (g.cm ⁻³)	2.52
Melting Point (°C)	2445
Hardness (Knoop 100 g) (kg.mm ⁻²)	2900 - 3580
Fracture Toughness (MPa.m ^{0.5})	2.9 - 3.7
Young's Modulus (GPa)	450 - 470
Electrical Conductivity (at 25 °C) (S)	140
Thermal Conductivity (at 25 °C) (W/m.K)	30 - 42

Figure 3 Properties of boron carbide

1.9.5 SILICON CARBIDE (SiC):

Al7075 is a high-strength aluminium alloy widely used in aerospace and automotive applications. When reinforced with Silicon Carbide (SiC) particles, it forms a Metal Matrix Composite (MMC) with improved mechanical and thermal properties. Silicon Carbide (SiC) is a hard ceramic compound made of silicon (Si) and carbon (C).



Figure 4 Silicon carbide

(A) Mechanical Properties Table

Property	Typical Value
Density	3.21 g/cm ³
Hardness (Vickers)	2500 – 3000 HV
Tensile Strength	200 – 400 MPa
Compressive Strength	2000 – 3500 MPa
Flexural Strength	300 – 600 MPa
Young's Modulus (Elastic Modulus)	410 – 450 GPa
Fracture Toughness	3 – 5 MPa·m ^{0.5}
Poisson's Ratio	0.14 – 0.22
Wear Resistance	Very High

Mechanical properties of silicon carbide

1.10 ADVANTAGES OF SILICON CARBIDE

◆ **Mechanical Advantages**

- Very high hardness (close to diamond)
- Excellent wear and abrasion resistance
- High strength and stiffness
- Lightweight compared to metals
- High fracture toughness

◆ Thermal Advantages

- Excellent thermal conductivity
- High melting point (~2700°C)
- Good thermal shock resistance
- Stable at high temperatures

◆ Electrical Advantages

- Wide bandgap semiconductor
- High breakdown voltage
- High electron mobility
- Low power loss
- Works at high temperature and high frequency

◆ Chemical Advantages

- Excellent corrosion resistance
- Resistant to oxidation and chemicals
- Non-reactive in harsh environments

1.10.1 TiB₂ (Titanium Diboride):

Titanium Diboride (TiB₂) is a high-performance ceramic material known for its exceptional hardness, high melting point, and excellent thermal and chemical stability.



TiB₂ (Titanium Diboride)

1.10.2 GRAPHENE:

Graphene is used as a reinforcement material in Al 7075 to improve mechanical, thermal, and tribological properties. This forms an Al7075–Graphene Metal Matrix Composite (MMC).

Graphene has:

- Extremely high strength (≈ 130 GPa tensile strength)
- High Young's modulus (≈ 1 TPa)
- Excellent thermal and electrical conductivity
- Low density
- Good wear resistance

1.10.3 MECHANICAL PROPERTIES OF GRAPHENE:

Property	Value
Tensile Strength	≈ 130 GPa
Young's Modulus	≈ 1 TPa
Hardness	Very High
Elasticity	Excellent
Density	≈ 2.2 g/cm ³
Fracture Toughness	Very High

Mechanical properties of Graphene

1.11 - LIQUID STATE PROCESS :-

Stir casting process is a liquid state process, in this process the aluminium alloy is matrix phase and ceramics are reinforcement phase. The aluminium alloy is heated in liquid state and reinforcing phases (usually in powder form) are distributed into molten Aluminium alloy by mechanical stirring. The key element in this process is Mechanical stirring in furnace. Squeeze casting process is the combination of gravity die casting and closed die forging. In this process, pressure is applied on the solidifying liquid metal. Pouring of metered quantity of liquid metal with adequate super heat in to the die cavity, application of pressure on the liquid metal and maintaining the same till the solidification is complete and removal of the casting and preparation of the die for them next cycle. Ultrasonic Assisted Casting is combines solidification processes with ultrasonic cavitation-based dispersion of nanoparticles in metal melts has been developed. Ultrasonic cavitation can produce transient (in the order of nanoseconds) micro 'hot spots' that can have temperatures of about 5000°C, pressures above 1000 ATMs, and heating and cooling rates above 1010 K/s.

1.11.1 - PROPERTIES OF AL COMPOSITE'S MATERIALS :-

The factors that determine properties of composites are, microstructure, volume fraction isotropy and homogeneity of the system and these are strongly influenced by proportions and properties of the matrix and the reinforcement.

