INVESTIGATION OF STRUCTURAL AND MECHANICAL BEHAVIOR OF AA6351/Gr/TiC/B_4C/WC HYBRID METAL MATRIX COMPOSITES

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by

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DECLARATION

I Shahazad Ali hereby declare that the work which is being presented in the thesis entitled **"Investigation of Structural and Mechanical Behavior of AA6351/Graphite/TiC/B_4C/WC Hybrid Metal Matrix Composites"** in partial fulfillment of the requirements for the award of the Degree of Doctor of Philosophy, submitted in the Department of Mechanical Engineering, Delhi Technological University is an authentic record of my own work carried out during the period from Aug 2018 to Dec 2024 under the supervision of Dr. Qasim Murtaza (Professor Mechanical Engg., DTU) and Dr. Pallav Gupta (Assistant Professor (Grade-III) Mechanical Engg., Amity University, UP, Noida).

The matter presented in this thesis has not been presented by me for the award of any degree of this or any other institute.

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CERTIFICATE

Certified that Shahazad Ali (Roll no. 2K18PhDME42) has carried out the research work presented in thesis **"Investigation of Structural and Mechanical Behavior of AA6351/Graphite/TiC/B_4C/WC Hybrid Metal Matrix Composites"** For the award of Doctor of Philosophy from Department of Mechanical Engineering, Delhi Technological University, Delhi, under our joint supervision. The thesis embodies results of original work, and studies are carried out by the student himself and the contents of the thesis do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University/Institution.

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ABSTRACT

Pure materials, despite their widespread use throughout history, have been constrained by deficiencies in strength, toughness, corrosion resistance, wear resistance and hardness. Hybrid metal matrix composites (HMMCs), a leap forward in overcoming the inherent limitations of pure materials These limitations have catalysed the evolution of composite materials, specifically MMCs, which combine the strengths of distinct materials to form an advanced, hybrid composite.

Hybrid MMCs are superior to pure materials due to their improved mechanical and wear properties. These composites amalgamate different elements, generating a balance of properties that far exceed those of their individual constituents. Metal Matrix Composites (MMCs) offer a unique blend of properties by incorporating high-performance reinforcements into a metallic matrix. To achieve this composite structure, various fabrication techniques exist, each with its own advantages and limitations. Powder metallurgy offers precise control over the reinforcement distribution but can be expensive and time-consuming. Friction stir processing utilizes friction heat to develop the composite, but its applicability is limited to specific shapes. In-situ processing mix the reinforcement while melting the matrix, but often requires complex process control. Squeeze casting offers good density control but can be restricted in terms of part geometry.

This study specifically focuses on stir casting for the fabrication of MMCs due to its twin benefits of versatility and cost-effectiveness. Stir casting employs a mechanical stirrer to uniformly distribute reinforcement particles within the molten metal matrix. This relative simplicity translates to lower production costs compared to other techniques. Moreover, stir casting allows for the incorporation of a wider range of reinforcement types and volume fractions, making it highly adaptable for the creation of MMCs with diverse properties. By achieving a good balance between quality and affordability, stir casting becomes a favourable choice for a wide array of MMC production applications.

To get the enhanced mechanical and wear characteristics, four reinforcements: Graphite (Gr), Boron Carbide (B_4C), Titanium Carbide (TiC), and Tungsten Carbide (WC) were selected. Four sets of hybrid MMCs were fabricated: AA6351/Gr/B_4C, AA6351/Gr/TiC, AA6351/Gr/WC, and AA6351/B_4C/TiC/WC. The proportion of each reinforcement varied equally from 0.5 to 2.0 wt% in each set. Samples were prepared through stir casting process followed by basic machining processes.

The composites that were produced went through a thorough characterization and testing process. The microstructure of the composites was examined using scanning electron microscopy (SEM) and optical microscopy to determine the distribution and bonding of the reinforcing phases within the metallic matrix. This analysis helped evaluate the effectiveness of the stir casting process. The mechanical properties of the composites were assessed through hardness testing, impact testing, tensile testing, and wear testing. These tests provided information on the composites' resistance to indentation, toughness, strength, deformation behavior, and wear resistance. A comparative analysis was also performed to understand how different reinforcing phases influenced the mechanical properties of the composites. By examining the

hardness values, impact strength, tensile properties, and wear resistance of the different configurations, insights were gained into the performance of the composites. Finally developed composites were raked using TOPSIS method.

Through comprehensive characterization, it was observed that the developed hybrid MMCs exhibited superior mechanical and wear properties compared to pure materials.

In set 1, The lowest density, 2.62 g/cc, was found in the sample AlGrB05 having 2 wt% each of Gr and B_4C. The hardness of hybrid metal matrix composite having 1 wt% Gr and 1 wt% B_4C recorded the highest of 82. Sample AlGrB03 has the highest impact strength of 32 Joules. Sample AlGrB03 shows the highest engineering ultimate tensile strength and true ultimate tensile strength as 134.3 MPa and 167.0 MPa in comparison to other samples.

In set 2, Due to the presence of graphite and porosity in the fabricated samples, the density of the aluminium metal matrix decreased. The samples with a reinforcement proportion of 2.0 wt% graphite and 2.0 wt% TiC exhibited the lowest density of 2.61 gram/cc. The maximum levels of hardness, impact strength, engineering ultimate tensile strength, and true ultimate tensile strength were observed at a weight percentage of 1.0 wt% for both Gr and TiC, with values of 85 HRC, 33 Joule, 206.7 N/mm^2, and 260.43 N/mm^2 respectively.

In set 3, incorporating graphite and tungsten carbide into the composite led to enhancements in both microstructure and mechanical properties. The lowest density was observed with 0.5 wt% Gr and 0.5 wt% WC as 2.73 g/cc. A uniform dispersion of reinforcement particles was observed. The sample reinforced with 1 wt% Gr and 1 wt% TiC demonstrated the highest tensile strength and hardness as 199.2 N/mm^2 and 76 HRC, respectively. On the other hand, the composite that contained 0.5 wt% graphite and 0.5 wt% tungsten carbide of both reinforcements exhibited the best toughness as 28 joules, among all the samples that were produced.

In set 4, lowest density was recorded with 0.5% of each reinforcement while in the hybrid metal matrix composite composed of 1.5 wt.% B_4C, 1.5 wt.% TiC, and 1.5 wt.% WC, the highest tensile strength of 140.7 MPa, and hardness of 76 HRC are observed.

Conversely, the hybrid metal matrix composite with 0.5 wt.% of each reinforcement exhibits the maximum toughness of 28 Joules. These research findings offer valuable insights for the design and development of high-performance metal matrix composites with potential applications in industries such as aerospace, automotive, and manufacturing. In TOPSIS test AlGrT03 ranked 1 due to its excellent mechanical characteristics.

The tribological characteristics of hybrid Metal Matrix Composites reinforced with Gr and TiC surpass others, attributed to the effective bonding between the reinforcement and the AA6351 matrix. The wear rate ranged from 0.007621 mm^3/m for Al6351 to 0.00592 mm^3/m for AlGrT03, showing the lowest wear. Additionally, the coefficient of friction increased with higher loads, with AlGrT03 exhibiting the lowest friction at 40 N, measured at 0.374286. Microphotographs revealed the least debris and plowing among the samples tested.

Based on the findings, potential applications for the developed composites include automotive brake rotors and pistons, high-speed cutting tools and dies, aerospace components such as engine parts and landing gear, and defence applications requiring armour and ballistic-resistant materials. These composites offer superior mechanical and wear characteristics, making them suitable for demanding environments that demand exceptional performance. The use of a low proportion of reinforcement, which has shown favourable results, further enhances the cost-effectiveness and viability of these composites in various industries.

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LIST OF SYMBOLS, ABBREVIATIONS AND NOMENCLATUREN

AHMMCs	Aluminum Hybrid Metal Matrix Composites
AMCs	Aluminum Matrix Composites
AMMCs	Aluminum Metal Matrix Composites
ANN	Artificial Neural Network
ASTM	American Society for Testing and Materials
BHN	Brinell Hardness Number
CNC	Computerized Numerical Control
COF	Coefficient of Friction
CTE	Coefficient of Thermal Expansion
EBSD	Electron Backscatter Diffraction
EDS	Energy Dispersive X-Ray Spectroscopy
FSP	Friction Stir Processing
FSW	Friction Stir Welding
GA	Genetic Algorithm
HMMC	Hybrid Metal Matrix Composite
HMMCs	Hybrid Metal Matrix Composites
MMC	Metal Matrix Composite
MMCs	Metal Matrix Composites
P/M	Powder Metallurgy
PMCs	Polymer Matrix Composites
SEM	Scanning Electron Microscopy
TEM	Transmission Electron Microscopy
UTS	Ultimate Tensile Stress
VMC	Vertical Milling Center
XRD	X-Ray Diffraction

Chapter 1: Introduction

Aluminum, denoted by the letter Al in the periodic table, is a common, lightweight metal with a wide range of applications because of its unique combination of qualities. With its low density and remarkable strength-to-weight ratio, aluminum is renowned for its exceptional strength and excellent resistance to corrosion. It also showcases excellent thermal and electrical conductivity, rendering it a highly sought-after material in diverse applications, including aerospace, automotive, construction, and packaging. The versatility and advantageous attributes of aluminum have resulted in its extensive utilization in engineering and manufacturing, where its distinct properties enable the creation of innovative and efficient products. This thesis focuses on the exploration of a specific aluminum alloy, AA6351, as well as its hybrid metal matrix composites. The objective is to investigate their structural and mechanical characteristics, unveiling their potential to augment material performance across a wide spectrum of applications.

Pure aluminum presents numerous advantages, positioning it as a favoured choice across diverse industries. A central advantage lies in its inherent lightweight attribute. With a density significantly lower than that of steel, aluminum weighs approximately one-third as much, making it particularly appealing in contexts where weight reduction holds paramount importance, such as aerospace and automotive sectors. The lightweight quality of aluminum facilitates the creation of structures and products that are inherently lightweight, thereby enhancing fuel efficiency and overall performance.

Another notable merit of pure aluminum rests in its exceptional resistance to corrosion. When exposed to air, aluminum naturally generates a thin oxide layer on its surface, acting as a protective barrier against corrosive elements. This inherent trait confers high resilience to atmospheric and chemical-induced corrosion, a particularly valuable feature when the material encounters moisture or aggressive substances. Pure aluminum's corrosion resistance diminishes the necessity for supplementary coatings or safeguarding measures, ultimately reducing upkeep costs and prolonging product longevity.

Furthermore, pure aluminum boasts commendable thermal and electrical conductivity. It serves as an efficient conductor of both heat and electricity, facilitating efficient heat dissipation and the seamless transmission of electrical currents. These attributes render aluminum fitting for applications including heat exchangers, electrical conductors, and various electronic components.

The repertoire of physical, mechanical, and thermal properties exhibited by aluminum underscores its adaptability and widespread utility in diverse sectors. This overview delves into the pivotal properties of Aluminum, encompassing its physical attributes. With a density of around 2.7 g/cm^3, Aluminum emerges as a lightweight contender among metals, facilitating various applications. Its relatively low melting point of approximately 660°C (1220°F) accelerates casting and processing endeavors. Sporting a silver-white appearance with a metallic luster, aluminum exudes a distinctive visual appeal. Noteworthy for its remarkable ductility, Aluminum can be easily shaped into diverse forms without significant cracking or fracturing. Additionally, its exceptional electrical conductivity, ranking at approximately two-thirds of copper's conductivity, makes it suitable for a wide range of applications, including electrical.

Despite its myriad advantages, it is important to acknowledge that pure aluminum does have certain limitations that warrant attention. A prominent drawback is its relatively modest strength compared to robust structural materials like steel. Specifically, pure aluminum manifests lower tensile strength, which can pose restrictions in applications demanding high load-bearing capabilities or situations necessitating unwavering structural integrity under substantial loads.

Nevertheless, it is important to note that these limitations can be effectively mitigated through diverse strategies. One prevalent approach involves alloying, wherein specific elements are introduced to pure aluminum to bolster its mechanical attributes. Alloying imparts improved strength and overall performance to aluminum, rendering it more adaptable to a broader array of applications spanning various industries.

An equally effective tactic to counteract pure aluminum's lower strength entails integrating it within composite structures. By amalgamating aluminum with alternative materials like reinforcement particles or fibers, hybrid metal matrix composites can be developed. These composites can exhibit elevated mechanical properties, including augmented tensile strength and stiffness, rendering them ideal contenders for demanding engineering applications.

Furthermore, pure aluminum's comparatively lower melting point could limit its applicability in high-temperature-resistant applications. However, this drawback can be remedied by employing aluminum alloys characterized by enhanced thermal stability and higher melting points.

Aluminum alloys are extensively employed across various industries to overcome the limitations of pure aluminum. These alloys offer an advantageous blend of attributes, including lightness, robust strength, corrosion resistance, and malleability. To tailor these alloys for specific applications, they are classified into distinct series, each distinguished by its own set of characteristics. These series align with different industries, catering to their respective key needs.

Series 1xxx: Pure Aluminum: The 1xxx series encompasses pure aluminum containing a minimum of 99% aluminum content. These alloys display remarkable corrosion resistance and high electrical conductivity. They find common usage in electrical applications like power transmission lines, electrical conductors, and heat exchange systems.

Series 2xxx: Copper Alloyed Alloys: In the 2xxx series, copper emerges as the chief alloying element. These alloys showcase heightened strength and exceptional resistance to fatigue. They carve a niche in the aerospace sector for structural components, aircraft wings, and fuselage structures.

Series 3xxx: Manganese Alloyed Alloys: Manganese is the primary alloying element in the 3xxx series. These alloys present moderate strength, commendable formability, and impressive corrosion resistance. Their wide application is observed in the construction domain, encompassing architectural structures, roofing, and siding.

Series 4xxx: Silicon Alloyed Alloys: The 4xxx series introduces silicon as the primary alloying element. These alloys demonstrate fluidity during casting procedures and excel in weldability. They serve industries like automotive manufacturing, marine equipment, and heat exchange systems.

Series 5xxx: Magnesium Alloyed Alloys: Magnesium is the dominant alloying element in the 5xxx series. These alloys offer a spectrum of strength from moderate to high, coupled with favourable formability and exceptional resistance to corrosion. The automotive sector embraces them for body panels, chassis components, and wheels.

Series 6xxx: Magnesium and Silicon Alloyed Alloys: The 6xxx series amalgamates magnesium and silicon as primary alloying components. These alloys exhibit formability, weldability, and moderate strength. They find a niche in construction, contributing to structural elements, architectural extrusions, and window frames.

Series 7xxx: Zinc Alloyed Alloys: The 7xxx series infuses zinc as the central alloying element. These alloys deliver an amalgam of robust strength, resilience, and admirable fatigue resistance. Aerospace applications, including aircraft wings, structural components, and high-performance sports equipment, are the natural domains for these alloys.

Series 8xxx: Alloys Altered by Various Elements: The 8xxx series enlists aluminum alloys endowed with a range of alloying elements like lithium, tin, and others. These alloys find their calling in aerospace and defence spheres, capitalizing on their potent strength, lightweight profile, and stellar performance at elevated temperatures.

Each aluminum alloy series possesses distinct attributes that render them fit for specific applications. Grasping the unique characteristics and applications of these series empowers engineers and manufacturers to opt for the most suitable alloy for their intended purposes. This informed selection ensures optimum performance and cost-effectiveness. The versatility of aluminum alloys, spanning technology, transportation, construction, and beyond, underscores their pervasive influence and contribution across diverse industries.

1.1 METAL MATRIX COMPOSITES

Metal matrix composites (MMCs) represent an innovative category of materials that integrate the merits of metallic matrices with the fortification of ceramic or metallic elements. These composites showcase an exceptional fusion of attributes that outperform traditional single-material structures, thus rendering them exceedingly appealing across a diverse spectrum of applications. Within MMCs, the metallic matrix contributes to strength, ductility, and toughness, while the reinforcements augment distinct traits such as rigidity, resistance to wear, thermal and electrical conductivity. By meticulously selecting the reinforcing constituents and strategically distributing them within the metallic matrix, the properties of MMCs can be meticulously tailored to align with specific engineering prerequisites. The remarkable versatility of MMCs has steered them into the limelight of sectors like aerospace, automotive, defence, and electronics, where their elevated performance levels and distinct characteristics confer a multitude of benefits.

1.2 HYBRID METAL MATRIX COMPOSITE

Hybrid metal matrix composites (HMMCs) represent a specialized subset of MMCs, incorporating multiple distinct reinforcing phases within a metallic matrix. This integration of diverse reinforcements within HMMCs leads to a collective enhancement of properties, transcending the advantages offered by individual reinforcement types. The careful selection and amalgamation of these reinforcements assume critical importance, as they dictate the composite's equilibrium among properties like strength, ductility, wear resistance, and thermal stability. The realm of possibilities HMMCs offer in terms of design is extensive, providing engineers and material scientists the capability to finely tune composites for precise applications through judicious reinforcement combinations. The surging interest in HMMCs emanates from their potential to surmount traditional material limitations, offering novel avenues for industries seeking high-performance materials imbued with multifunctional traits.

The genesis and application of HMMCs stem from the imperative to contend with conventional materials' constraints and meet the escalating demands of contemporary engineering needs. Monolithic materials possess inherent merits, but they often exhibit shortcomings in facets such as strength, wear resistance, thermal stability, or weight. HMMCs present an ingenious remedy by amalgamating the merits of distinct reinforcing phases, intent on obviating these constraints and augmenting the overall composite performance.

HMMCs can deliver an enviable strength-to-weight ratio, underpinning the creation of lightweight aircraft structures. In the automotive realm, the infusion of wear-resistant reinforcements in HMMCs extends the lifecycle of components subject to harsh operational conditions. Likewise, the electronic sector can benefit from HMMCs, offering heightened thermal management capabilities and enhanced electrical conductivity. The orchestration of specific reinforcement combinations in HMMCs facilitates the attainment of targeted traits, catalysing the emergence of advanced materials tailored to the nuanced requisites of varied industries.

Delving into the study and comprehension of HMMCs assumes paramount importance to unlock their full potential and broaden their pragmatic application horizons. Research endeavours in this domain strive to decipher the microstructure, mechanical dynamics, and operational performance of HMMCs, ushering valuable insights into material design, processing techniques, and optimization strategies. By catering to the clamour for high-performance materials endowed with bespoke properties, HMMCs are poised to spark innovation and catalyse advancements across numerous domains, thereby fostering the creation of more effective, robust, and sustainable engineering solutions.