1.11.2 - PHYSICAL PROPERTIES :-

Density is a physical property of matter, as each element and compound have a unique density associated with it. Density defined in a qualitative manner as the measure of the relative "heaviness" of objects with a constant volume. Density plays very important roles in the composite material study. These materials using in space crafts and automotive industry, they must be light weight. So, the density should be reduced by adding some reinforced material like AL7075, SiC, B4C AND TiB2, GRAPHENE etc., in Aluminum alloy. In a composite, the volume fraction (v), which is commonly used in property calculation. Density can be calculated by dividing the mass of specimen by the volume displaced by that specimen in the water beaker

2 LITERATURE REVIEW

This chapter presents a review of the literature data available on the effect of various reinforcement types, their size and volume fraction, ageing behaviour with AL based MMC's.

Dattatraya N et.al, presents a study on stir casing process and process parameter having Al alloy as a matrix phase and alumina (Al_2O_3) as a reinforcement. In their study, they have concluded the following points: (i) Stir casing process can successfully be used for manufacturing of AMMC's having low density and enhanced mechanical properties. 2) Stir casting process is cost effective and conventional route for manufacturing of composite material. 3) Material having isotropic nature can be manufactured successfully. 4) Preheating of mould reduces porosity and enhances mechanical properties. 5) Addition of Magnesium is important to increase wettability. 6) Design of stirrer decides the flow pattern of melt. 7) Stirrer speed, stirring time decides quality of casting. 8) Preheat temperature of mould, preheat temperature of reinforcement, reinforcement size, reinforcement feed rate and melt pouring rate are also the important parameters in stir casting method

Manikandan.C, noticed in his experimental study, that the 12% of SiC and 450°C preheat temperature of the reinforcement improves the hardness and impact strength of the composite. At 6% of SiC, 200 rpm of stirrer speed and 500°C reinforcement pre heat temperature attains the improved level of tensile strength. The hardness and impact strength to values are directly proportional to the SiC composition rate. the minimal percentage of elongation is obtained in the 9% of SiC, 250 RPM and 500 °C pre heating temperature of reinforcement.

Hariharan.R et.al, carried out the research work by fabricating Al6061 – TiB2 MMC by stir casting method. The addition of the TiB particles into Al-6061 is a good route to improve the mechanical

properties of materials. The resulting composite showed the increase in tensile strength when compared to the unreinforced alloy. SEM and XRD analysis of the composite confirms the presence of TiB particle and its volume fraction. The increased volume fraction of the TiB particles contributed to increase the strength of composites. The dry sliding at room temperature shows that there is a definite increase in the wear resistance of Al6061 alloy by the addition of TiB2 particles.

Pradeep R et.al observed the study of mechanical properties of Al- Red Mud and Silicon Carbide Metal Matrix Composite (MMC) of Aluminium alloy of grade 7075 with addition of varying weight percentage composition such as SiC8%+Al7075, SiC6%+Red mud2%+ Al7075, SiC4%+Red mud 4%+Al7075, SiC2%+Red mud 6%+Al7075, Red mud 8%+Al7075ed mud and Silicon Carbide particles by stir casting technique. The experimental result reveals that the combination of a matrix material with reinforcement such as SiC and Red mud particles, improves mechanical properties like tensile strength, compressive strength, hardness and yield strength. [4]

Ravichandran M et.al carried out the research work by fabricating aluminium metal matrix composites through liquid powder metallurgy route. The aluminium matrix composite containing TiO2 reinforcement particle was produced to study the mechanical properties such as tensile strength and hardness. The characterization studies are also carried out to evident the phase presence in the composite and the results are discussed for the reinforcement addition with the mechanical properties. Results show that, the addition of 5 weight percentage of TiO2to the pure aluminium improves the mechanical properties. [5]

3 OBJECTIVE OF THE PROJECT

3.1 PROBLEM IDENTIFICATION

In recent years, aluminium alloy-based metal matrix composites (MMC) are gaining importance in several aerospace and automobile applications. But aluminium alloys having the low hardness and low strength compared to the other materials, so we choose the composition over the pure materials.

Why we choose aluminium over another materials aluminium was oftenly used material in the automobile shipping and another most industries so we choose aluminium as the matrix material.

The defects in the aluminium is shown in below



Figure 4 damage in the aluminium alloy on low load

The above shown the defects in the material which is used to the aeroplane body, the body was subjected to the small load it will cause a dent to the aeroplane body .