1.3 CLASSIFICATION OF METAL MATRIX COMPOSITES

Metal Matrix Composites (MMCs) encompass a wide range of materials that can be classified according to several crucial criteria, such as the specific type of reinforcement employed, the manner in which the reinforcement is structured, and the particular matrix material chose.

1.3.1 Categorization Based on Type of Reinforcement

Figure 1.2 and 1.3 shows the different types of reinforcement used for developing the metal matrix composite. Which are as follows:

Particulate MMCs: Within this class of composites, small particles, often ceramics or carbides, are strategically dispersed within the matrix material. The presence of these finely distributed particles serves to enhance specific material properties.

Fiber MMCs: In fiber-reinforced composites, continuous or discontinuous fibers, such as metallic fibers, carbon fibers, or glass fibers, are embedded into the matrix material. These fibers contribute significantly to the overall material strength and durability.

Whisker MMCs: Whisker composites introduce whisker-shaped reinforcements, which can either be single crystal or polycrystalline in nature. These whiskers are integrated within the matrix to provide targeted enhancements to specific properties.

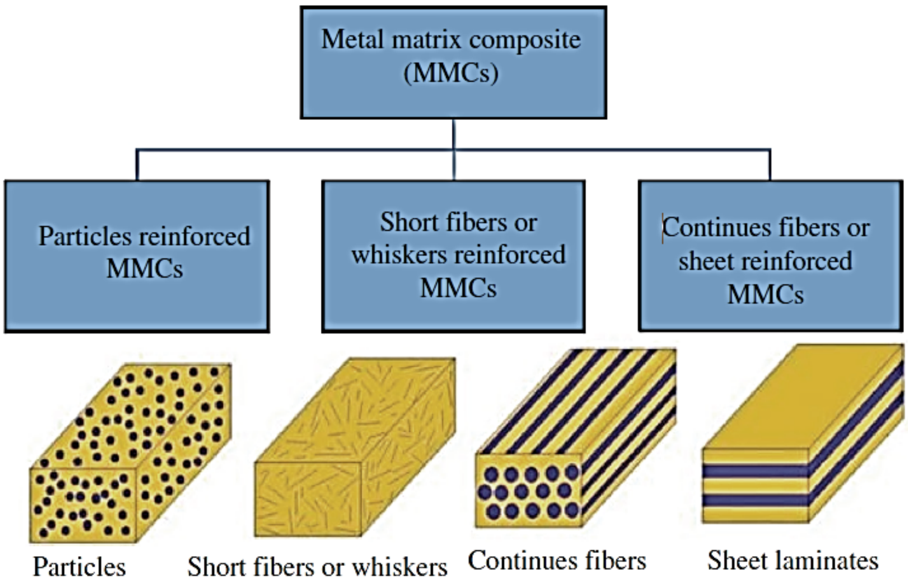

Figure 1:1 Types of MMC Composites [1]

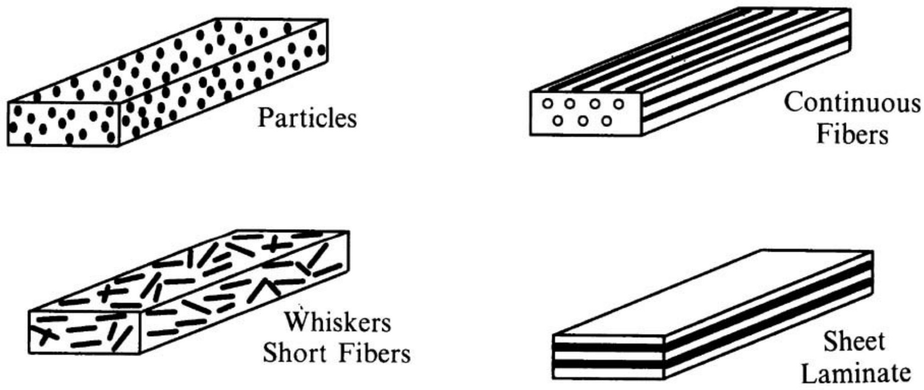

Figure 1:2 Types of Reinforcement [2]

1.3.2 Categorization Based on Form of Reinforcement

Continuous Reinforcement MMCs: This subset of composites leverages continuous fibers or reinforcements that span the entire length of the composite. This configuration imparts exceptional strength and stiffness, making these composites suitable for applications demanding structural integrity.

Discontinuous Reinforcement MMCs: Also known as short fiber composites, this category features shorter fibers or reinforcements that are either randomly or uniformly dispersed within the matrix material. Despite the discontinuity, these reinforcements enhance certain material attributes.

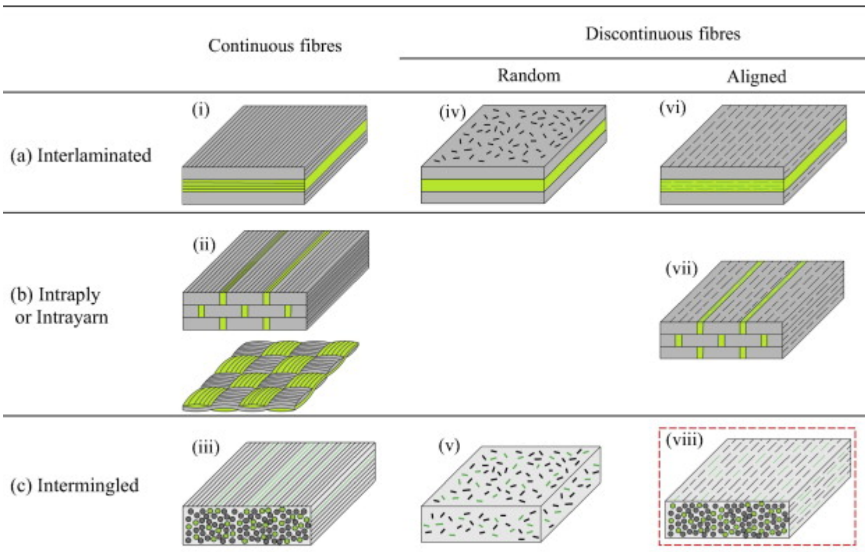

Figure 1:3 Continuous and Discontinuous Fibers[2]

1.3.3 Categorization Based on Matrix Material

Based on Matrix material, composites are classified as:

Aluminum Matrix Composites (AMCs) are composites that utilize aluminum as the primary matrix material and can incorporate a diverse range of reinforcements, such as ceramics, carbides, or fibers. AMCs are widely utilized across various industries due to their improved properties and performance.

Magnesium Matrix Composites (MMCs): In MMCCs, magnesium serves as the matrix material, which can be augmented with reinforcements such as ceramics, carbon fibers, or metallic particles. The resulting composites showcase a blend of desirable attributes.

Titanium Matrix Composites (TMCs): TMCs utilize titanium as the core matrix material and integrate reinforcements like ceramics or carbon fibers. The combination of titanium's inherent properties with the reinforcement results in composites tailored for specific applications.

Nickel Matrix Composites (NMCs): NMCs capitalize on nickel as the matrix material and can integrate reinforcements like ceramics, carbides, or metallic particles. The synergistic effects between nickel and the reinforcements make these composites valuable for certain scenarios.

1.3.2 Categorization Based on Number of Reinforcement

HMMCs contains more than one reinforcement, such as particles, fibers, or whiskers, within a metallic matrix. The hallmark of HMMCs lies in their ability to harness the collective strengths of multiple reinforcement types, resulting in tailored and multi-faceted material properties. The judicious selection of these reinforcing materials empowers engineers and materials scientists to design composites that cater precisely to the requirements of specific applications.

1.4 FABRICATION TECHNIQUES OF HYBRID METAL MATRIX COMPOSITES

Creating Hybrid Metal Matrix Composites (HMMCs) involves intricate processes that integrate multiple reinforcement phases into a metallic matrix. This section explores various fabrication techniques employed to craft these advanced materials, unveiling the ingenuity behind their production.

1.4.1 Stir Casting:

Among the array of methods for developing HMMCs, liquid metallurgy route has emerged as a prominent and widely adopted approach. This technique entails a meticulous process of blending molten metal with reinforcement phases, ultimately yielding an identical dispersal within the metal matrix. The process begins with the matrix material melting, and then selected reinforcements are progressively added. This stage involves the application of mechanical stirring, a pivotal step that ensures comprehensive mixing and the even dispersal of reinforcements. Subsequently, the amalgamated mixture is allowed to solidify, giving rise to the final composite structure. Figure 1.4 shows stir casting setup.

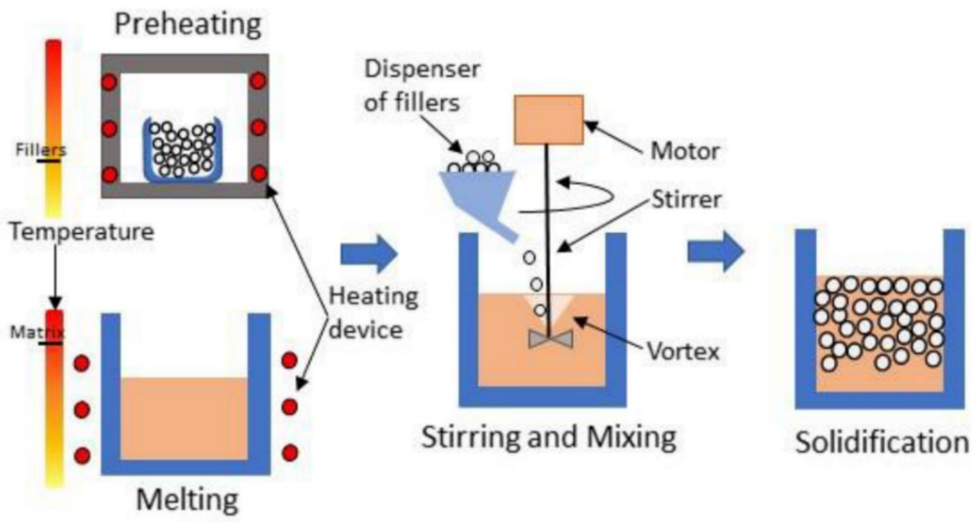

Figure 1:4 Stir casting Process [3]**.**

Stir casting demonstrates a remarkable versatility in terms of the types and concentrations of reinforcements it can accommodate. It proves especially well-suited for producing HMMCs infused with particulate, fiber, or whisker reinforcements. Mechanical stirring is an essential step that plays a critical role in breaking apart agglomerates, ensuring that reinforcements are uniformly distributed throughout the matrix. This process is crucial for achieving a homogenous composite material. Beyond its basic function, this technique provides the advantage of regulating parameters like stirring speed, duration, and pouring temperature. Such precision enables the meticulous customization of the composite's microstructure and mechanical properties to meet specific engineering demands.

1.4.2 Diffusion Bonding Process

The diffusion bonding process constitutes a fundamental method cantered around the fusion of ceramic reinforcement with a metallic matrix. This intricate procedure involves the precise application of elevated pressure and temperature to establish a robust connection between the matrix and ceramic constituents. The schematic representation of the diffusion bonding process is provided in Figure 1.5.

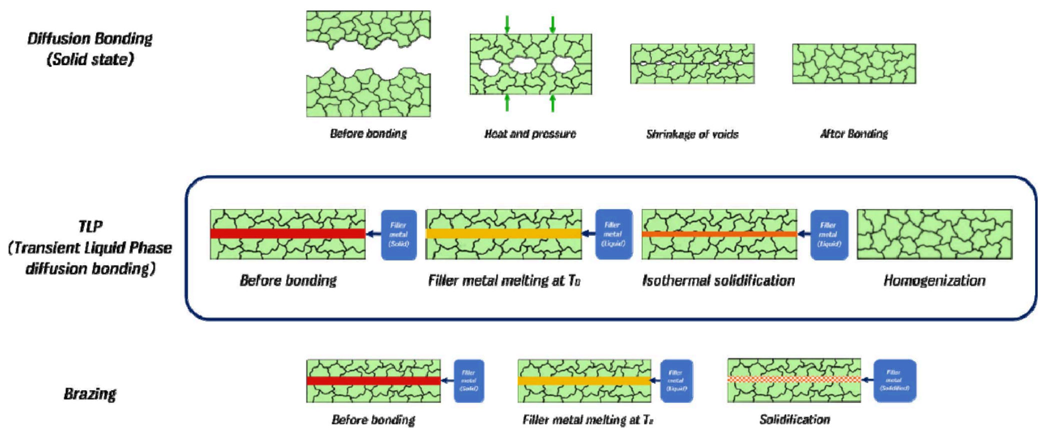

Figure 1:5 Diffusion Bonding [4]

A variant of diffusion bonding known as the Foil-Fiber-Foil approach introduces a distinctive strategy. In this approach, a sequence of alternating layers, comprising fiber reinforcement and matrix material, is stacked together and subsequently bonded. Figure 1.6 shows the bonding transpires through a two-stage sintering sequence:

a) The matrix laminates undergo plastic flow, leading to the creation of a consolidated structure.

b) Mechanisms operate to bond the ceramic fibers with the matrix at the interface.

The outcome of this technique manifests in composite materials characterized by augmented tensile and compressive strength. Nonetheless, a limitation associated with this method is its demand for exceptionally high compaction loads and temperatures, presenting economic challenges [2].

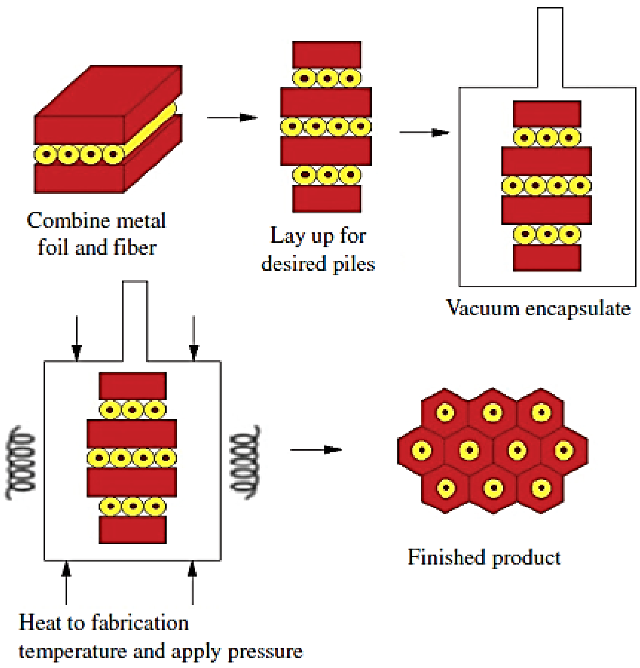

Figure 1:6 Diffusion Bonding Manufacturing Process [1]

1.4.3 Powder Metallurgy

The process of crafting specimens through the Powder Metallurgy (PM) technique encompasses a meticulously orchestrated sequence of steps designed to achieve the intended composition and effective consolidation of metal matrix composites (MMCs). These procedural stages are pivotal in securing a uniform dispersion of the reinforcement phases, ultimately yielding a final product boasting the desired attributes.

The PM process commences with the precise measurement of metal and ceramic powders in accordance with the specified composition. The ratios of these powders are meticulously calculated to attain the targeted properties within the resultant MMC. Employing accurate measurement practices ensures both constancy and repeatability across the fabrication process.

Following this, the amalgamation of metal, ceramic powder, and binder undergoes ball milling, a mechanical milling operation serving two pivotal purposes. Foremost, it ensures the equitable distribution of reinforcement particles throughout the metallic matrix. Additionally, it comminutes the powder particles, amplifying their reactivity and facilitating a more thorough amalgamation of the components.

The binder assumes a critical role in the PM process, introduced to the powder amalgam during ball milling to temporarily bolster binding strength. This aspect contributes to sustaining the form and structural integrity of the green compact during ensuing processing phases.

Subsequent to ball milling, the powder composite is meticulously compacted within a die utilizing hydraulic press technology. The exerted pressure solidifies the powders into a green body, characterized by a secure yet partially bound compact structure. The hydraulic press affords precise control over the compaction endeavour, thus ensuring uniform density and exact dimensions of the green body.

The green compact then proceeds to undergo sintering within an atmosphere-controlled furnace. Sintering, a thermal treatment process, raises the green body's temperature, remaining below the matrix material's melting point. Throughout sintering, a fusion of diffusion and solid-state reactions culminates in powders bonding together, resulting in densification and heightened mechanical properties. This sintering process eradicates porosity and encourages grain growth, contributing to the MMC's augmented mechanical resilience and refined microstructure.

In certain scenarios, post-sintering secondary processes, such as stamping, rolling, or extrusion, can be introduced to amplify MMC properties. These additional procedures work towards eliminating any residual porosity, enhancing dimensional accuracy, and inducing plastic deformation to heighten interfacial adherence between the matrix and reinforcement phases. Such secondary processes are commonly harnessed to fine-tune the microstructure and augment the mechanical prowess of the fabricated MMC. The schematic diagram of the Powder Metallurgy (PM) process, illustrating the sequential stages involved in the fabrication of metal matrix composites, can be found in Figure 1.7. This diagram outlines the essential steps intrinsic to the production of these composites.

The characteristics of metal matrix composites (MMCs) produced using powder metallurgy are affected by a variety of factors. The proportion of reinforcement plays a key role in determining the mechanical and physical properties of the MMC. Specifically, the volume fraction of reinforcement particles has a significant impact on attributes like strength, rigidity, and resistance to wear.

The phase and microstructure of the MMC exhibit significant reliance on the processing parameters and the regimen of heat treatment. Variables encompassing sintering temperature, rates of heating and cooling, profoundly dictate the evolution of phases, the size of grains, and the volumetric distribution of reinforcing particles within the matrix. Vigilant manipulation of these parameters emerges as a prerequisite, ensuring the realization of the targeted microstructure and the ensuing properties inherent to the MMC.

The alignment and bonding between the reinforcement particles and the matrix play a crucial role in determining the overall performance of the metal matrix composite. Strong interfacial bonding ensures effective transfer of loads between the matrix and reinforcements, resulting in improved mechanical properties and overall enhancement of the composite's performance. Microwave sintering is also considered as emerging technology for developing aluminium based metal matrix [6].

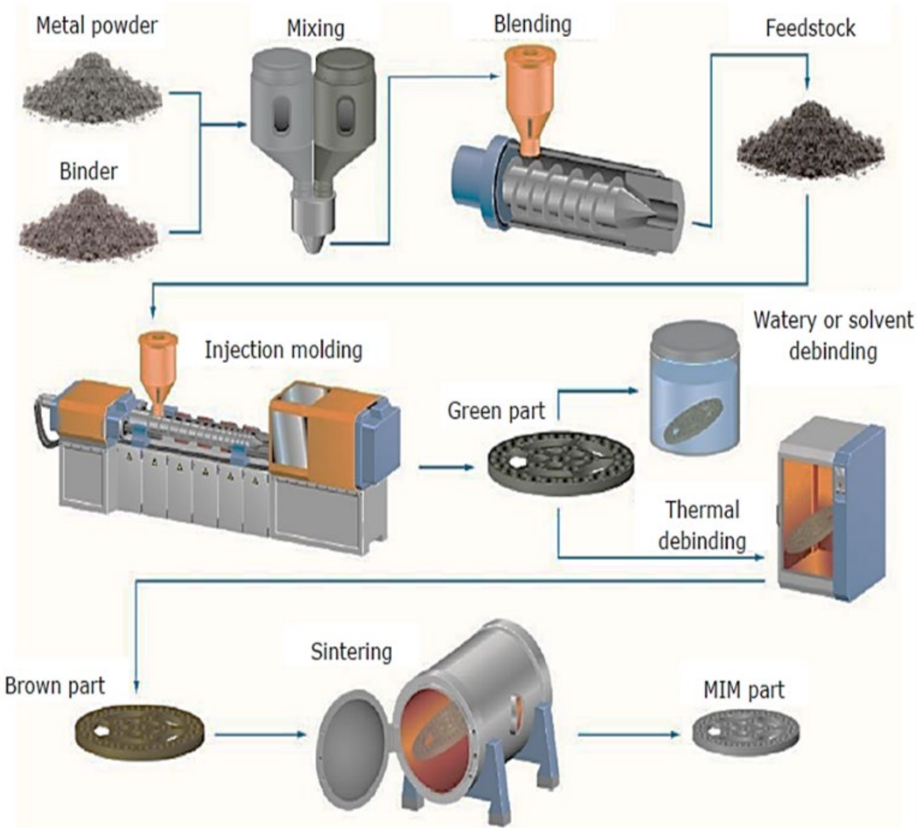

Figure 1:7 Schematic Diagram for Powder Metallurgy [5]

1.4.4 Pressure Infiltration Process

This innovative technique has received considerable attention because of its exceptional capability to create complex and well-defined composite structures. The process involves using pressurized inert gases, such as argon or nitrogen, to facilitate the infiltration of liquid metal into a preform made of reinforcement materials.

The pressure infiltration process serves as an effective means of producing near-net-shape components and prototypes. Its utilization is particularly advantageous when intricate shapes or complex geometries are required, as it enables the creation of precise and intricate composite structures with minimal need for further machining or finishing.

In the pressure infiltration process, an enclosed die chamber is used to house the composite assembly. The die chamber is equipped with a sophisticated pressurization system which permit precise control over the gas pressure. This pressurization forces the liquid metal to permeate the reinforcement particles thoroughly, ensuring a even distribution of the metal within the preform.

The pressure infiltration technique offers a significant advantage in achieving high levels of consolidation and density in the final composite product. By applying pressure, voids and air pockets are effectively eliminated, leading to a composite material that exhibits improved mechanical properties and enhanced structural integrity.

The Pressure Infiltration manufacturing process involves several crucial steps, including the preparation of the reinforcement preform, assembly within the die chamber, and pressurization with inert gas. The pressurization level, along with factors like temperature and dwell time, is carefully controlled to achieve optimal infiltration and consolidation of the composite.

Figure 1.8 sows Pressure Infiltration process, highlighting the key components and stages involved. This technique offers a promising avenue for producing advanced composites with intricate shapes and superior mechanical properties, making it a valuable asset in modern manufacturing and engineering applications.

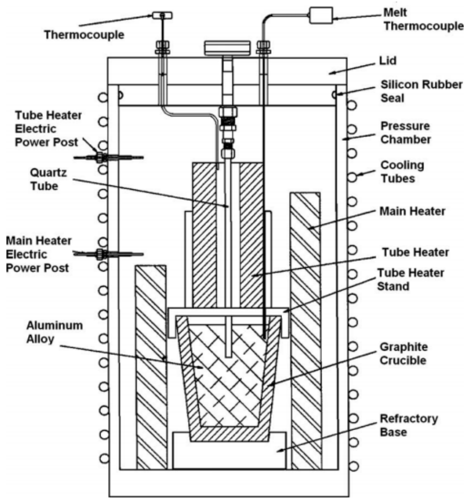

Figure 1:8 Pressure Infiltration Manufacturing Process [7]

1.5 SQUEEZE CASTING

Squeeze casting is an advanced manufacturing technique characterized by the pouring of molten metal into a pre-heated die, accompanied by the simultaneous application of forging pressure during the solidification phase. This innovative process integrates casting and forging, resulting in a composite material that bears similarities to a plastically deformed sample. This phenomenon arises due to the minimal porosity present in the material, achieved through the dynamic forging during solidification.

The initiation of the forging load coincides with the commencement of the solidification process and persists until the complete solidification of the molten metal.

This synchronized action is illustrated in Figure 1.9, providing a visual representation of the squeeze casting process. The outcome of this technique is a composite material with exceptional mechanical properties akin to those obtained through plastic deformation.

Squeeze casting is particularly advantageous for the fabrication of composites featuring discontinuous reinforcement. This technique has found application across various industries due to its fully automated nature, which eliminates the necessity for labour-intensive post-machining operations. The remarkable feature of minimal porosity in squeeze cast materials contributes to the formation of a microstructure characterized by small and equiaxed recrystallized grains.

In essence, squeeze casting combines the principles of both casting and forging, resulting in a material that inherits the benefits of both processes. The dynamic forging during solidification contributes to the elimination of porosity, enhancing the structural integrity and mechanical properties of the composite. As a result, squeeze casting presents a compelling option for the efficient production of high-quality composite materials with improved microstructures and mechanical performance.

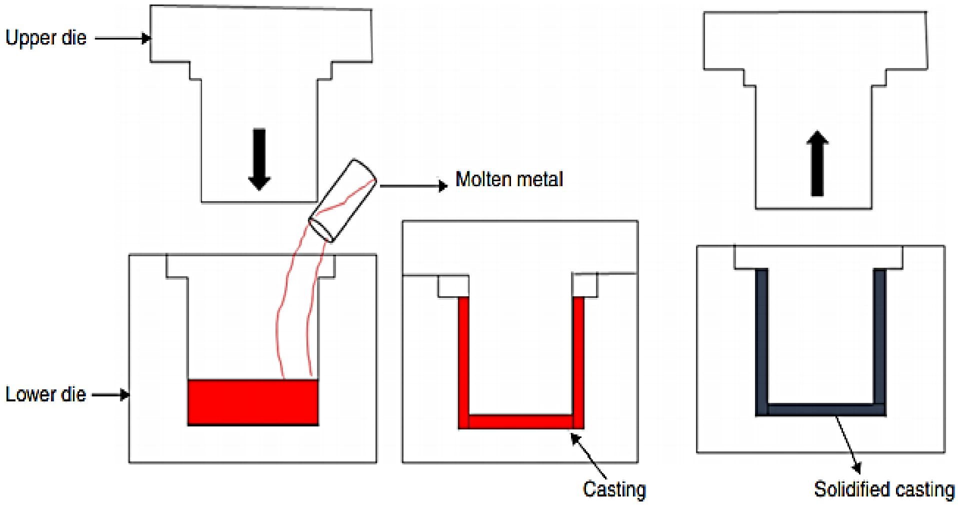

Figure 1:9 Squeeze Casting Manufacturing Process [8]

1.5.1 In-situ Synthesis

In addition to the traditional powder metallurgy process, an alternative method known as in-situ synthesis has emerged as a viable approach for producing metal matrix composites (MMCs). Instead of incorporating pre-made reinforcing materials, this technique involves the formation of reinforcement within the molten aluminum matrix during the fabrication process. This innovative method offers several advantages, notably enhancing the bond between the matrix materials and reinforcing particles. Figure 1.10 illustrates the in-situ process.

The in-situ synthesis method operates by initiating a chemical reaction between the aluminum matrix and a precursor material to generate the desired reinforcing phase within the composite structure. This precursor material is introduced in various forms such as powders or flakes. Notably, this chemical reaction takes place at elevated temperatures while the molten aluminum undergoes stirring or agitation. The deliberate stirring action is pivotal in achieving the uniform dispersion of the newly formed reinforcing materials within the matrix.

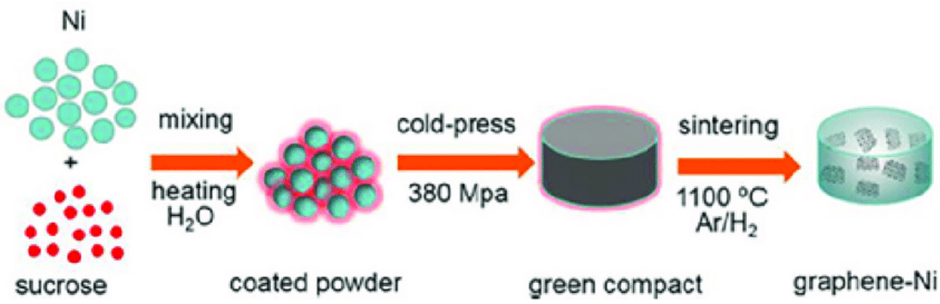

Figure 1:10 In-Situ Fabrication Process[9]

The in-situ synthesis technique stands out due to the strong bond formed between the matrix and the reinforcing materials. This robust bonding is achieved through a chemical reaction that occurs within the molten aluminum, resulting in reinforcing phases that are inherently and strongly linked to the matrix. This intrinsic bond greatly enhances the efficient transfer of loads between the matrix and the reinforcements, ultimately leading to improved mechanical properties and overall performance of the composite material.

Moreover, the in-situ synthesis method provides precise control over the configuration, size, and dispersal of the reinforcing particles. Through meticulous adjustment of chemical reaction parameters—such as precursor composition and reaction conditions—the attributes of the reinforcing particles can be precisely tailored to cater to specific requisites. This degree of control empowers the optimization of the composite's characteristics, encompassing factors like strength, stiffness, and thermal stability.

The versatility of the in-situ synthesis technique has been harnessed across various domains, including aerospace, automotive, and electronics, where the pursuit of high-performance materials characterized by tailored attributes is paramount. The capacity to produce MMCs featuring closely bonded reinforcing phases through the in-situ synthesis route ushers in novel opportunities for the evolution of advanced composites. These composites exhibit not only enhanced mechanical properties but also elevated thermal conductivity and augmented wear resistance—attributes poised to redefine the landscape of material performance.

1.5.2 Spark plasma sintering

Spark plasma sintering (SPS) emerges as an accelerated sintering process that dramatically curtails the time necessary to execute the procedure in contrast to the protracted durations associated with conventional sintering methods, which can extend over hours or even days. Figure 1.11 visually depicts the essential framework of the spark plasma sintering process.

The distinctive characteristic of SPS lies in its capacity to facilitate a remarkable sintering pace, rendering it a sought-after choice in the realm of composite production.

Notably, the inherent mechanism of internal heating in the specimen underpins the capability to effortlessly achieve elevated heating rates within the ambit of SPS [10].

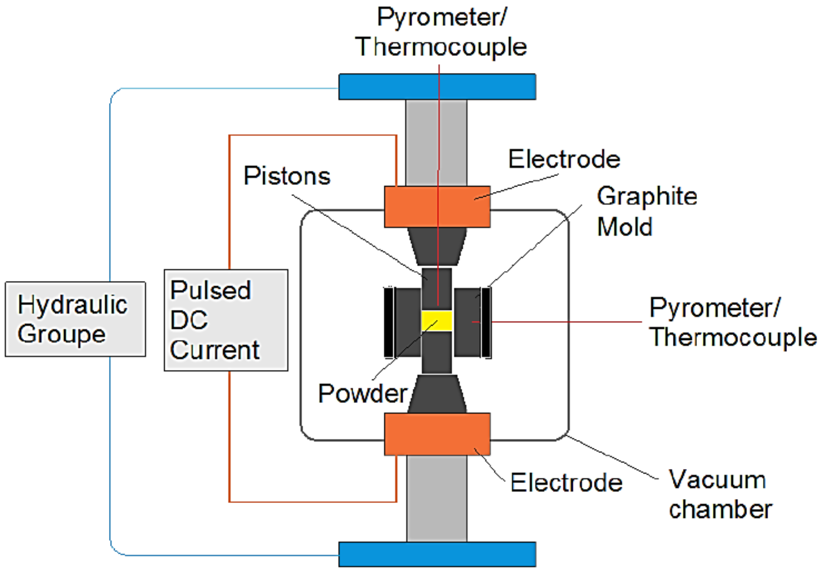

Figure 1:11 Spark Plasma Sintering (SPS) [10]

1.5.3 Spray Deposition

In the realm of metal matrix composites (MMCs), the horizon of fabrication techniques expands further with the advent of spray deposition, an innovative method complementing conventional powder metallurgy and in-situ synthesis approaches. In this context, spray deposition entails the simultaneous deposition of molten aluminum and reinforcing elements onto a substrate surface, ushering in the creation of composite coatings wherein the reinforcing constituents are seamlessly integrated into the aluminum matrix. Figure 1.12 shows the schematic spray deposition process.

The commencement of the spray deposition procedure pivots on the atomization of molten aluminum into diminutive droplets. This atomization process is achieved through diverse means, encompassing gas atomization or centrifugal atomization. The resultant minute molten aluminum droplets are subsequently propelled towards the substrate utilizing a high-velocity gas stream, typically comprising an inert gas like nitrogen or argon.

Concurrently, during the deposition phase, the reinforcing materials are introduced into the spray stream. These materials exhibit diverse forms, spanning powder, fibers, or particles, contingent upon the intended attributes of the composite coating. The reinforcement elements can either be premixed with the molten aluminum or introduced autonomously into the spray stream.

Upon impingement on the substrate surface, the molten aluminum droplets undergo prompt cooling and solidification, thereby bestowing form to a composite coating. The reinforcing materials, meticulously infused into the spray stream, become enmeshed within the congealed aluminum matrix. This yields the emergence of a composite coating in which the reinforcing components are universally disseminated across the expanse of the aluminum matrix.

Emanating from the spray deposition technique are a multitude of merits pertinent to MMC fabrication. Firstly, it negates the necessity for subsequent joining or bonding procedures by permitting the direct deposition of composite coatings onto the substrate. This pivotal feature propels it into a realm of high efficiency and cost-effectiveness in the MMC production domain.

Furthermore, the prowess of spray deposition encompasses the precise manipulation of the distribution and alignment of the reinforcing constituents within the composite coating. By adeptly tuning process parameters such as gas flow rate, spray distance, and the feed rate of reinforcing materials, the dispersion and alignment of reinforcements stand amenable to tailored adjustments, aligning with bespoke requisites.

Equally noteworthy is the breadth of materials that the spray deposition technique accommodates for reinforcement, spanning particles, fibers, and even nanoparticles. This inherent versatility translates into the capacity to craft MMCs boasting a myriad of reinforcement combinations, thereby engendering escalated mechanical, thermal, and electrical attributes.

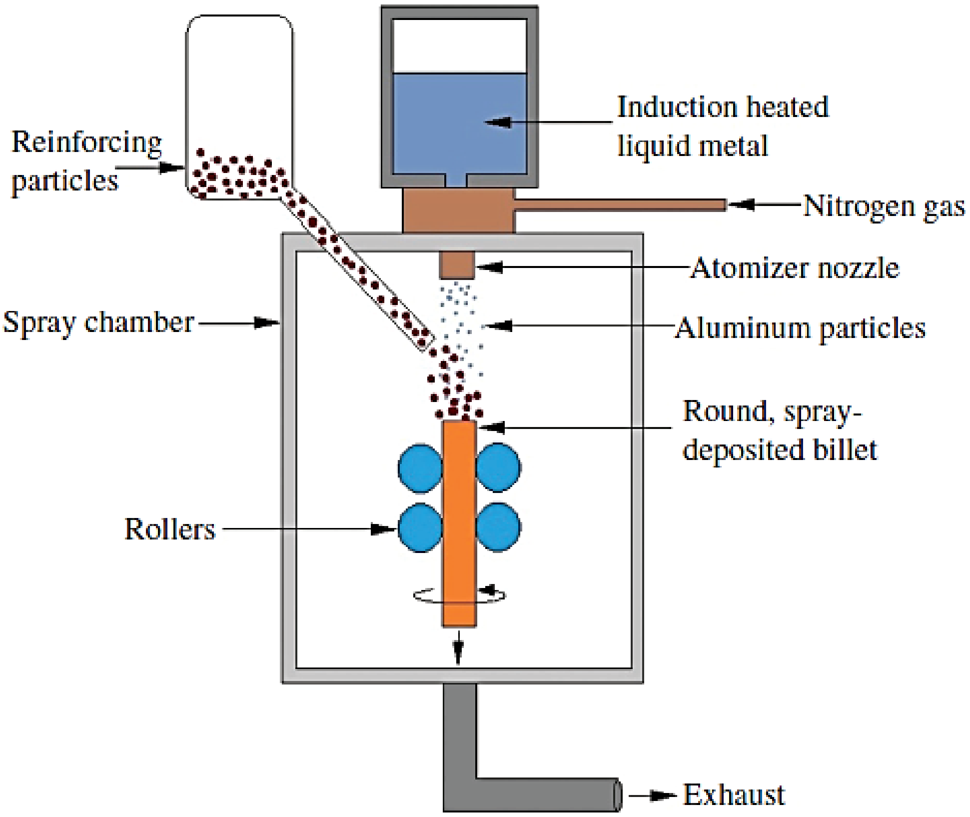

Figure 1:12 Spray Co-Deposition Manufacturing Process [1]

Various methodologies within the realm of spray deposition are harnessed for the fabrication of MMCs, encompassing the following two prominent techniques:

a. Cold Spray Deposition

Operating within the ambit of this technique entails the acceleration of metal particles and reinforcing elements to substantial velocities by means of a supersonic gas stream. Upon impact with the substrate surface, these particles bind through solid-state bonding mechanisms, thus engendering the development of a composite coating characterized by density and robust bonding.

b. Thermal Spray Deposition

Underpinning this technique is the utilization of a heat source, which could manifest as a flame or a plasma, to induce the melting of both aluminum and reinforcing constituents. Subsequent to liquefaction, these molten materials are forcefully propelled onto the substrate surface, where they undergo the process of solidification, ultimately culminating in the configuration of a composite coating.