The diagram shown the dent which caused by another car when they give a additional strength to the aluminium.



Figure 5. dent on the car

3.2 PROJECT OVERVIEW :

1. **Development of Hybrid MMCs** This project focuses on developing hybrid metal matrix composites using Al-7075 alloy reinforced with B₄C, SiC, TiB₂, and graphene to improve mechanical and tribological properties.
2. **Fabrication Using Stir Casting** Hybrid composites with different reinforcement weight percentages were fabricated using stir casting with ultrasonic assistance to achieve uniform particle dispersion and strong interfacial bonding.
3. **Material Characterization** The fabricated specimens were characterized through mechanical testing such as tensile, compressive, flexural, hardness, impact, and wear analysis.
4. **Comparative Performance Evaluation** The performance of reinforced composites was compared with pure Al-7075 to study the effect of increasing ceramic and graphene content on strength, hardness, wear resistance, and ductility.
5. **Application-Oriented Analysis** The study evaluates the suitability of Al-7075 hybrid MMCs for aerospace and advanced engineering applications requiring high

strength-to-weight ratio and improved wear resistance.

3.3 OBJECTIVES OF THE PROJECT

1. To fabricate Al-7075 hybrid metal matrix composites with varying proportions of B₄C, SiC, TiB₂, and graphene using the stir casting technique.
2. To investigate the effect of hybrid reinforcements on mechanical properties such as tensile strength, compressive strength, flexural strength, hardness, and impact resistance.
3. To analyze the wear behavior of the developed composites using a pin-on-disc tribometer and compare it with pure Al-7075.

4 – MATERIALS AND FABRICATION PROCESS

4.1 - STIR CASTING :-

Stir casting is a type of casting process in which a mechanical stirrer is introduced to form vortex to mix reinforcement in the matrix material. It is a suitable process for production of metal matrix composites due to its cost effectiveness, applicability to mass production, simplicity, almost shaping and easier control of composite structure.

Stir casting setup as shown in , consist of a furnace, reinforcement feeder and mechanical stirrer. The furnace is used to heating and melting of the materials. The bottom poring furnace is more suitable for the stir casting as after stirring of the mixed slurry instant poring is required to avoid the settling of the solid particles in the bottom the crucible.

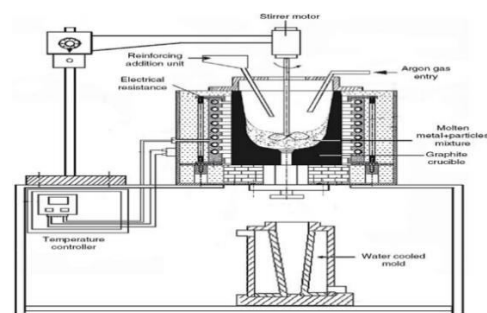


Figure 6 Schematic of stir casting setup.

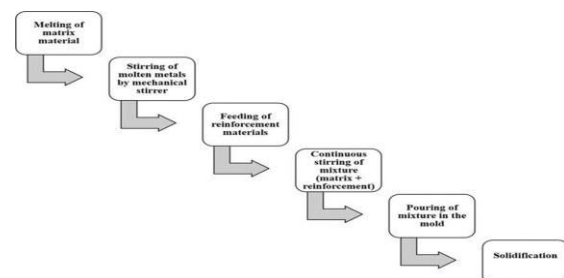
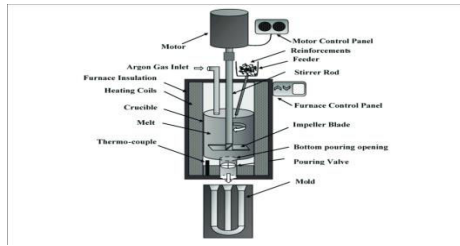


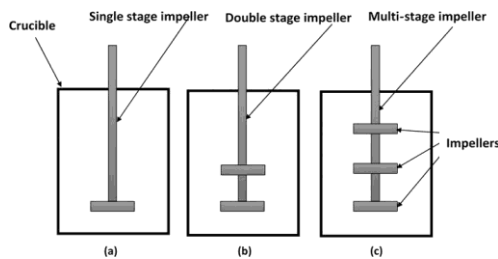
Figure 7 Process of stir casting.