1.5.4 Friction Stir Processing

In conjunction with the above-mentioned methodologies, an additional solid-state processing approach employed to produce aluminum-based hybrid metal matrix composites, is friction stir processing (FSP). This technique entails the utilization of a rotating tool characterized by a specifically designed geometry, which is immersed into the aluminum matrix concurrently with the introduction of the reinforcing elements. Figure 1.13 shows the FSP setup.

The friction stir processing (FSP) procedure involves inserting a rotating tool into the aluminum matrix, which generates both frictional heat and mechanical agitation. The heat generated from the friction between the rotating tool and the aluminum matrix causes the material to soften, intentionally avoiding reaching the melting point. This strategic modulation permits the execution of a processing method that remains within the confines of solid-state conditions. Simultaneously, the mechanical stirring action invoked by the rotating tool engenders an intimate amalgamation between the aluminum matrix and the reinforcing constituents. This amalgamation results in the creation of a composite material characterized by a finely grained structure and a uniform distribution of the reinforcing particles throughout the aluminum matrix.

The rotating tool encompasses two distinct components: the shoulder and the pin. The shoulder functions to apply downward pressure onto the workpiece, while the pin penetrates the material and initiates a stirring action. The geometrical configuration of the tool, encompassing factors like the diameter of the shoulder, the length of the pin, and the profile of the pin, can be finely tuned to align with the precise requisites of the composite production process.

The FSP procedure yields a range of advantages pertinent to the fabrication of aluminum-based hybrid metal matrix composites. First and foremost, it facilitates the creation of composites characterized by a finely grained structure, a feature that significantly bolsters the material's mechanical attributes. The confluence of substantial plastic deformation and the occurrence of dynamic recrystallization during

FSP contribute to grain refinement and the consequent augmentation of mechanical strength.

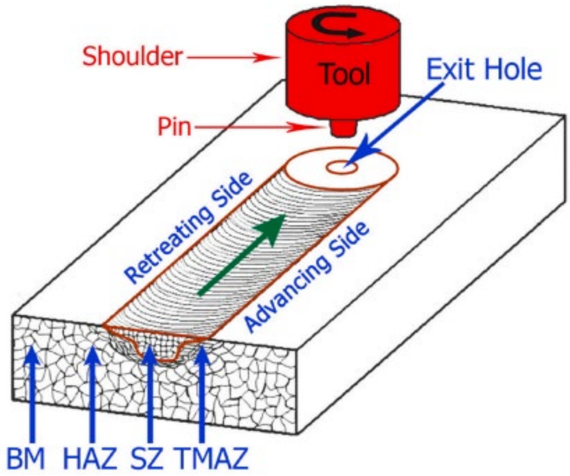

Figure 1:13 Friction Stir Processing [11]

Moreover, FSP guarantees an even dispersion of the reinforcing constituents within the aluminum matrix. This phenomenon is a consequence of the mechanical stirring effect, coupled with the localized softening of the matrix. The combined impact of these factors engenders the dispersion and integration of the reinforcing phases throughout the composite. This uniform distribution accentuates the efficiency of load transfer and amplifies the comprehensive mechanical performance of the composite material.

Furthermore, FSP emerges as an adaptable technique, amenable to diverse aluminum alloy compositions and an array of reinforcing materials. Its malleability is evidenced by its capacity to accommodate variable volume fractions and categories of reinforcements that can be seamlessly integrated into the matrix. This adaptability, in turn, empowers the creation of Al-HMMCs equipped with tailored properties, purpose-built to align with specific application demands.

The implementation of FSP within the domain of Al-HMMC fabrication has elicited considerable enthusiasm from industries encompassing aerospace, automotive, and transportation. The resultant composites manifest elevated mechanical attributes, such as amplified strength, enhanced stiffness, and heightened wear resistance. This profile renders them an optimal choice for lightweight structural components and applications characterized by high-performance prerequisites.

1.5.5 Electromagnetic Stirring

In addition to the methods previously discussed, electromagnetic stirring represents another technique utilized in the fabrication process of metal matrix composites. This method involves the utilization of electromagnetic fields applied to the molten aluminum matrix to induce stirring and ensure the even dispersion of the reinforcing materials as shown in Figure 1.14.

Electromagnetic stirring entails the generation of an electromagnetic field, achieved either by passing an electric current through a coil encircling the molten metal or by implementing a series of permanent magnets. This electromagnetic field interacts with the conductive molten aluminum, generating Lorentz forces that induce a stirring motion within the liquid metal. This stirring action effectively promotes the mixing and uniform dispersion of the reinforcing materials.

The primary goal of electromagnetic stirring is to achieve a uniform distribution of the reinforcing constituents within the aluminum matrix. This even dispersion plays a crucial role in improving the mechanical and physical characteristics of the final composite material. The electromagnetic stirring technique is employed to ensure that the reinforcing elements are evenly distributed throughout the aluminum matrix, thereby enhancing the overall properties of the composite. By ensuring the proper dispersion, electromagnetic stirring mitigates the likelihood of aggregation or clustering of the reinforcing particles. Such aggregation can lead to localized weak points or compromised performance of the composite material.

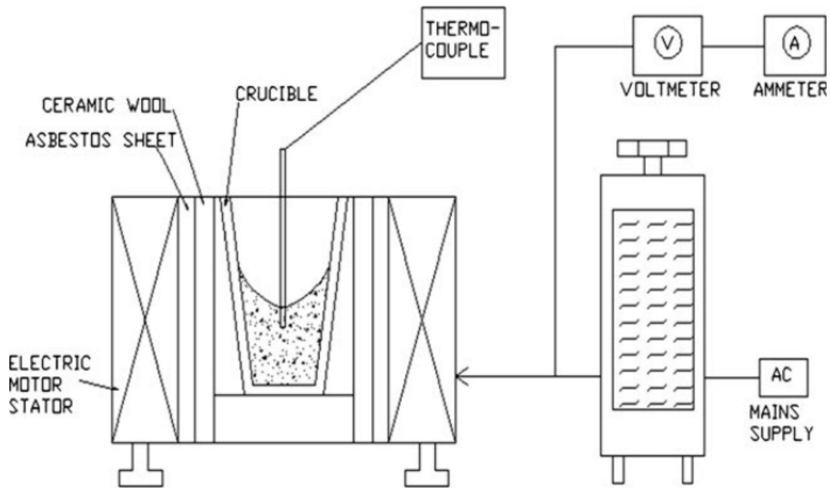

Figure 1:14 Electromagnetic Stir Casting Setup[12]

The stirring motion generated by electromagnetic fields helps improve the interfacial bonding between the aluminum matrix and the reinforcing materials. This enhanced mixing promotes better wetting and interaction between the matrix and the reinforcements, resulting in improved load transfer and enhanced mechanical properties in the composite material. The stirring action induced by the electromagnetic fields facilitates a stronger bond between the aluminum matrix and the reinforcing materials, leading to enhanced performance and mechanical strength in the composite.

The electromagnetic stirring technique offers several notable advantages in the context of metal matrix composite fabrication. Foremost, it is a non-contact method, obviating the necessity for physical contact between the stirring apparatus and the molten metal. This characteristic eliminates contamination risk from the stirring tool and diminishes the need for upkeep or replacement of stirring components. Moreover, electromagnetic stirring facilitates meticulous control over the intensity, direction, and duration of the stirring action. By adjusting electromagnetic field parameters like current strength, frequency, and positioning of the stirring device, the stirring process can be fine-tuned to meet specific requisites, thereby ensuring the optimal dispersion of the reinforcing materials.

Additionally, electromagnetic stirring can be synergistically employed in tandem with other fabrication techniques, such as powder metallurgy or in-situ synthesis. This combined application enhances the uniformity and dispersion of the reinforcing elements within the aluminum matrix. Such an integrated approach yields a synergistic outcome, leading to an overall improvement in the properties and performance of the resulting metal matrix composite. The utilization of electromagnetic stirring in MMC fabrication has found application across diverse industries, encompassing aerospace, automotive, and electrical component manufacturing. The resultant composites showcase augmented mechanical strength, elevated thermal conductivity, and superior resistance to wear. These attributes render them particularly suitable for applications necessitating high-performance materials.

1.5.6 In-Situ Reactive Processing:

In-situ reactive processing exploits chemical reactions between the matrix and reinforcement elements to fabricate HMMCs. The matrix and reinforcement materials are carefully chosen to enable desirable reactions that yield the desired reinforcement phases. This technique demands precise control over processing conditions to ensure uniform distribution and optimal property enhancement.

In-situ reactive processing enhanced the interfacial bonding between the matrix and reinforcement particles. As a result of chemical reactions that occur during processing, new phases may emerge that contribute to enhanced mechanical qualities.

1.6 APPLICATION OF HYBRID METAL MATRIX COMPOSITES

Hybrid Metal Matrix Composites (HMMCs) offer a distinctive array of properties and performance benefits that position them as a viable choice for a diverse spectrum of applications spanning various industries. The following examples underscore the versatile application of HMMCs across these industries:

Aerospace Sector: HMMCs have garnered considerable traction within the aerospace domain due to their remarkable lightweight quality, impressive strength-to-weight ratio, and superior mechanical attributes. These attributes render them indispensable in the creation of pivotal aircraft components including structural elements, engine parts, landing gear components, and interior fittings. The strategic integration of hybrid reinforcements further amplifies the endurance and robustness of these components[13].

Automotive Field: In the automotive realm, HMMCs serve as a pivotal asset, combining weight reduction with heightened strength and stiffness characteristics. Their utilization extends to the creation of critical engine components, suspension systems, brake mechanisms, body panels, and chassis elements. The incorporation of HMMCs contributes to the optimization of fuel efficiency, emission reduction, and the overall advancement of vehicle performance[15].

Figure 1:15 Application of HMMCs[14]

Renewable Energy Sector: HMMCs have found a purposeful role within the renewable energy landscape, particularly in wind turbine and solar power systems. Their lightweight and enduring properties make them an optimal choice for turbine blades, rotor hubs, and structural constituents, thereby elevating energy efficiency and augmenting the operational efficiency of renewable energy setups.

Defence and Military Applications: The defence and military sector harnesses HMMCs for their elevated robustness, resilience, and resistance to challenging environments. These composites are pivotal in the fabrication of armoured vehicles, ballistic protection mechanisms, missile constituents, and aerospace systems for defence-oriented deployments[16].

Electronics and Electrical Industry: Within the electronics and electrical realm, HMMCs emerge as an asset, underpinned by their impressive thermal conductivity and electrical insulation attributes. Their strategic employment encompasses applications such as heat sinks, printed circuit boards (PCBs), electronic encasements, and components pertaining to power transmission[17].

Marine and Maritime Arena: The marine and maritime domain derives substantial benefits from the adoption of HMMCs, primarily due to their intrinsic corrosion resistance and lightweight constitution. These qualities render HMMCs indispensable in sectors like shipbuilding, offshore structures, marine propulsion systems, and underwater equipment, all of which demand a fusion of heightened strength, durability, and resilience against corrosive seawater conditions[18].

Sports and Recreation: HMMCs make a notable imprint in the arena of sports and recreational equipment, encompassing domains such as bicycles, golf clubs, tennis rackets, and fishing rods. Their incorporation translates into elevated performance benchmarks, weight reduction, and heightened longevity, thereby elevating the overall experience in sports and recreational activities[19].

Hybrid metal matrix composites (HMMCs) have emerged as promising materials with a diverse range of applications within the medical field. Their unique combination of properties, including exceptional strength, lightweight characteristics, and biocompatibility, positions them as valuable materials for various medical applications. One of the foremost applications is in orthopaedic implants, where HMMCs can be employed to manufacture hip and knee replacements that offer both strength and reduced patient burden. Additionally, dental implants benefit from their corrosion resistance and durability. HMMCs also find utility in the development of prosthetic limbs, enhancing their overall performance and comfort. Beyond this, they contribute to the creation of surgical instruments known for their precision and longevity, while also reinforcing diagnostic equipment such as MRI machines. Furthermore, researchers explore their potential in bone scaffolds for tissue engineering and regenerative medicine. In radiation therapy, HMMCs can provide effective shielding, and they even hold promise for use in biodegradable implants and medical robotics. It is crucial to emphasize that the application of HMMCs in the medical sector necessitates adherence to rigorous testing and regulatory approval processes to ensure patient safety and compliance with medical device standards[20][21].

In conclusion, the application of aluminum metal matrix composites (AMMCs) holds great promise across various industries due to their remarkable combination of lightweight characteristics, excellent mechanical properties, and enhanced performance. Within the automotive sector, AMMCs are driving innovations in vehicle design, contributing to fuel efficiency, and reducing emissions. In aerospace, they are revolutionizing aircraft structures, making air travel safer and more fuel-efficient. Furthermore, AMMCs are actively improving the efficiency and sustainability of renewable energy systems, from wind turbines to solar panels. In the field of electronics, their superior thermal conductivity is enabling the development of more efficient and compact electronic devices. Additionally, AMMCs are contributing to the advancement of medical technology, particularly in orthopaedics and prosthetics. As we look ahead, ongoing research and development in material science are likely to unlock even more applications for aluminum metal matrix composites, further underscoring their significance in shaping the future of numerous industries.

1.7 THESIS ORGANIZATION

In Chapter 1, the thesis begins with an introduction to aluminum and aluminum alloys, emphasizing their properties and significance. This chapter explores the need for composites, particularly focusing on the advancements that hybrid composites offer. Various development techniques for hybrid composites are discussed, followed by an examination of the applications of hybrid metal matrix composites (HMMCs) in different industries.

Chapter 2 provides a comprehensive literature review, covering the application and role of carbide, oxide ceramics, and agro-waste materials in enhancing material characteristics. This chapter also identifies research gaps in the existing studies on HMMCs and defines the research objectives based on these gaps.

Chapter 3 outlines the materials and methodology used in the research. It discusses the characteristics of AA6351 and the reinforcement materials Graphite, B_4C, TiC and WC. The development process using stir casting is explained in detail. Additionally, the chapter describes the various tests conducted, including the testing procedures and the machines used.

In Chapter 4, the results of microstructural and mechanical testing are presented. The chapter begins with the density test results, followed by a detailed analysis of the SEM (Scanning Electron Microscope) results. It continues with a discussion of the XRD (X-Ray Diffraction) and EDS (Energy Dispersive Spectroscopy) results.

Chapter 5 of the study focuses on analysing the mechanical properties of the developed composites. It covers the findings from impact tests, hardness tests, and tensile strength tests. The chapter examines how the inclusion of reinforcements affects the mechanical properties, with supporting evidence from microstructural tests. Furthermore, statistical techniques are employed to rank the hybrid metal matrix composites that have been developed. This chapter provides a comprehensive exploration of the mechanical behavior of the composites, including the influence of reinforcements and the use of statistical analysis to evaluate their performance.

Chapter 6 examines the wear characteristics of the selected hybrid metal matrix composites. It includes an estimation and analysis of the coefficient of friction and wear rates, providing a comprehensive understanding of the wear behavior.

Finally, Chapter 7 concludes the thesis by summarizing the findings discussed in Chapters 4 and 5. It also outlines the future scope for further research and potential developments in the field of hybrid metal matrix composites.

Chapter 2: Literature Review

The literature review thoroughly examines previous studies and academic research that have investigated the structural and mechanical properties of hybrid metal matrix composites (HMMCs) made of AA6351/Graphite/TiC/B_4C/WC. Metal matrix composites have garnered considerable interest due to their unique combination of properties. These include a high strength-to-weight ratio, low thermal expansion coefficient, and excellent wear and abrasion resistance, characteristics that are difficult to achieve in single-component materials. The literature review provides a comprehensive analysis of the AA6351/Graphite/TiC/B_4C/WC HMMCs, highlighting their exceptional properties and the advantages they offer over traditional monolithic materials [22]. The characteristics of MMCs are intricately interwoven with the production methodology, the matrix material employed, and the nature of the reinforcing components. An array of fabrication techniques has been explored, spanning both liquid-state and solid-state processing approaches. Liquid-state techniques such as stir casting, compo-casting, and squeeze casting are used in mass production due to their simplicity and cost-effectiveness. On the contrary, solid-state methodologies like powder metallurgy and spark plasma sintering have been harnessed to surmount the limitations of liquid-state processing. Additionally, in-situ processes have been introduced, entailing chemical reactions between elements to yield stable reinforcements within the metallic matrix. MMCs bolstered by ceramic particles have of the reinforcing material in terms of type, size, and composition [23]. By critically analysing and synthesizing the existing literature, this review aims to identify research gaps and provide a foundation for the present study on AA6351/Graphite/TiC/B_4C/WC hybrid MMCs.

Stir casting, a widely utilized technique, has consistently exhibited superior mechanical and tribological features when contrasted with a pure metal matrix. However, the enhancements in these features do not have a direct relationship with the volume of reinforcement applied. Among these diverse MMC manufacturing methods, stir casting emerges as a simple and cost-efficient technique ideally suited for mass production [24]. The mechanical properties are notably subject to the choice of manufacturing method, its specific parameters, and the characteristics technique for producing metal matrix composites. However, several critical challenges impede its full commercial exploitation. Achieving a uniform distribution of reinforcement particles, particularly for micron-sized and nano-sized variants, significantly impacts MMC mechanical properties.

A non-uniform distribution might result from differences in the densities of the matrix and reinforcement, so it is important to carefully tune variables such liquid metal viscosity, stirrer rotation per minute, mixing time, and particle size to achieve homogeneity. Another significant factor influencing the mixing of reinforcement is the wettability of the reinforcement and the liquid aluminum matrix. Porosity reduction is crucial but challenging, and erosion of stainless-steel stirrer blades, especially in the presence of hard micro particles, poses both production rate and material contamination issues. Finally, addressing reinforcement mixing rate variability and the potential for undesirable phase formation due to matrix-reinforcement reactions are vital areas for future research and furnace design improvements within the MMC production process [25][26].

When it comes to the manufacturing of metal matrix composites, recycled aluminum is just as useful as its virgin equivalent. This means that the material feedstock for creating these advanced composites isn't restricted solely to newly processed aluminum; instead, recycled aluminum, sourced from various post-consumer and industrial sources, can be effectively employed in this innovative manufacturing process. The utilization of recycled aluminum to develop metal matrix composites highlights the environmentally sustainable nature of this method, as it not only preserves valuable raw materials but also lowers energy usage and lessens the environmental impact of producing primary aluminum. This dual capability, utilizing both virgin and recycled aluminum, grants manufacturers greater flexibility in material sourcing, aligning with the growing emphasis on sustainable practices within the industry [27].

Numerous studies have explored the use of silicon carbide as a reinforcement in liquid-processed aluminum metal matrix composites. These investigations consistently show significant improvements in mechanical and tribological properties, underscoring the importance of SiC in enhancing composite performance[28]. Additionally, reinforcements like SiC can be incorporated through friction stir processing, a method recognized for producing excellent microstructural qualities. However, it's worth noting that the commercial feasibility of friction stir processing in this application remains somewhat restricted.

Izadi et al. investigated the use of friction stir processing (FSP) do develop Al-SiC composite. The study investigates at composites with two distinct SiC particle sizes and concentrations of SiC particles ranging from 4 to 16 vol%. Due to the uniform dispersal of SiC during FSP, the hardness of the composites containing 4 and 8 vol% of 490N grade SiC rose significantly after the process. However, the composites with 16 vol% SiC could not be adequately combined by FSP, leading to residual holes and lack of fusion, because of the initial low density and increased surface area of microscopic particles as shown in Figure 2.1.

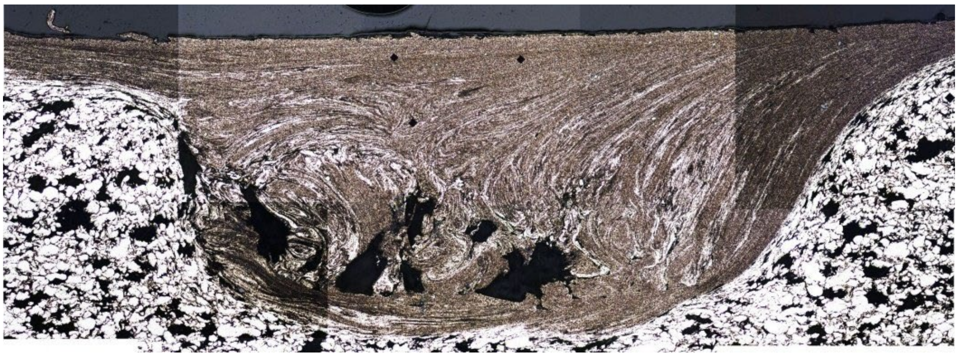

Figure 2:1 Composite with 16 vol% SiC [29].

The study establishes a correlation between hardness and mean inter-particle spacing for composites comprising 4 and 8 vol% SiC. FSP is shown to be effective in improving microhardness of the composites. However, employing FSP to achieve complete fusion with high SiC volume fractions still present difficulties [29].

Bhowmik et al. studied wear characteristics of SiC reinforced Al matrix developed by stir casting technique, with varying SiC reinforcement concentration (0, 3%, 6%, and 9wt%). X-ray diffraction (XRD) examination confirmed that the SiC particles in the composite were uniformly mixed.

The wear properties were established through Pin-on-disc wear tests by altering the sliding velocities while maintaining a constant load and sliding distance. The results depicted in Figure 2.2 show that as the sliding speed escalates, the wear rate rises and the coefficient of friction decreases. This trend is driven by increased friction between the surfaces of the disc and the pin.

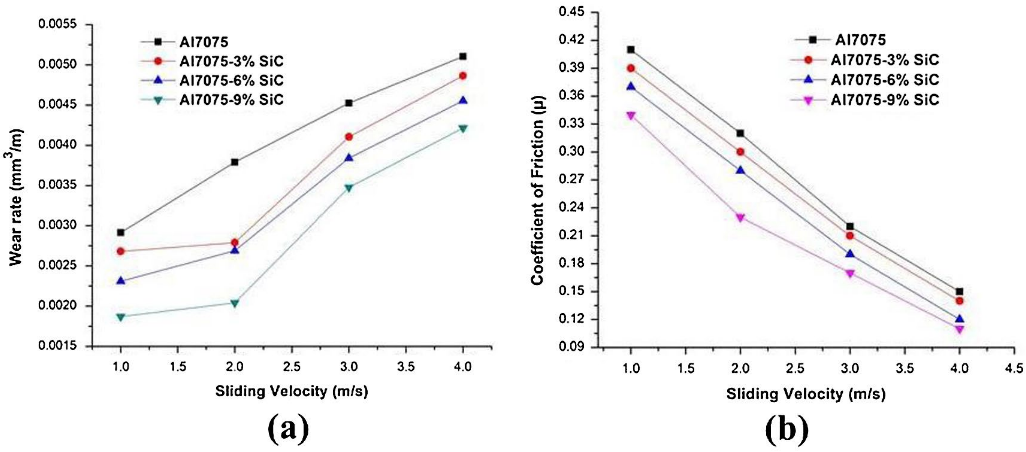

Figure 2:2 (a) Wear Rate vs wt%, (b) Coefficient of Friction vs wt% [30]

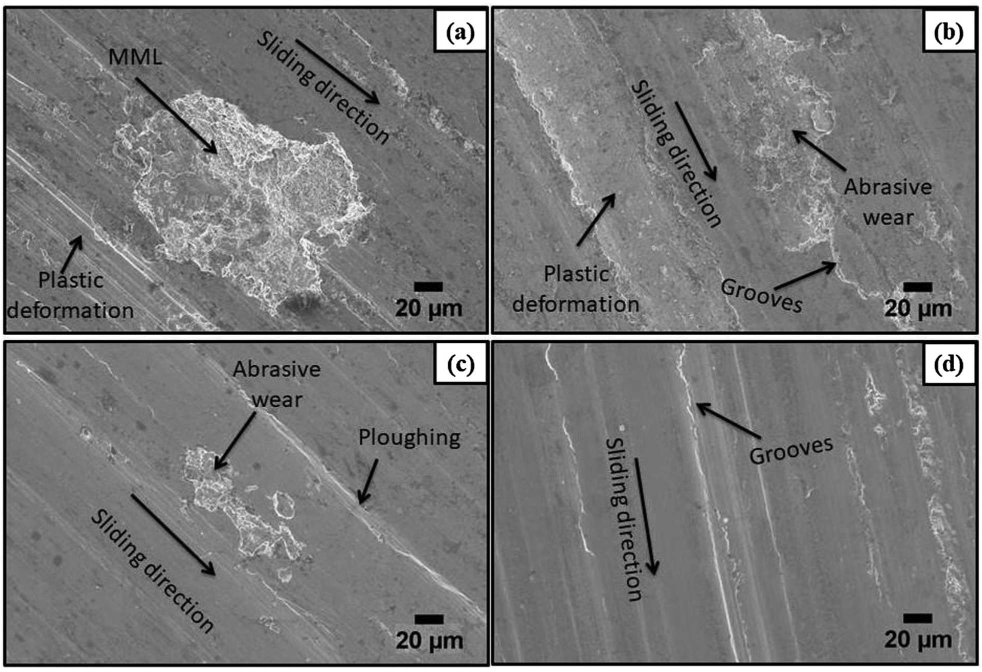

Figure 2:3 Worn Surface Micrograph [30]

Figure 2.3 shows the worn surface morphology of the developed composites indicating mechanically mixed layer possessed by Al7075-SiC, which causes a reduced rate of MRR during sliding in comparison with the matrix composite Al7075. Elevated pressure and frictional heat cause an oxide layer to develop on the surface as sliding velocities increase. It was observed that Al7075-SiC composite with 9 wt% SiC reinforcement has the lowest rate of material removal. [30].

Thirugnanam et al. investigated the mechanical performance of AA6351 reinforced with nanosilicon carbide. Metal matrix composites were developed through the liquid metallurgy route, incorporating varied weight percentages of nSiC. Figures 2.4 and 2.5 shows the mechanical and flexural characteristics of MMCs.

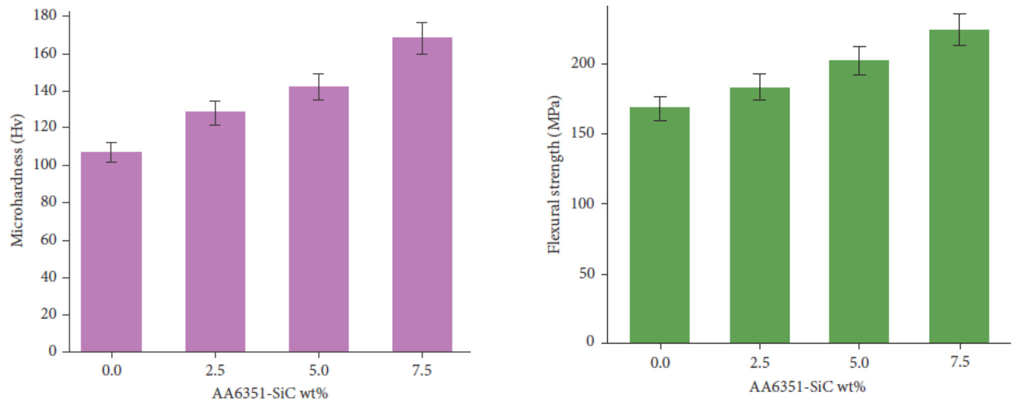

Figure 2:4 Hardness and Flexural Properties [31].

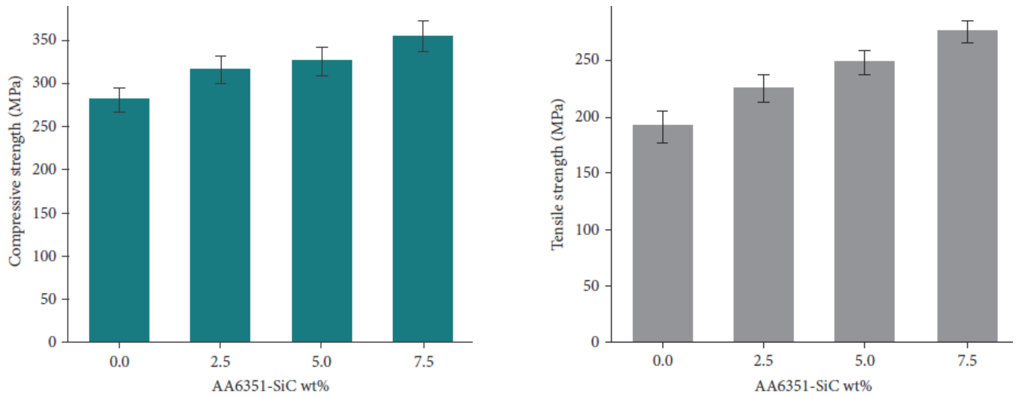

Figure 2:5 Compressive and Tensile properties [31]**.**

The findings showed that adding nSiC particles to AA6351 improved the mechanical properties of the MMCs. In comparison to the other samples, the specimen with the largest volume percentage of SiC (7.5 wt%) showed the highest strength. The presence of SiC particles improved grain refinement and dispersion, which contributed to improved mechanical properties. According to the study, these MMCs have potential for use in the automotive and aerospace sectors, where both improved strength and decreased weight are required. The developed MMCs' equal distribution of SiC particles was verified by the SEM examination, hence enhancing their practical applicability. Future research may explore the use of TOPSIS approaches to identify optimal parameters for MMC fabrication [31].

Incorporating SiC and another reinforcement into hybrid Metal Matrix Composites (MMCs) offers a substantial enhancement to the mechanical and tribological properties of the resulting composites. The synergistic effect of these combined reinforcements significantly elevates the overall performance of the composite.

Ahamad et al. conducted research on the structural and mechanical characteristics of a hybrid Metal Matrix Composite reinforced with Al_2O_3-SiC, which was developed using liquid metallurgy. Various weight percentages of Al_2O_3-SiC were incorporated into the Al matrix in equal proportions for the study. Excellent interatomic bonding was indicated by the XRD investigation, which revealed transitional phase development between the Al matrix and reinforcement. As per SEM, Al_2O_3-SiC particles were distributed uniformly throughout the Al matrix. As the amount of reinforcement increases, a reduction in density is noted, while the hardness initially rises before subsequently declining. Impact strength improved with higher ceramic content and the hybrid MMCs reinforced by 2.5 wt.% of each reinforcement, showed the highest tensile strength [32]. Furthermore, subjecting the fabricated metal matrix to heat treatment under the T6 condition can significantly improve its mechanical properties. To confirm this, Suryakumai et al. focused on the development of an aluminum based MMC reinforced with 7.5 wt% SiC and 7.5wt% Al_2O_3 using the liquid metallurgy route. The developed composite is subjected to solution treatment and precipitation treatment for the T-6 condition. The mechanical characteristics of hybrid MMC were evaluated before and after the heat treatment. The findings demonstrate a 34% and 7% improvement in micro hardness and tensile strength, respectively, following heat treatment. The consistent dispersion of reinforcements throughout the matrix is validated by microscopic examination. The investigation comes to the conclusion that heat treatment and reinforcements greatly improve the mechanical characteristics of the aluminum hybrid MMC [33]. Adding Al_2O_3 as a reinforcement using through powder metallurgy also shows promising improvements in the mechanical and tribological characteristics [34].

To find the ideal composite composition and wear parameter combination to reduce wear rates, several experiments were carried out. It was discovered that adding reinforcement elements such as SiC and Al_2O_3 formed a protective barrier between the pin and disk face, improving wear resistance. However, excessive reinforcement beyond a certain percentage could lead to agglomeration and increased brittleness, adversely affecting wear rates [35]. Ahmad et al. focused on investigating the Vickers hardness and wear performance of Aluminium hybrid reinforced with Al_2O_3-graphite developed by liquid metallurgy route. The HMMC was developed by incorporating equal proportions of Al_2O_3 and graphite. As the weight intensity of reinforcement particles increased, the hybrid composite exhibit improved hardness. Because of its lubricating qualities, the hybrid composite's wear rate reduced as the percentage of graphite particles increased, increasing wear resistance. When examined using scanning electron microscopy after the wear test, the pure Al matrix exhibited deeper grooves, more debris, and a rougher surface in contrast to the heavily reinforced composites. Figure 2.6 presents the findings related to hardness and wear rate.

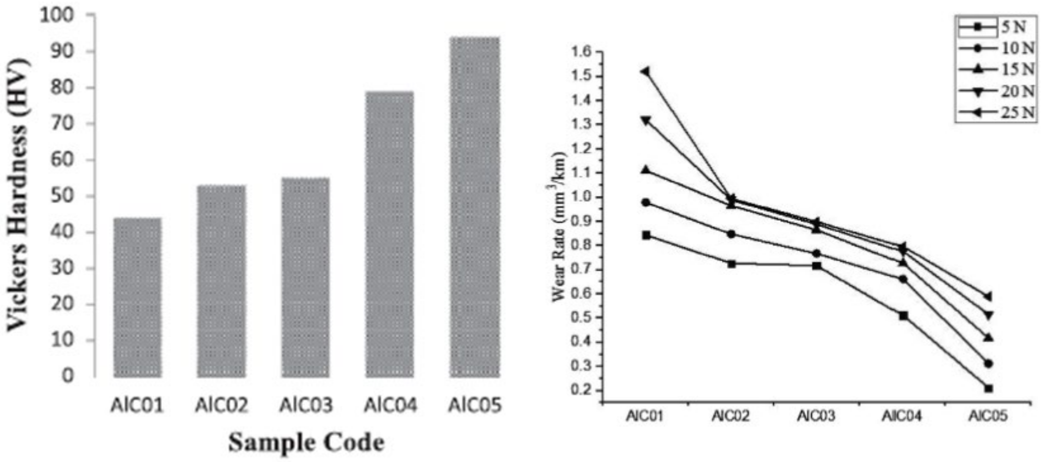

Figure 2:6 Vicker Harness and Wear Rate [36]

The findings showed adding reinforcement effect the microstructure, hardness, and the wear endurance of the hybrid MMCs. As of the reduced flexibility brought on by the reinforcement particles, the composite specimen with the highest weight proportion of Al_2O_3-graphite reinforcements (10 wt% each) had the highest hardness and wear resistance [36][37].

Al6063 reinforced with Al2O3, SiC, and TiO2 exhibits significantly enhanced hardness, tensile strength, and yield strength compared to pure Al 6063. Notably, an increase in SiC particle content corresponds to an upward trend in hardness, tensile strength, and yield strength. This study provides valuable insights into the mechanical and surface properties of the materials, showcasing the potential to develop high-performance, cost-effective metal matrix composites suitable for automotive and aerospace applications. The analysis demonstrates that these composites surpass pure Al6063 metals in terms of mechanical features such as hardness, tensile strength, and yield strength. The investigation also shows that the Al6063 matrix has particles of Al_2O_3, SiC, and TiO_2 distributed uniformly, all of which contribute to the improved characteristics of the composite material. The results imply that these particles' existence and dispersion are important factors in defining the characteristics of the MMC. The results of this study have significant implications for the development of advanced materials that meet modern engineering requirements for robust, lightweight, and cost-effective solutions in a variety of applications[38].

Ahamad et al. explored the impact of equal proportions of Al_2O_3 and TiC reinforcements on the properties of an Al matrix in hybrid MMCs, developed through Stir casting. X-ray diffraction revealed the formation of intermediate phases due to interfacial bonding between the matrix and reinforcement phases. Furthermore, scanning electron microscopy demonstrated a uniform distribution of Al_2O_3 and TiC particles within the aluminum matrix. Additionally, a decrease in density was observed after preheating. A decrease in hardness was noted upon increasing the reinforcement proportion because of reinforcement agglomeration. However, improvement in impact strength is observed with the addition of reinforcements. The hybrid with 5 wt.% of each of the reinforcements exhibited the highest tensile strength. However, the researchers noted that at elevated concentrations, achieving a homogeneous distribution becomes challenging due to the heightened density variation between the matrix and reinforcement phases during the stirring process [39].

Ashebir et al. studied Hybrid Reinforced Particulate Aluminum Matrix Composites (HAMCs), which are developed by mixing in SiC and Al_2O_3. It is discovered that the mechanical and wear behavior improved by up to 25% and 40%, respectively, by using SiC and Al_2O_3 particles respectively. However, the volume wear loss and friction coefficient increase when graphite particles above 2 wt% are included, which is associated with the reduced toughness and hardness of the composite. The aerospace, automotive, and other industries that need strong, lightweight, and wear-resistant materials have a lot of potential uses for these hybrid composites [40].