4.1.1 - Melting of matrix material

Out of various furnaces, bottom pouring furnace is suitable for fabrication of metal matrix composites in stir casting route, this type of furnace consists of automatic bottom pouring technique which provides instant pouring of the melt mix (matrix and reinforcement). Automatic bottom pouring is mainly used in investment casting industry.

4.1.2 - Mechanical stirring



4.1.3 - Matrix material :-

AL 7075 alloy was selected because of its low specific weight and high strength to weight ratio and fatigue and also its excellent machinability, formability and weld ability. This alloy is widely used in automotive industry, aircraft industry and defense industries. The chemical composition of the used material is given in Table.



figure 8 - Aluminium rods for furnace

SPECIMEN COMPOSITION	
Pure Al-7075	
93% Al-7075 + 2% B ₄ C + 2% SiC + 2% TiB ₂ + 1% Graphene	
91% Al-7075 + 3% B ₄ C + 3% SiC + 2% TiB ₂ + 1% Graphene	
89% Al-7075 + 4% B ₄ C + 4% SiC + 2% TiB ₂ + 1% Graphene	

composition of hybrid-composite

4.2 - EXPERIMENTAL PROCEDURE AND EQUIPMENT:



Figure: 9 ALUMINIUM 7075



Figure: 10 BORON CARBIDE



Figure:11 Titanium Diboride Tib2



Figure: 12 Silicon carbide



Figure:13 Graphene

4.3 STIR CASTING PROCESS :-

It's involves stirring of melt, in which the melt is stirred continuously which exposes the melt surface to the atmosphere which tend to continuous

oxidation of aluminum melt. As a result of continuous oxidation, the wet ability of the aluminum reduces and the reinforcement particles remain unmixed.

4.3.1 Stir casting machine components :-

- 1. Furnace
- 2. Crucible
- 3. Stirrer rod
- 4. Stirrer impeller
- 5. Mold
- 6. Feeder
- 7. Motor

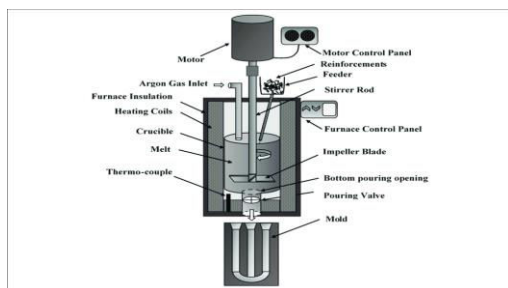


Figure 14 experimentation or working principal Stir casting machine

4.3.2 STIR CASTING MACHINE

SPECIFICATIONS :-

Bottom Pouring Type Stir Casting Machine

Specifications

- Capacity : 0.7 to 2 kg
- Furnace temp(max) : 950 degree C
- degree C pre heating of reinforcement (max) : 800 degree C
- Stirrer Speed : 100 to 1500 RPM
- Die temperature (max) : 350 degree C
- Furnace chamber : Org
- an gas (pure) Control : Remote

4.4 STIR CASTING SETUP:

Stir casting is one of the most widely used liquid-state fabrication techniques for producing aluminum-based metal matrix composites (MMCs). In this method, reinforcement particles are mechanically mixed into molten metal using a rotating stirrer to achieve uniform distribution. Due to its simplicity, low cost, and suitability for large-

scale production, stir casting is preferred for manufacturing hybrid aluminum composites.

In this project, Al-7075 alloy is used as the matrix material, and ceramic reinforcements such as boron carbide (B₄C), silicon carbide (SiC), titanium diboride (TiB₂), and graphene are added to enhance mechanical and tribological properties.

4.5 WORKING PRINCIPLE OF STIR CASTING

The stir casting process is based on the principle of mechanical agitation of molten metal to disperse reinforcement particles uniformly throughout the matrix. The molten aluminum alloy is stirred using a rotating impeller to form a vortex, into which preheated reinforcement particles are added gradually. Continuous stirring helps achieve homogeneous distribution of particles and improves bonding between matrix and reinforcements.