The incorporation of Boron Carbide as a reinforcement in aluminum metal matrix significantly enhances their mechanical and tribological characteristics. B_4C is known for its excellent hardness and anti-wear characteristics, making it a valuable addition to aluminum matrices, which typically lack these attributes. When B_4C particles are introduced, they effectively reinforce the aluminum matrix, resulting in improved hardness, wear resistance, and overall strength, key factors in tribological performance. The improved properties make B_4C-reinforced aluminum composites highly sought after for applications that demand strong materials, such as armour plating, aerospace components, and automotive parts, where friction and wear characteristics are crucial. Furthermore, these composites largely maintain aluminum's corrosion resistance, providing a compelling blend of strength and durability while retaining favourable tribological properties [41][42].

Chen et al. studied Al6061 reinforced with boron carbide for neutron shielding based on Monte Carlo Particle transport program MCNP simulations. Hot pressing in a vacuum and hot rolling in an atmosphere were used to develop the composites with the four distinct B_4C volume fractions. The simulation findings showed that as plate thickness and B_4C content increased, the neutron transmission ratio decreased. According to the microstructure investigation, the B_4C particles had sturdy bonding at the interface and were consistently dispersed throughout the 6061Al matrix.

Along with trace amounts of AlB_2 and Al_3B-C phases, B_4C and Al were the primary phases in the neutron absorbers. Dislocations occurred around the B_4C particles as the matrix's grain became more polished. Initially, as the B_4C content increased, the tensile characteristics of the composite improved, but beyond a certain point, the tensile strength started to decrease. The B_4C/Al6061 NACs failed due to cleavage fracture and interfacial debonding of the B_4C particles. This work sheds important light on the development and manufacturing processes for neutron absorber composites, which are useful in a variety of applications, especially nuclear shielding domains [43].

Incorporating B_4C along with SiC as reinforcements leads to notable improvements in hardness and tribological characteristics due to their inherent hardness properties. This dual reinforcement strategy harnesses the hardness of both materials, resulting improved wear and mechanical performance. Poovazhagan et al. conducted a study on hybrid nanocomposites of Al6061 reinforced with varying ratios of silicon carbide and boron carbide nanoparticles. They employed an ultrasonic cavitation-based solidification process to successfully introduce the nanoparticles into the aluminum matrix. The findings revealed that the transient cavitation and acoustic streaming effects of ultrasonic cavitation aided in the even distribution of SiC and B_4C nanoparticles in the aluminum matrix. SEM analysis with EDS confirmed the presence of both types of nanoparticles in the metal matrix. The hybrid composites showed significantly improved room-temperature hardness and tensile strength compared to the unreinforced alloy, although there was a slight reduction in ductility and impact strength. Notably, the hybrid MMC with 1.0 vol. % SiC and 0.5 vol. % B_4C exhibited the highest tensile strength [44].

Using a double stir casting method, Prasad et al. studied A356.2 aluminum matrix composites with variable volume fractions of rice husk ash while maintaining similar quantities of silicon carbide (SiC). The results, as illustrated in Figure 2.7, demonstrated that density declined while hardness and porosity increase with increasing reinforcing fractions. Furthermore, tensile strength improves as reinforcement concentration increase and elongation decreased. The enhanced dislocation density in the composites was identified as the cause of this strength improvement.

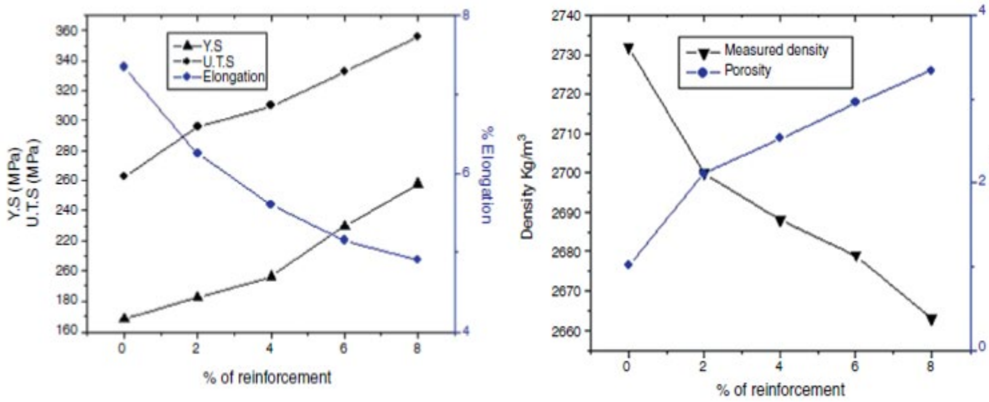

Figure 2:7 Effect of % Reinforcement on Tensile Strength and Density [45].

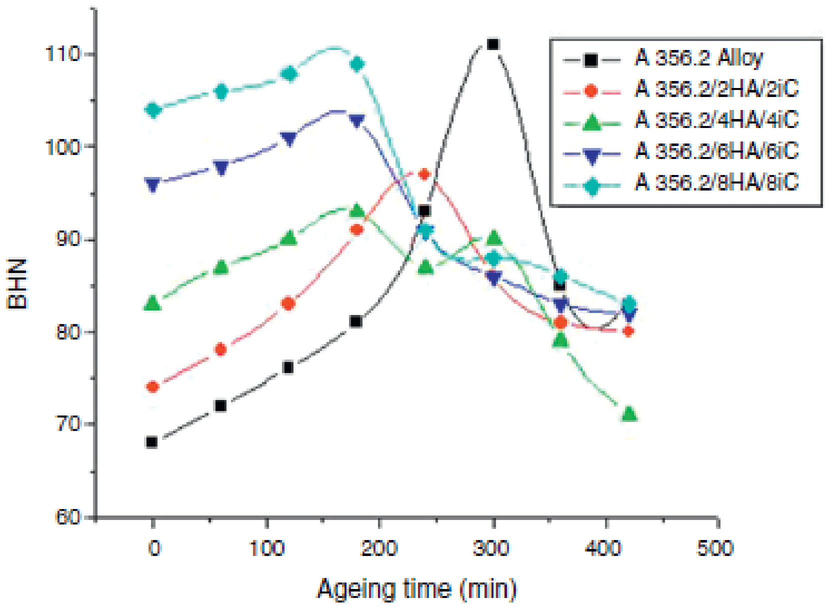

Figure 2:8 Brinell Hardness and Aging Time [45].

The research also examined the age hardening characteristics of the MMCs depicted in Figure 2.8. The addition of reinforcement accelerated the aging kinetics [45].

Graphite possesses inherent self-lubricating characteristics, and when combined with SiC in a composite, it exhibits favourable tribological characteristics. This combination offers improved friction and wear properties, making it valuable for applications where lubrication is challenging or undesirable. Sneha et al. focused on fabrication of AA6351 reinforced with Gr and SiC reinforcement through squeeze casting. Based on the results depicted in Figure 2.9, the hardness and tensile strength showed enhancement with an increase in the proportion of SiC and a decrease in the proportion of Gr. Furthermore, all manufactured composites demonstrated an escalation in wear rate with higher applied loads.

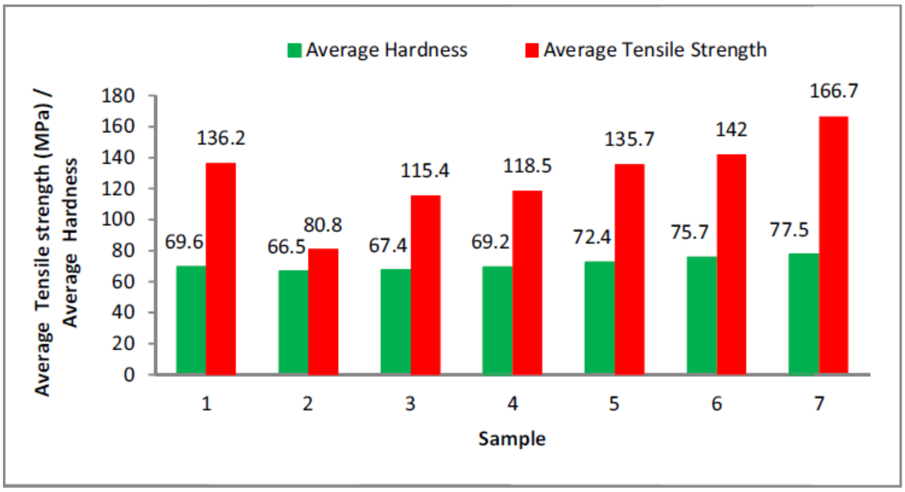

Figure 2:9 Hardness and Tensile Strength [46].

According to the study, the density of the Al6351 alloy increased when SiC particles were gradually added, but it dropped as the weight fraction of graphite increased. A pattern of increasing hardness is shown when the amount of SiC is increased, and the proportion of graphite is decreased. This is because SiC is a hard substance. In comparison to pure aluminum alloy, the Al6351/ 0 wt % Gr/ 10 wt% SiC composite showed better wear resistance by improved by 46.3% and hardness increased by 11.35%. Figure 2.10 illustrates the wear rate of the hybrid composites, which first dropped when SiC and Gr were added up to the fourth sample (6 wt% SiC/4 wt% Gr), but then started to increase.

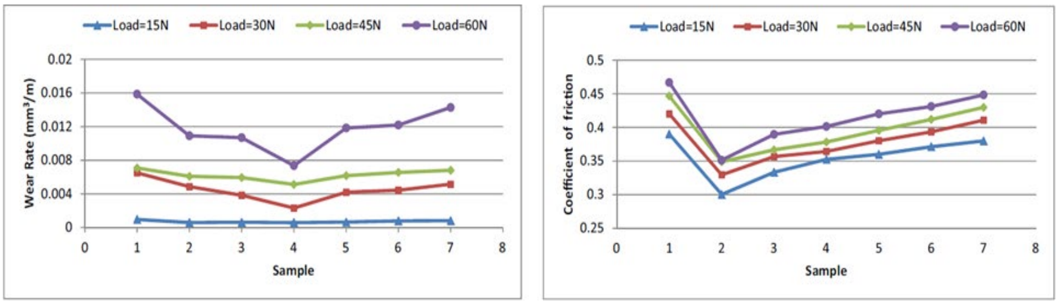

Figure 2:10 Coefficient of Friction [46]

Graphite's lubricating properties and SiC's hard nature are responsible for this observed enhancement in wear resistance. Due to decreased graphite content and SiC agglomeration, there is an increase in wear rate after the fourth sample [46].

The fusion of Al_2O_3 and Gr as reinforcements in hybrid metal matrix composites results in enhancements in both tribological and mechanical characteristics. Mohanavel et al. Studied the physical and tribological behavioural pattern of AA6351/Al_2O_3/Gr hybrid MMCs developed through liquid metallurgy process.

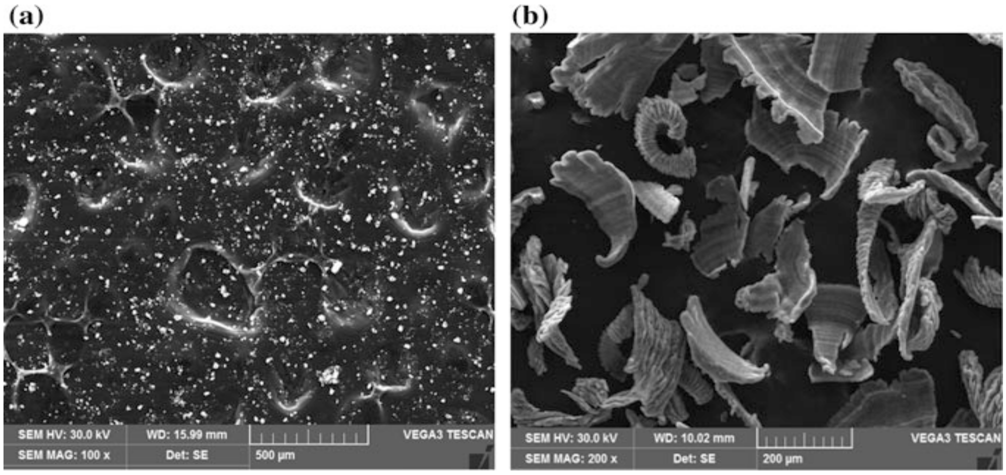

Figure 2:11 SEM for (a) Al_2O_3 (b) Gr [47]

Figure 2.11 illustrates the worn surface morphology of the hybrid composites as observed through SEM. The experimental results indicated that the inclusion of filler reinforcements improved the tribological properties of the composites.

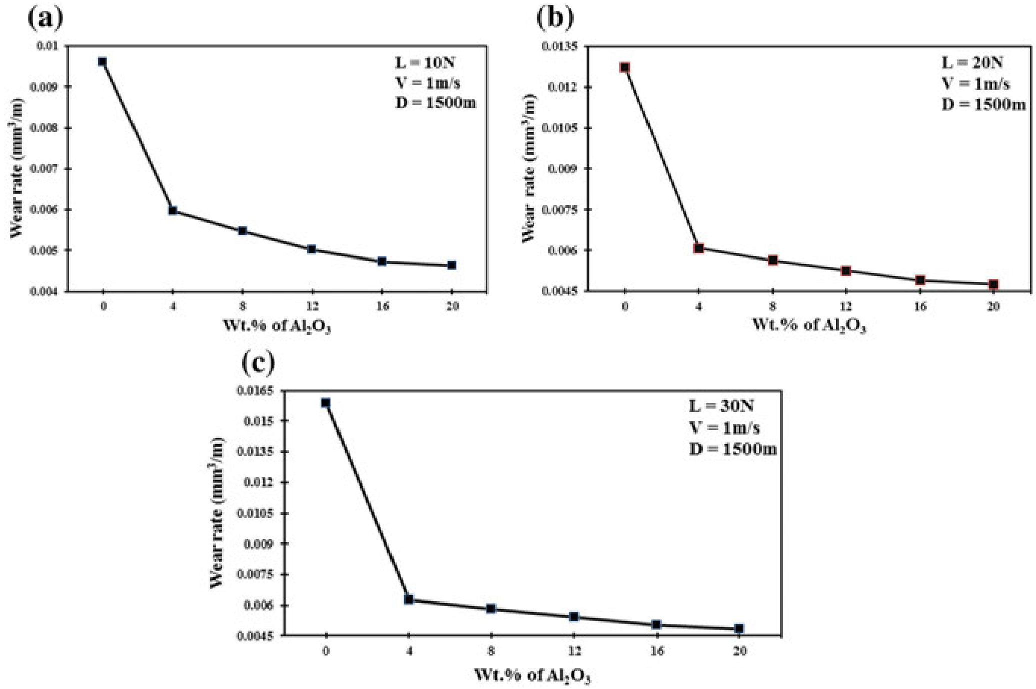

Figure 2:12 Wear Rate of AA6351/Al_2O_3/Gr [47]

The inclusion of dual reinforcing materials, such as ceramic particulates like BN, Gr, and Al_2O_3, greatly enhanced the mechanical and wear properties of the developed composites. Moreover, due to their low density, these reinforcements help reduce the overall density of the composite materials. Due to the composites' higher hardness and strong matrix-reinforcement bond, a notable drop-in wear rate has been observed [47]. Extensive research has been conducted to determine the optimal machining process parameters for functionally graded aluminum metal matrix composites. These investigations have led to the conclusion that FGAMCs, particularly the A356-SiC composite, exhibit suitability for use in intricate engineering tasks across industries such as automobile and aviation. The optimization of EDM parameters has resulted in enhanced machining efficiency and reduced wear rates, showcasing their potential applicability in demanding areas like brake rotor discs and other high-performance material applications [48] [49]. Extensive research has been dedicated to utilizing FSW for joining aluminum metal matrix composites. This method stands out for its eco-friendly and sustainable approach to welding technology [50][51].

Several studies have explored the utilization of rare earth particles (REP), including common types like CeO_2 and La_2O_3, as reinforcements in materials, resulting in substantial enhancements in their mechanical characteristics. Sharma et al. Studied Al6063 matrix reinforced with a mixture of rare earth particulates (REP) CeO2 and La2O3 along with silicon carbide particles. These hybrid composites were developed with varying compositions of SiC (3, 6, and 9 wt%) and REP (1, 2, and 3 wt%) using a bottom-pouring casting technique. Microstructural analysis revealed that REP was uniformly dispersed throughout the Al6063 matrix, resulting in grain refinement. Mechanical and tribological properties were evaluated at room temperature. The results revealed that incorporating up to 2 wt.% of REP mixture led to enhanced mechanical characteristics and increased wear resistance, with a slight refinement in elongation. However, an increase in the REP proportion to 3 wt.% resulted in a decline in mechanical properties and a reduced wear resistance [52].

The incorporation of a combination of Al_2O_3 (alumina), SiC (silicon carbide), and C (carbon) as reinforcements in an aluminum metal matrix leads to a multifaceted enhancement of its properties. Alumina brings heightened hardness, wear resistance, and thermal stability, particularly valuable in applications demanding elevated temperatures. Silicon carbide bolsters mechanical strength and wear resistance, crucial for high-durability scenarios like aerospace components. With its excellent electrical and thermal conductivity as well as self-lubricating properties, carbon enhances the matrix's functionality for applications that require electrical conductivity and reduced friction and wear. This combination forms a hybrid composite offering a balanced spectrum of properties, catering to various industrial needs, albeit the specific outcomes depend on factors like composition, processing, and targeted application requirements. Careful design and customization are essential to harness these reinforcements effectively in aluminum metal matrices. [53][54].

Aluminum alloy Al7075 is well-known for its exceptional strength-to-weight ratio, making it a preferred choice for aerospace components and high-stress applications. Its ability to be heat-treated and its resistance to corrosion further enhance its suitability for demanding engineering uses. By adding reinforcements to Al7075, the properties of the aluminum metal matrix can be further enhanced. In a study by Khan et al., the microstructural and mechanical properties of a new ternary reinforced AA7075 hybrid metal matrix composite (HMMC) were investigated. Four samples were developed using stir casting liquid metallurgy and subsequent heat treatment: AA7075 (base alloy), AA7075 reinforced with 5.0 wt %SiC (MMC), AA7075 reinforced with 5.0 wt %SiC & 3.0 wt %RHA (s-HMMC), and AA7075 reinforced with 5.0 wt %SiC, 3.0 wt %RHA & 1.0 wt %CES (n-HMMC).

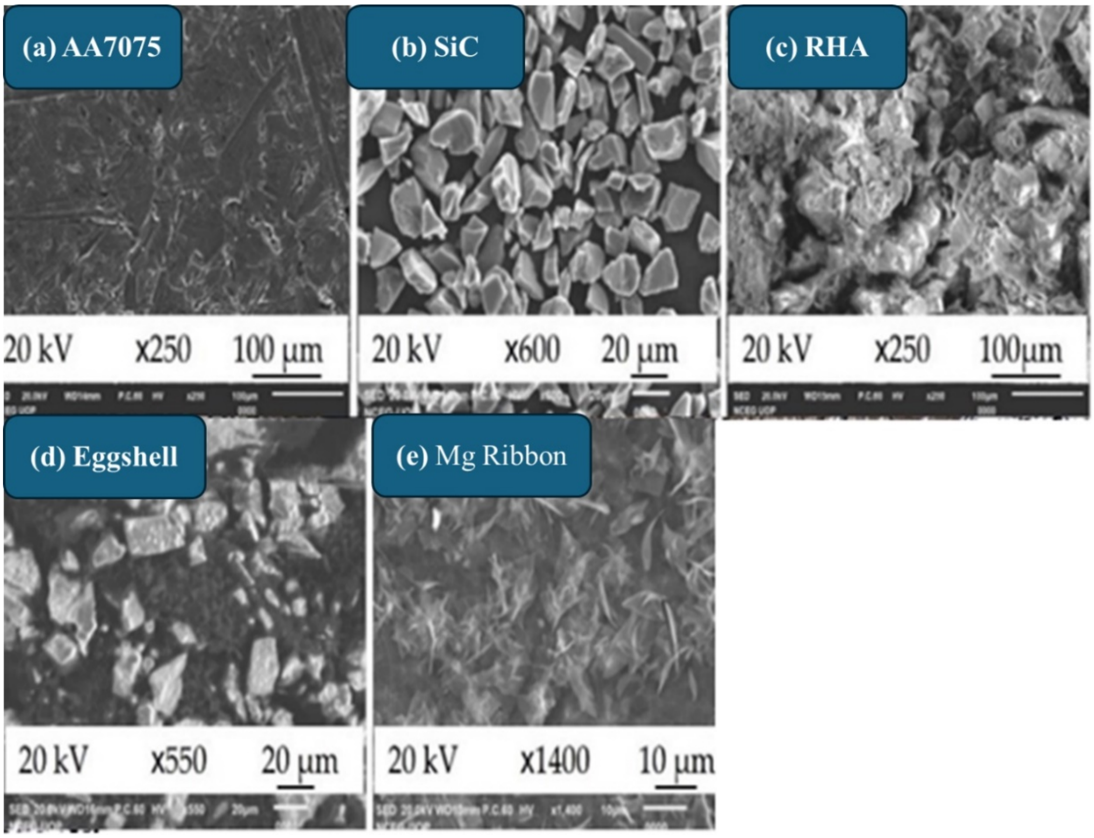

Figure 2:13 SEM (a) AA7075 and Reinforcements particles

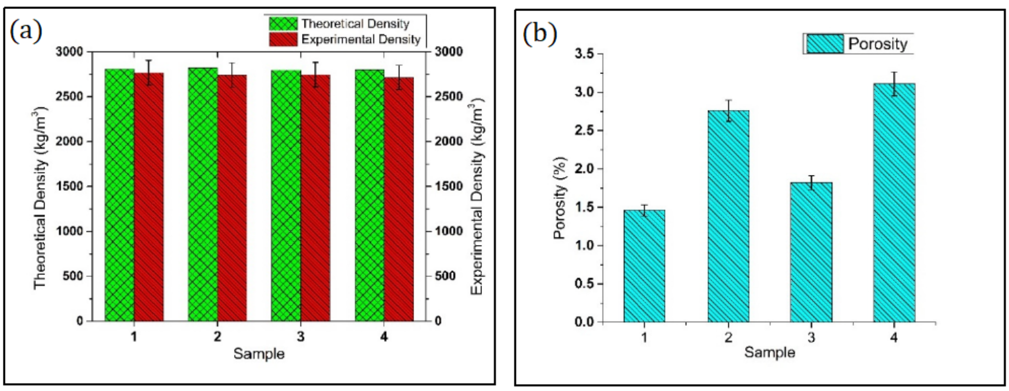

Figure 2:14 Densities and porosity of HMMCs [55]**.**

The developed samples exhibited densities that matched theoretical values, indicating that the production process was successful. The n-HMMC had the maximum porosity of 3.11% together with the lowest density. Even though n-HMMC outperformed the base alloy in terms of UTS by 24.4% and hardness by 32.8%, its ductility and impact strength were reduced by agglomerates in the matrix, which caused stress concentration.

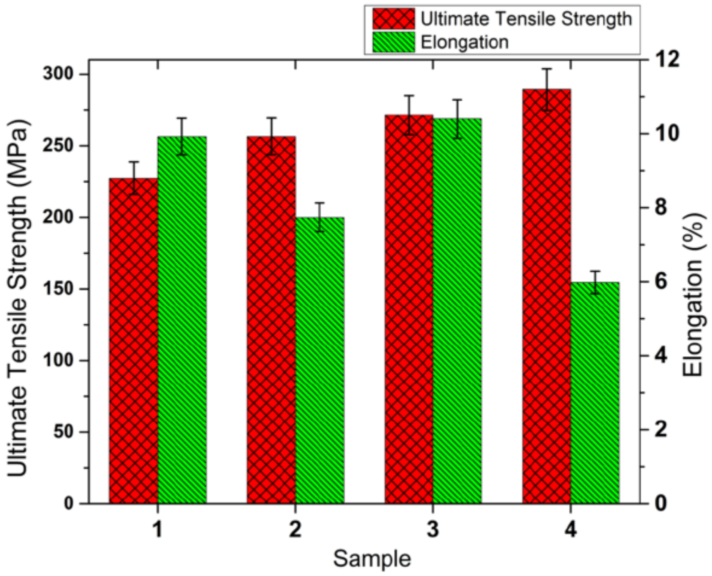

Figure 2:15 Strength and Elongation of HMMCs [55]**.**

The novel ternary reinforced HMMC outperformed the MMC and its base alloy in terms of mechanical characteristics despite the difficulties in mixing [55].

Adding graphene to aluminum alloy as a reinforcement boosts its mechanical strength, thermal and electrical conductivity, wear resistance, and corrosion resistance. The outstanding features of graphene, such as its high strength, light weight, superior thermal and electrical conductivities, and self-lubricating properties, enhance the performance of the composite. These composite materials are ideal for applications requiring strength, thermal management, electrical conductivity, and resistance to wear and corrosion, and are utilized across various sectors like electronics, automotive, and aerospace. Bastwros et al. focused on using a ball milling technique to produce an Al6061 composite with 1.0 wt% graphene reinforcement. The study found that the flexural strength increased by up to 47% compared to the standard Al6061 processed in the same way [56].

Raj et al. concentrated on developing and evaluating graphene-reinforced aluminum alloy 7075. The composites were produced using a mechanical alloying process under wet conditions. Uniaxial die pressing was employed to increase densification, followed by sintering in an inert atmosphere. Since longer milling times resulted in more refined grains, adding graphene to nanocomposites increased their density. Effective dissemination of graphene in the aluminum matrix was shown by XRD and TEM analysis. The incorporation of graphene led to a proportional increase in composite hardness, attributed to grain refinement. Wear morphology analyses revealed abrasive and plowing wear mechanisms in microcomposites, while adhesive wear with delamination and particle pull-out were identified in nanocomposites.

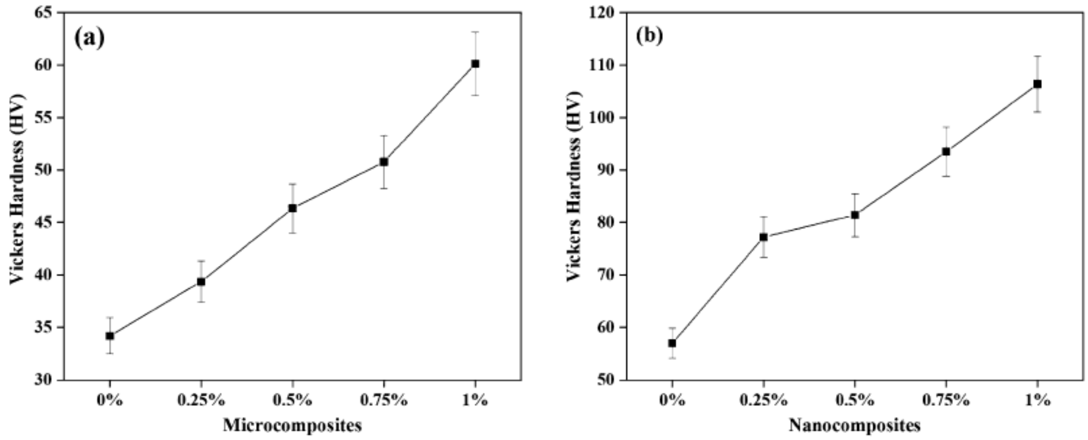

Figure 2:16 Vickers Hardness [57]

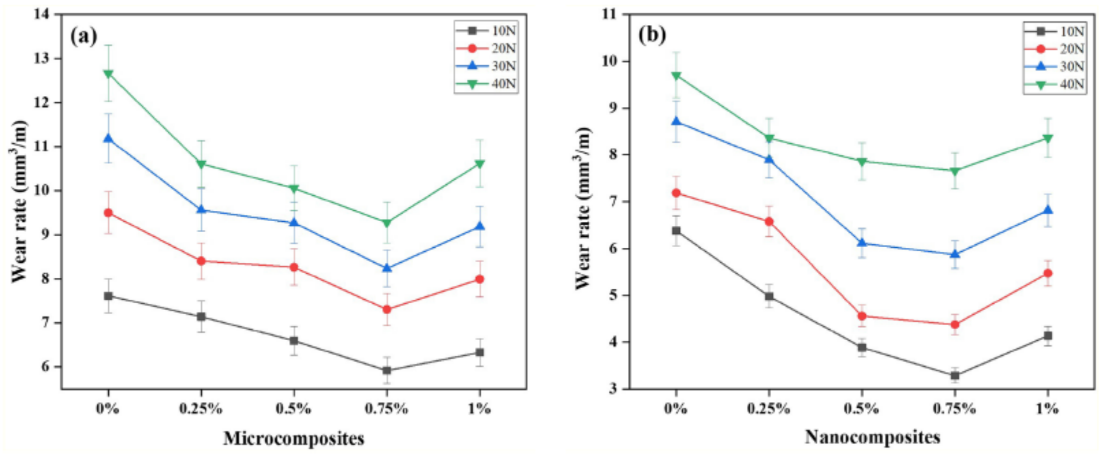

Figure 2:17 Wear Rates [57]

As depicted in Figures 2.16 and 2.17, the incorporation of graphene improved the hardness and wear resistance of the nanocomposites, reaching a peak hardness of 106.4 HV with 1 wt% of graphene. However, when exceeding 0.75 wt%, an excessive quantity of graphene led to agglomeration and increased brittleness, negatively impacting the wear rate [57].

Mechanical characteristics of AA6351 are considerably improved with the inclusion of Si_3N_4 as reinforcement. Mohanavel et al. developed aluminum composites by adding Si_3N_4 particles as reinforcement to the AA6351 matrix. The composites were developed using various weight fractions of Si_3N_4. The findings displayed in Figures 2.18 and 2.19 demonstrate that increased Si_3N_4 reinforcing weight percentages enhanced the AMCs' tensile strength, hardness, and compression resistance. Moreover, the wear rate dropped when nano sized Si_3N_4 reinforcement was added; the lowest wear rate was seen at 3 weight percent Si_3N_4 content.

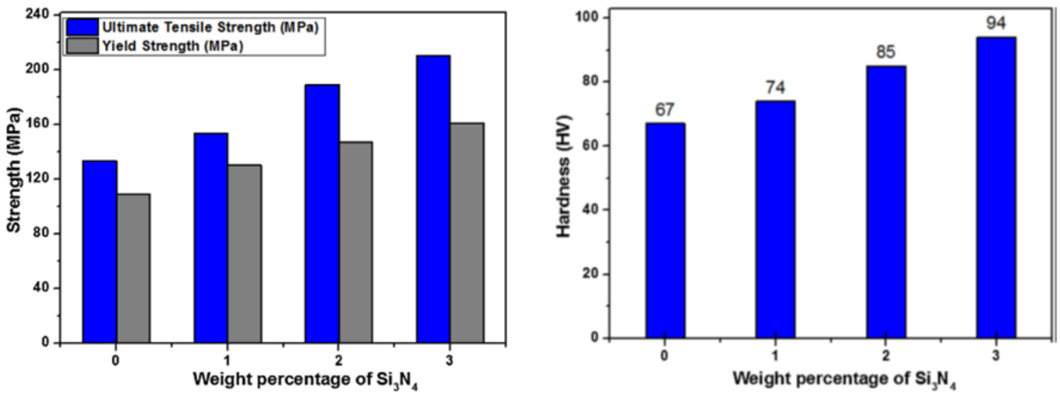

Figure 2:18 Strength and Micro-Hardness [58]

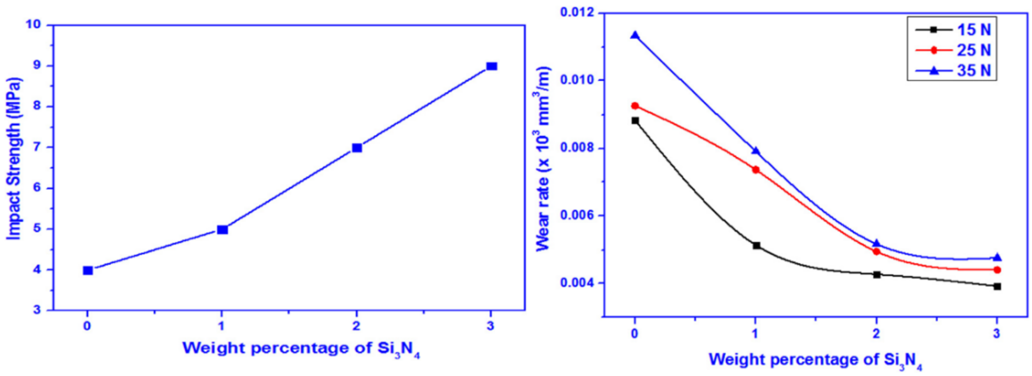

Figure 2:19 Impact Strength [58]

The analysis of the microstructure verified the even distribution and strong bonding between the matrix and reinforcement materials. The AA6351 composites with 3 wt.% Si3N4 demonstrated a 57.89% increase in tensile strength compared to the AA6351 alone [58].

Kumar et al. Studied AA6061-T6 added with 15 and 20 wt% of Si_3N_4 particles using bottom discharge arrangement stir casting furnace to ensure proper mixing of reinforcement. The addition of 2 wt% magnesium in the melt, appropriate stirring speed, and incorporation time were crucial in achieving good wettability and uniform dispersal of Si_3N_4 in the developed metal matrix composite.

The inclusion of Si_3N_4 reinforcement resulted in a substantial increase in the microhardness, macrohardness, and UTS of the composite. In the case of the AA6061 reinforced with 20 wt.% Si_3N_4 composites, the microhardness and macrohardness measured 98 VHN and 91 BHN, respectively, representing a 117.8% and 111.63% improvement over those of the AA6061 matrix alloy. Likewise, the composite's UTS rose from 159.82 MPa to 249.12 MPa. However, the composite's percent elongation decreased after the addition of Si3N4 reinforcement, suggesting a reduction in ductility [59]. Similar results were shown by AA6082-T6 reinforced by Si_3N_4 [60].

Mondal et al. examined the dry sliding wear characteristics of the AA6351 reinforced with variable amounts of Al_4SiC_4 under low sliding speed and high loads. The abrasive wear mechanism, which includes micro-cutting and micro-ploughing, occurs at high stresses. Comparing the unreinforced Al alloy to the Al4SiC4 reinforced composites, the composites show greater wear rates. This is primarily because cavitation along with rapid material removal from the surface are caused by the removal of reinforcing particles by micro-cutting abrasion.

This is in contrast to the author's earlier findings at lower loads, when the Al6351-Al_4SiC_4 composites' wear endurance was enhanced by the presence of Al_4SiC_4 particles. Wear mechanisms such as adhesion, abrasion, and oxidation occur during sliding. The material type, sliding speed, load, and ambient factors all affect how quickly material is removed from the surface. Higher loads cause abrasive wear in the Al-Al4SiC4, which removes material from the surface quickly [61].

The incorporation of carbon nanotubes (CNTs) as reinforcement significantly improves the mechanical and thermal properties of aluminum alloys. Aluminum Alloy reinforced with CNTs demonstrates enhanced tensile strength, stiffness, and thermal conductivity in comparison to pure aluminum. The aerospace, automotive, and electronics industries have a strong demand for lightweight materials with exceptional strength and heat dissipation capabilities, making these composites highly desirable in these sectors. Moreover, the exceptional electrical conductivity of CNTs makes these composites suitable for applications involving electrical and thermal management, such as heat sinks and electronic packaging. However, achieving a uniform distribution of CNTs in the aluminum matrix and preventing agglomeration poses a significant challenge during the manufacturing process. Employing proper dispersion techniques and precise control of CNT content are essential for unlocking the full potential of these advanced materials. The versatility and scalability of CNT production methods contribute to the growing anticipation surrounding their extensive utilization in future technologies [62].

Refaai et al. studied Al7149 alloy reinforced with multiwalled carbon nanotube (MWCNT) developed using liquid metallurgy route. The study aims to optimize the parameters to produce these composites and investigate their mechanical properties. The optimal mechanical properties in the composite were achieved by incorporating 1 wt% multiwalled carbon nanotubes, 0.75 wt% magnesium, and stirring for 10 minutes. This resulted in a composite with an ultimate tensile strength of 278.1 MPa and a hardness of 107.8 HV. The composite displayed a remarkable 108.4% improvement in ultimate tensile strength and a 76.3% increase in hardness compared to the Al7149 alloy. However, increasing the carbon nanotube concentration beyond 2 wt% by volume was found to reduce the toughness of the composite due to accumulation in the metal matrix. Additionally, the mechanical properties were significantly influenced by the addition of magnesium, with 0.75 wt% of magnesium contributing to higher values for hardness and ultimate tensile strength [63].

The inherent hardness of titanium-based materials has prompted extensive research into their use as reinforcements for aluminum alloys. The incorporation of TiC reinforcement greatly enhanced the composites' mechanical and load-bearing capabilities, indicating their potential as materials for automotive applications, particularly in crucial structural elements such as the steering knuckle [64].