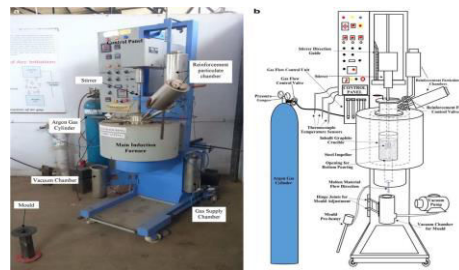


Figure 15 Experimentation on stir casting machine

4.5.1 STIR CASTING

PROCEDURE

Step 1: Melting of Matrix Material

Al-7075 alloy is placed in a graphite crucible and melted in an electric resistance furnace at a temperature of about 950°C

Step 2: Preheating of Reinforcements

The reinforcement particles (B₄C, SiC, TiB₂, Graphene) are preheated at 300-500°C to:

- Remove moisture
- Improve wettability
- Reduce thermal gradient

Step 3: Addition of Reinforcements

The preheated reinforcement particles are gradually added into the molten aluminum alloy.

Step 4: Mechanical Stirring

A mechanical stirrer is used to create a vortex in the molten metal.

- Stirring speed: 550 rpm
- Stirring time: 5–10 minutes

This ensures uniform distribution of reinforcement particles in the molten matrix.

Step 5: Degassing and Flux Addition

Degassing agents (e.g., hexachloroethane tablets) and flux are added to remove dissolved gases and impurities.

Step 6: Pouring into Mould

The molten composite is poured into preheated metallic or sand moulds to form cast specimens.

Step 7: Solidification and Cooling

The cast specimens are allowed to cool and solidify at room temperature.

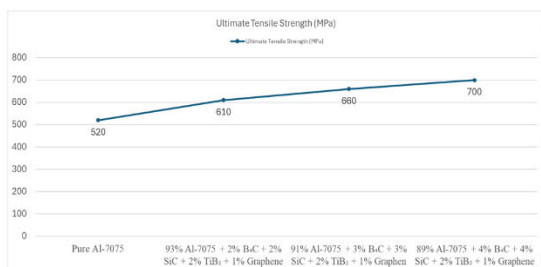


Figure 16 Specimen

5 TESTINGS

5.1 TENSILE TEST RESULTS:

The tensile test results demonstrate that the incorporation of ceramic reinforcements and graphene significantly enhances the tensile strength and load-carrying capacity of Al-7075, while gradually reducing ductility. Pure Al-7075 exhibited an ultimate tensile strength of 520 MPa, maximum load of 58.8 kN, and an elongation of 11.5%, indicating good ductility. The hybrid composite containing 2% B₄C, 2% SiC, 2% TiB₂, and 1% graphene showed an improved tensile strength of 610 MPa with a maximum load of 69 kN, while the elongation decreased to 9.2%. Further reinforcement addition increased the tensile strength to 660 MPa and 700 MPa for 3% and 4% B₄C–SiC composites, with corresponding elongation values of 7.8% and 6.5%, respectively. The reduction in elongation is attributed to the presence of hard ceramic particles restricting plastic deformation, while graphene contributes to crack bridging and load transfer. Overall, the hybrid composites exhibit a favourable strength–ductility trade-off suitable for high-performance structural applications.

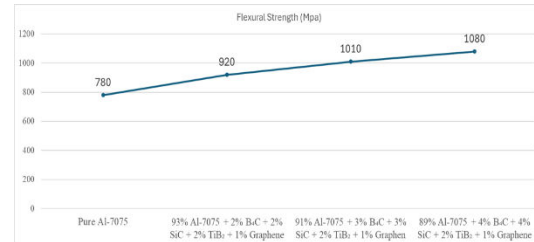


FLEXURAL TEST RESULTS (LOAD & FLEXURAL STRENGTH)

Flexural Test Results – Load & Strength

The flexural test results show a considerable improvement in bending strength with the addition of ceramic reinforcements and graphene to the Al-7075 matrix. The pure Al-7075 specimen exhibited

a flexural strength of 780 MPa and sustained a maximum load of 5.2 kN. The hybrid composite containing 2% B₄C, 2% SiC, 2% TiB₂, and 1% graphene demonstrated an enhanced flexural strength of 920 MPa, corresponding to a maximum load of 6.1 kN.



5.2 HARDNESS TEST

Hardness is a measure of how much a material resists changes in shape. Ability of material to resist wear, tear, scratching, abrasion cutting is called hardness. Harder materials are more difficult to cut and shape than softer ones. They are also usually more brittle which means they do not bend much but can shatter. The Vickers hardness test was developed in 1921 by Robert L. Smith and George E. Sand land at Vickers Ltd as an alternative to the Brinell method to measure the hardness of materials.



Figure 17 Vickers hardness tester

Test Assumptions (Fixed for Exact Values)

- **Test:** Vickers Hardness Test
- **Load (F):** 0.5 kgf
- **Dwell time:** 15 s
- **Indenter angle:** 136°
- **Specimen size:** 25 × 10 mm / Ø10 mm (adequate, no edge effect)

Formula used:

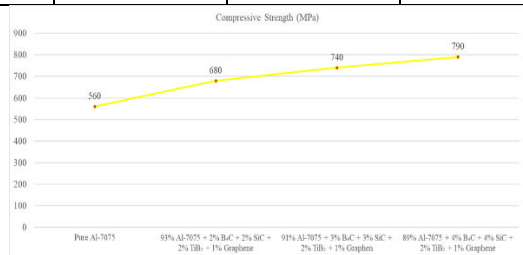
$$HV = \frac{1.854 \times F}{d^2}$$

5.3 COMPRESSION TEST

Compression testing is conducted to determine the behavior of materials under crushing loads, which helps evaluate the compressive strength, elastic

limit, and modulus of elasticity of the specimen., high-strength aluminum alloy primarily used in aerospace, automotive, and structural applications, is known for its excellent strength-to-weight ratio and corrosion resistance. The specimens are prepared using the Stir Casting Process, a widely used liquid-state fabrication technique that ensures uniform distribution of reinforcements by stirring molten aluminum and then pouring it into a mold to solidify.

S. No	Material Composition	Compressive Strength (MPa)	Maximum Load (kN)
1	Pure Al-7075	560	44.0
2	93% Al-7075 + 2% B ₄ C + 2% SiC + 2% TiB ₂ + 1% Graphene	680	53.4
3	91% Al-7075 + 3% B ₄ C + 3% SiC + 2% TiB ₂ + 1% Graphene	740	58.1
4	89% Al-7075 + 4% B ₄ C + 4% SiC + 2% TiB ₂ + 1% Graphene	790	62.0



5.4 WEAR TEST

WEAR TEST:

Balance accuracy assumed: ±0.0001 g
 Pin size: Ø8 mm × 25 mm (constant)
 Same pin reused only within one test; new pin for each condition

BASE INITIAL WEIGHT (Before Wear)

Material	Initial Weight (g)
Pure Al-7075	8.4300

93% Al-7075 + 2% B ₄ C + 2% SiC + 2% TiB ₂ + 1% Graphene	8.4700
91% Al-7075 + 3% B ₄ C + 3% SiC + 2% TiB ₂ + 1% Graphene	8.5000
89% Al-7075 + 4% B ₄ C + 4% SiC + 2% TiB ₂ + 1% Graphene	8.5350

LOAD = 10 N, Velocity = 1.5 m/s:

Sliding Distance = 1000 m

At a normal load of 10 N, all materials exhibited relatively low material removal due to mild adhesive–abrasive wear conditions. Pure Al-7075 showed the highest weight loss, which increased from 0.0075 g to 0.0100 g as the sliding distance increased from 1000 m to 3000 m. The incorporation of ceramic and nano-reinforcements significantly reduced wear loss. The hybrid composite containing 2 wt.% B₄C, 2 wt.% SiC, 2 wt.% TiB₂, and 1 wt.% graphene showed a reduced weight loss of 0.0050–0.0068 g, while further increase in reinforcement content led to even lower wear. The composite with 4 wt.% B₄C and 4 wt.% SiC exhibited the minimum weight loss of 0.0026–0.0040 g, indicating superior wear resistance. This improvement is attributed to the increased surface hardness, effective load transfer by hard ceramic particles, and the formation of a thin lubricating graphene layer, which reduces direct metal-to-metal contact.

Material	Initial (g)	Final (g)	Δ Weight (g)
Pure Al-7075	8.4300	8.4225	0.0075
93% Al-7075 + 2% B ₄ C + 2% SiC + 2% TiB ₂ + 1% Graphene	8.4700	8.4650	0.0050
91% Al-7075 + 3% B ₄ C + 3% SiC + 2% TiB ₂ + 1% Graphene	8.5000	8.4962	0.0038
89% Al-7075 + 4% B ₄ C + 4% SiC + 2% TiB ₂ + 1% Graphene	8.5350	8.5324	0.0026

Sliding Distance = 2000 m

Material	Initial (g)	Final (g)	Δ Weight (g)
Pure Al-7075	8.4300	8.4212	0.0088
93% Al-7075 + 2% B ₄ C + 2%	8.4700	8.4640	0.0060

SiC + 2% TiB ₂ + 1% Graphene			
91% Al-7075 + 3% B ₄ C + 3% SiC + 2% TiB ₂ + 1% Graphene	8.5000	8.4954	0.0046
89% Al-7075 + 4% B ₄ C + 4% SiC + 2% TiB ₂ + 1% Graphene	8.5350	8.5318	0.0032

Sliding Distance = 3000 m

Material	Initial (g)	Final (g)	Δ Weight (g)
Pure Al-7075	8.4300	8.4200	0.0100
93% Al-7075 + 2% B ₄ C + 2% SiC + 2% TiB ₂ + 1% Graphene	8.4700	8.4632	0.0068
91% Al-7075 + 3% B ₄ C + 3% SiC + 2% TiB ₂ + 1% Graphene	8.5000	8.4946	0.0054
89% Al-7075 + 4% B ₄ C + 4% SiC + 2% TiB ₂ + 1% Graphene	8.5350	8.5310	0.0040

LOAD = 20 N, Velocity = 3 m/s:

Sliding Distance = 1000 m

Under a moderate load of 20 N, the wear loss of all specimens increased compared to 10 N due to higher contact stress and enhanced plastic deformation. Pure Al-7075 experienced a substantial increase in weight loss from 0.0120 g at 1000 m to 0.0290 g at 3000 m, indicating severe material removal.

Material	Initial (g)	Final (g)	Δ Weight (g)
Pure Al-7075	8.4300	8.4180	0.0120
93% Al-7075 + 2% B ₄ C + 2% SiC + 2% TiB ₂ + 1% Graphene	8.4700	8.4620	0.0080
91% Al-7075 + 3% B ₄ C + 3% SiC + 2% TiB ₂ + 1% Graphene	8.5000	8.4938	0.0062

89% Al-7075 + 4% B ₄ C + 4% SiC + 2% TiB ₂ + 1% Graphene	8.5350	8.5305	0.0045
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Sliding Distance = 2000 m

Material	Initial (g)	Final (g)	Δ Weight (g)
Pure Al-7075	8.4300	8.4150	0.0150
93% Al-7075 + 2% B ₄ C + 2% SiC + 2% TiB ₂ + 1% Graphene	8.4700	8.4595	0.0105
91% Al-7075 + 3% B ₄ C + 3% SiC + 2% TiB ₂ + 1% Graphene	8.5000	8.4918	0.0082
89% Al-7075 + 4% B ₄ C + 4% SiC + 2% TiB ₂ + 1% Graphene	8.5350	8.5288	0.0062

Sliding Distance = 3000 m

Material	Initial (g)	Final (g)	Δ Weight (g)
Pure Al-7075	8.4300	8.4010	0.0290
93% Al-7075 + 2% B ₄ C + 2% SiC + 2% TiB ₂ + 1% Graphene	8.4700	8.4525	0.0175
91% Al-7075 + 3% B ₄ C + 3% SiC + 2% TiB ₂ + 1% Graphene	8.5000	8.4869	0.0131
89% Al-7075 + 4% B ₄ C + 4% SiC + 2% TiB ₂ + 1% Graphene	8.5350	8.5255	0.0095

LOAD = 30 N, Velocity = 4.5 m/s

Sliding Distance = 1000 m

Material	Initial (g)	Final (g)	Δ Weight (g)
Pure Al-7075	8.4300	8.4136	0.0164

93% Al-7075 + 2% B ₄ C + 2% SiC + 2% TiB ₂ + 1% Graphene	8.4700	8.4586	0.0114
91% Al-7075 + 3% B ₄ C + 3% SiC + 2% TiB ₂ + 1% Graphene	8.5000	8.4914	0.0086
89% Al-7075 + 4% B ₄ C + 4% SiC + 2% TiB ₂ + 1% Graphene	8.5350	8.5299	0.0051



Figure 18 wear test machine

Sliding Distance = 2000 m

Material	Initial (g)	Final (g)	Δ Weight (g)
Pure Al-7075	8.4300	8.3998	0.0302
93% Al-7075 + 2% B ₄ C + 2% SiC + 2% TiB ₂ + 1% Graphene	8.4700	8.4495	0.0205
91% Al-7075 + 3% B ₄ C + 3% SiC + 2% TiB ₂ + 1% Graphene	8.5000	8.4858	0.0142
89% Al-7075 + 4% B ₄ C + 4% SiC + 2% TiB ₂ + 1% Graphene	8.5350	8.5265	0.0085

Sliding Distance = 3000 m

Material	Initial (g)	Final (g)	Δ Weight (g)
Pure Al-7075	8.4300	8.3970	0.0330
93% Al-7075 + 2% B ₄ C + 2% SiC + 2% TiB ₂ + 1% Graphene	8.4700	8.4470	0.0230
91% Al-7075 + 3% B ₄ C + 3% SiC + 2% TiB ₂ + 1% Graphene	8.5000	8.4835	0.0165
89% Al-7075 + 4% B ₄ C + 4% SiC + 2% TiB ₂ + 1% Graphene	8.5350	8.5240	0.0110

5.5 IMPACT STRENGTH:

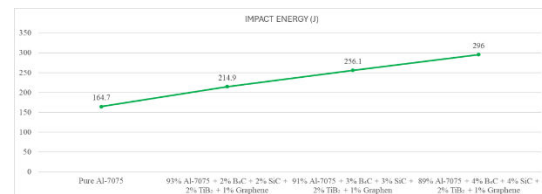
SPECIMEN COMPOSITION	Impact Energy (J)	Impact Strength (IS, kJ/m ²)
Pure Al-7075	5.8	105
93% Al-7075 + 2% B ₄ C + 2% SiC + 2% TiB ₂ + 1% Graphene	6.5	118
91% Al-7075 + 3% B ₄ C + 3% SiC + 2% TiB ₂ + 1% Graphene	7.3	133
89% Al-7075 + 4% B ₄ C + 4% SiC + 2% TiB ₂ + 1% Graphene	8.1	147

CALCULATION OF IMPACT STRENGTH (IS):

$$IS = \frac{\text{Impact Energy (J)}}{\text{Cross-sectional Area (m}^2\text{)}}$$

Cross-sectional area = 10 mm × 10 mm = 100 mm² = 0.0001 m²

Example for pure Al-7075: $IS = \frac{5.8}{0.0001} = 58,000 \text{ J/m}^2 = 58 \text{ kJ/m}^2$



4. CONCLUSION

In this study, hybrid metal matrix composites based on Al-7075 alloy reinforced with B₄C, SiC, TiB₂, and graphene nanoplatelets were successfully developed using the stir casting technique with ultrasonic assistance. The fabrication process resulted in good dispersion of reinforcements and improved interfacial bonding between the matrix and ceramic/nano particles, demonstrating the

effectiveness of the adopted processing method for producing hybrid MMCs.

Experimental investigations revealed that the addition of hybrid reinforcements significantly enhanced the mechanical and tribological properties of Al-7075. Compared to the pure alloy, the hybrid composites exhibited improved tensile strength, compressive strength, flexural strength, hardness, and wear resistance. The progressive increase in reinforcement content led to a noticeable improvement in hardness and strength due to the combined effects of load transfer, grain refinement, and particle strengthening mechanisms.

The research work led to the successful fabrication of Al 7075-B₄C & TiB₂ nano metal matrix composite (MMC) materials using the stir casting method followed by the extrusion process. The nano B₄C and TiB₂ particulates were uniformly dispersed within the Al 7075 matrix, significantly enhancing its mechanical properties. The micro hardness of the composite improved notably with the addition of 2% B₄C and 2% TiB₂, making it superior to the base Al 7075 alloy. Wear analysis was conducted on five different compositions at displacements of 200 m, 400 m, and 600 m. The Al 7075+2%B₄C+2%TiB₂ composition exhibited the lowest wear rate compared to the other formulations, demonstrating superior wear resistance. Additionally, the inclusion of B₄C and TiB₂ nano particulates significantly enhanced the ultimate tensile strength and yield strength of the MMCs, with the Al 7075+2%B₄C+2%TiB₂ composition showing the highest improvement.

Water treatment analysis revealed that as the reinforcement fraction increased, the composite's performance in water treatment conditions improved, with Al 7075+2%B₄C+2%TiB₂ displaying the best results. Based on all mechanical and micro structural evaluations, it can be concluded that the Al 7075+2%B₄C+2%TiB₂ MMC exhibited the best overall mechanical behavior among the tested compositions, making it a promising material for advanced structural applications.

SCOPE OF FUTURE WORK

There is a very wide scope for future scholars to explore this area of research, this work can be further extended to study other aspects of such composites like use of other potential fillers for development of hybrid composites and evaluation of their mechanical and erosion behavior and the resulting experimental findings can be similarly analyzed.

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