Ravikumar et al. studied stir casted AA6082 reinforced with a varying concentration of TIC from 2 wt% to 10 wt%. Results showed improved improvement in mechanical characteristics with increasing TiC, but it eventually decreased after reaching 8% by weight. Because of the robust interfacial interaction among tungsten carbide and the aluminum matrix at high strain rates, fracture analysis revealed brittle fractures with cracks and particle fracture [65].

In a similar study, Kumar et al. reviewed the development and characterization of MMC consisting of Al-Cu alloy (2014 series) matrix reinforced with Titanium Carbide (TiC) using the in-situ method. Ti and activated charcoal powder were mixed through in-situ method to get uniform dispersal. The fabricated hybrid reinforced with 4.5 wt% Cu and 10 wt% TiC exhibits enhanced mechanical properties compared to the composite reinforced with 4.5 wt% Cu alloy. The addition of TiC resulted in an approximate 15% increase in yield strength, a 24% increase in ultimate tensile strength, and a roughly 35% increase in hardness. The fracture morphology exhibited a ductile type of fracture [66]. Furthermore, Reddy et al. observed that the coefficient of thermal expansion (CTE) of TiC-reinforced aluminum nanocomposites decreased with the gradual addition of TiC nanoparticles [67].

Radhika et al. investigated the development and characterization of an LM25 alloy reinforced with 10 wt% TiC using the liquid metallurgy method. Microstructural analysis reveals a uniform distribution of TiC particles within the matrix, resulting in enhanced hardness and tensile strength. The composite's hardness is observed to increase by about 35% compared to the base LM25 alloy. Wear studies indicate that the wear rate increases with higher applied loads, decreases with higher sliding velocities, and exhibits a nonlinear relationship with sliding distance [68].

Arivukkarasan et al. examined the mechanical and tribological properties of an LM4 alloy reinforced with WC, produced via stir casting.

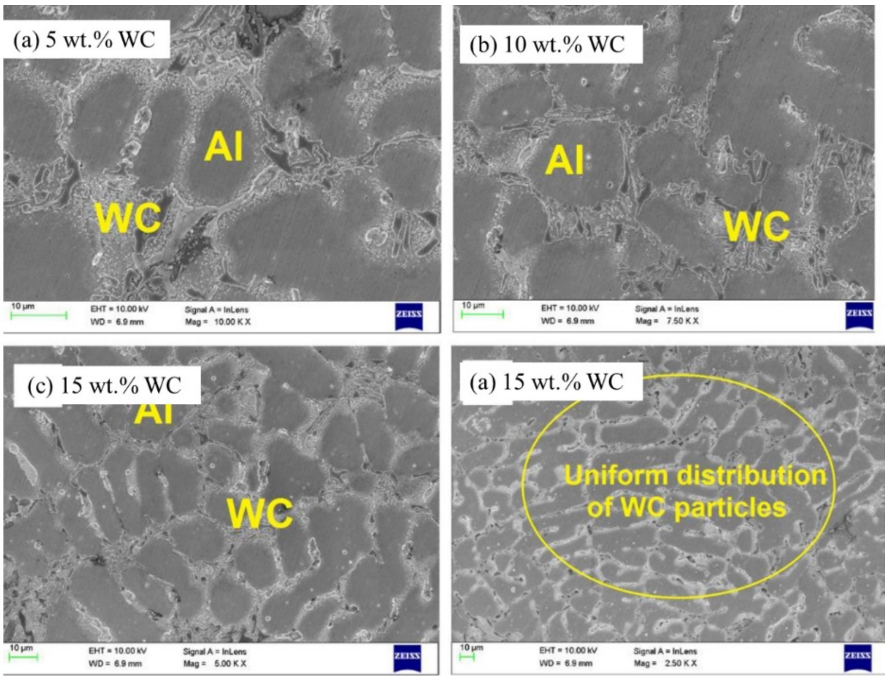

Figure 2:20 SEM of Developed Composite [69].

The research showed that increasing the WC content improved the alloy's mechanical properties. Additionally, wear tests revealed that the composite with 15 wt.% WC exhibited lower wear rates. The results highlight the crucial role of processing parameters and wettability in ensuring uniform distribution of reinforcement particles, thereby enhancing the composite's performance [69].

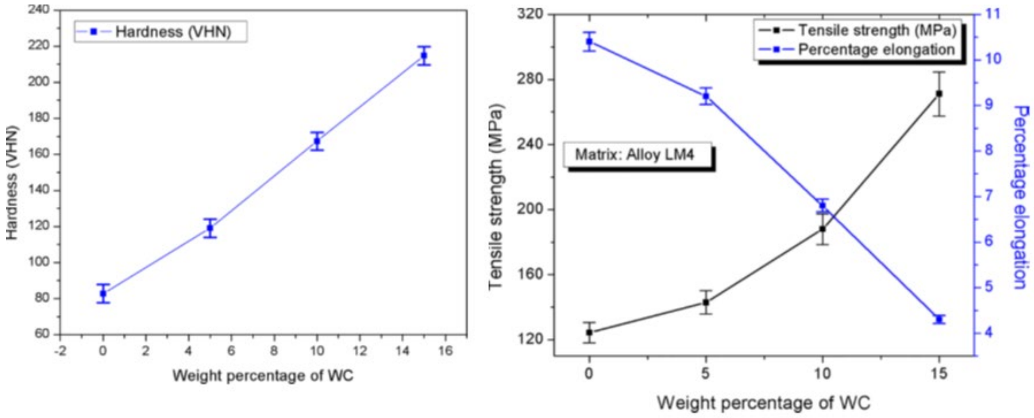

Figure 2:21 Impact Strength Vs Reinforcement [69]

Mohanavel et al. studied TiB2 reinforced AA6351 developed through in situ reaction of halide salt. The findings indicated that TiB_2 particles were evenly dispersed throughout the aluminum matrix, and the mechanical properties improved with higher weight percentages of TiB_2. Composite with 5 wt % TiB_2 is 15.38% stronger than AA6351 matrix, simultaneously it reduced the elongation of the composites. The resultant composites, which are stronger and more resistant to wear than unreinforced alloys, have prospective uses in a variety of industries, including automobile, aviation, transportation, and maritime [70]. Some other studies also shown similar improvement in mechanical and tribological characteristics of TiB_2 reinforced [71][72][73].

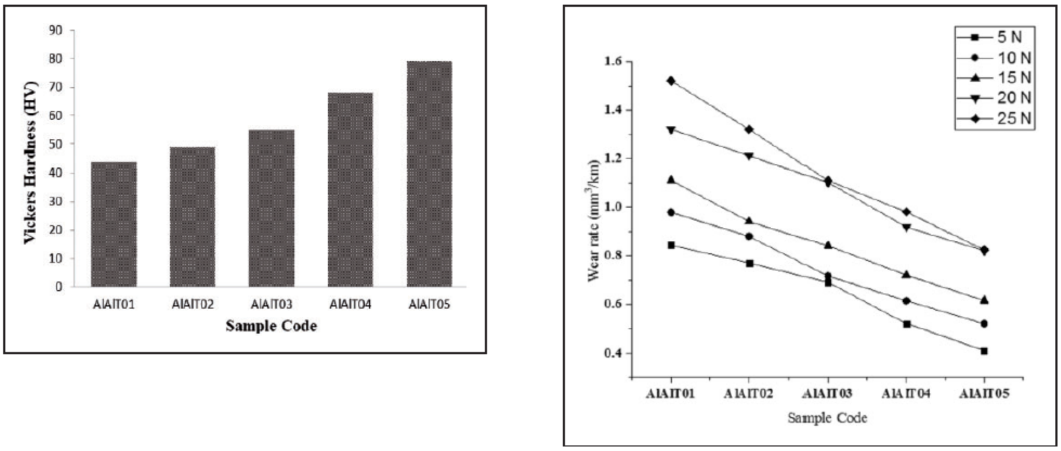

Figure 2:22 Vickers Hardness and Wear Rate [74].

Gui-rong et al. studied Al_3Ti reinforced aluminum alloy fabricated using electromagnetic stirring process. Fluxes were introduced to decrease the reaction temperature and accelerate the emulsion process of K_2TiF_6. The combination of these approaches led to refined endogenetic Al_3Ti particles, which decreased in size from 10−15 μm to 2−4 μm, as compared to composites without EMS and fluxes [75].

Ahamad et al. focused on investigating the Vickers hardness, wear behavior for Al-Al_2O_3 & TiO_2 reinforced AMC developed through mechanical stir casting. when weight percentage of reinforcements increased, so did Vickers hardness. Because titanium oxide particles have lubricating qualities, it has been shown that the hybrid composite's wear resistance rises as the amount of titanium oxide particles increases. The study used analysis of variance (ANOVA) to examine how load and reinforcements affected the specimens of the Al-Al_2O_3-TiO_2 hybrid composite's rate of wear. Furthermore, the samples were sorted according to their wear rates using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) analysis [74].

Proton exchange membrane fuel cells (PEMFCs), which have been shown to be a promising technology for sustainable energy, but difficult to widely adopt due to catalyst degradation and high material prices. A novel electrocatalyst based on nano-sized Pt-NbOx supported by TiN nanoparticles was developed by Daudt et al. as a substitute for conventional Pt/C electrocatalysts for the oxygen reduction process (ORR) to solve this problem. Pt–NbOx is used to improve catalyst performance and save material costs by reducing the amount of platinum that must be loaded [76].

Researchers are increasingly turning their attention to the use of post-consumer and agro-waste materials, which are cost-effective and have shown the potential to enhance various applications. Sydow et al. explore the use of waste materials as reinforcement in composites. Given the global challenge of waste management, recycling these materials for composite production not only carries environmental benefits but also bolsters strength and wear [77] [78]. Shaikh et al. studied hybrid composite developed by reinforcing fly ash and SiC using the powder metallurgy. The microstructural analysis indicates that increasing the fly ash content to 15% leads to decreased consistency, as the ash particles tending to segregate. In comparison to the base matrix and unreinforced Al-SiC composites, AMCs containing 10% SiC and 10% fly ash had the best hardness and wear resistance [79] [80]. Using sugarcane bagasse ash or RHA particles instead of fly ash have similar effect on the mechanical and wear characteristics of the aluminium metal matrix composite [81] [82] [83] [84].

Canute et al. produced a composite by reinforcing A356 with 4 wt% boron carbide powder and 4 wt% fly ash using stir casting. The mechanical properties of the hybrid composite's matrix showed significant improvement, though its ductility decreased. The wear rate of the hybrid composite increased with higher applied load and temperature but decreased with higher sliding velocity. The optimal wear rate was achieved at a load of 10 N, a sliding velocity of 3 m/s, and a temperature of 60°C [85].

Chechi et al. developed a novel hybrid metal matrix composite using scrap aluminum alloy reinforced with alumina oxide, graphite, and fly ash. The research reveals that the fabricated composite exhibits a fine grain structure compared to the as-cast aluminum alloy. Grain refinement, shear lag mechanism, and dislocation bending are responsible for the composite's better mechanical behavior. A transition from ductile to cleavage fracture is seen in the composite according to uniaxial tensile testing. 60°C in temperature and 3 m/s of sliding velocity. The maximum impact strength is achieved in the 10 wt% Al_2O_3-reinforced hybrid composite. Comparing the composite casted aluminum alloy, the tensile strength, hardness, and compressive strength are enhanced by around 34%, 63%, and 32%, respectively [86]. Al6061 reinforced with alumina and graphite shows improvement in wear characteristics of the hybrid as compared to Al6061 [87].

To optimize the characteristics of Al 6351/eggshell reinforced composite, Okoye et al. employed non-dominated sorting genetic algorithm-II, artificial neural networks, and response surface methodology. The study focused on enhancing the composite's toughness and hardness by adjusting production process parameters such as stirring duration, speed, and preheating temperature. A strong correlation (correlation coefficient > 0.9982) between experimental values and ANN predictions, using a Box-Behnken Design for the experimental setup and RSM model construction. The resulting optimized Pareto front serves as a valuable reference for engineering applications. The ANN model was integrated into NSGA-II for multi-objective optimization. Utilizing eggshell particles as reinforcement aligns with sustainable development goals and underscores the potential of AI-driven techniques for designing composites with specific properties [88].

Singh et al. developed a composite using Al7075-T6 as the base matrix, reinforced with graphite powder, waste tire rubber powder, and S-glass fibers through the stir casting process. Microstructural analysis, performed using optical microscopy, revealed that the reinforcements were uniformly distributed with fine grain boundaries throughout the base matrix. The resulting hybrid composite demonstrated a substantial increase in microhardness (up to 37.93%) and a slight reduction in surface roughness (up to 2.86%) compared to the unreinforced base matrix.

To enhance the outcomes, the Taguchi method and analysis of variance (ANOVA) are utilized. The contribution percentage of each reinforcement material is assessed, highlighting graphite powder and S-glass fiber as the most influential factors in enhancing microhardness and surface roughness [89].

Venkateswarlu et al. studied mechanical characterization of novel AA6351 reinforced with Al_2O_3 and Gr using a liquid metallurgy. The findings demonstrated that the AMCs' compression strength was considerably improved in compare of pure Al matrix and increase as dual particle concentration increased. Out of all the compositions, the composite reinforced with 3 wt% Gr and 20 wt% Al_2O_3 showed the maximum hardness, tensile strength, yield strength, and compression strength. Particles of alumina enhanced the tensile strength and counteracted the weakening impact of graphite. Furthermore, enhanced hardness resulted from the very homogeneous distribution of dual particles in the matrix. [90].

Oddone et al. used spark plasma sintering (SPS) to develop Al-Gr composites with remarkable thermal properties tailored for high-performance electronics and mobile applications. Incorporating up to 50 vol.% macroscopic graphite particles enabled the researchers to effectively manipulate the thermal expansion coefficient (CTE) of magnesium and aluminum alloys to zero or negative values, while achieving a specific thermal conductivity nearly four times higher than that of copper. Following thermal stress testing and cycling, the composites exhibited no evidence of degradation, underscoring their exceptional mechanical stability.

These lightweight materials demonstrated superior thermal management capabilities, outperforming copper in specific heat sink applications, making them ideal for use in mobile devices and aerospace technologies, where lightweight construction and efficient heat dissipation are crucial factors [91].

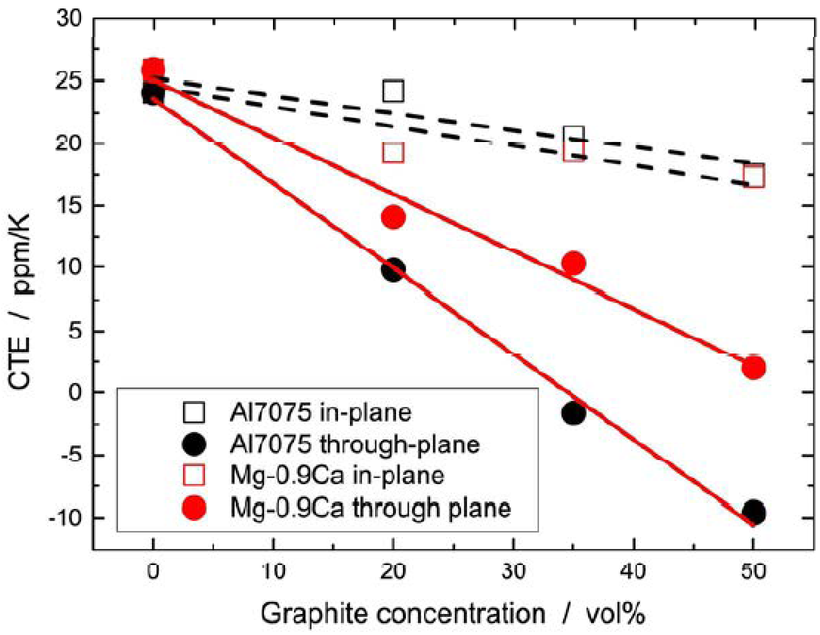

Figure 2:23 CTE vs % Reinforcement [91].

Sharma et al. studied microstructure of Al6082 reinforced 0 wt% to 2% in 3 wt% graphite. All weight percentages of Gr showed a non-uniform distribution of graphite particles. The soft Gr particles floating in high quantities caused the hardness of the composites to diminish as the amount of Gr reinforcement grew, increasing impurities on the aluminum melt's surface. Nonetheless, the lubricating impact of the Gr particles was identified as the cause of the composites' increased wear resistance [92].

Kumar et al. studied AA6351 aluminum alloy reinforced with varying proportion of ZrB_2 developed through an in-situ reaction method at 850°C. The results specified that as the ZrB_2 weight proportion increased, the wear resistance increased. The composites exhibited enhanced hardness and wear resistance, with the 9% ZrB_2 reinforced composite showing the highest performance. These findings suggest that these in situ composites have potential for applications requiring high-temperature performance and superior wear resistance.[93].

In another study, Kumar et al compared the abrasive wear behavior of functionally graded metal matrix composites and homogeneous composites, specifically aluminum/aluminum nitride (Al/AlN) and aluminum/SiO2 composites, developed through different methods. The outer surface wear resistance of AlN-reinforced FGM was observed to be highest, with SiO2-reinforced FGM trailing closely behind. Microstructural analysis revealed a high-hardness particle-enriched region on the surface of AlN/ FGM. While homogeneous composites demonstrated a higher tensile strength compared to functionally graded material counterparts, the research suggests that particulate-reinforced aluminum metal matrix composites offer promising applications in the automotive and aerospace sectors due to their superior mechanical properties, lightweight nature, specific strength, stiffness, and wear resistance [94].

Kumar et al. also explored the dry sliding wear characteristics of Al–4Mg alloy and Al–4Mg alloy/$MgAl_2O_4$ in-situ composites under varied conditions. H_3BO_3 powders were introduced during the ultrasonic cavitation process to fabricate the in-situ composites. It was found that the addition of $MgAl_2O_4$ significantly reduced the wear rate of Al–4Mg alloy, especially under higher loads. Figure 2.24 illustrates that the composite exhibited a minimum friction coefficient at a critical speed of 5 m/s and a normal load of 30 N, with friction coefficients ranging between 0.2 and 0.4. The dominant wear mechanisms identified in the study encompassed plastic deformation modes, adhesion, delamination, oxidation, abrasion, and thermal softening. Scanning electron microscopy and X-ray diffraction were employed to examine the worn-out samples and wear debris, aiding in the understanding of wear mechanisms in the produced composites.

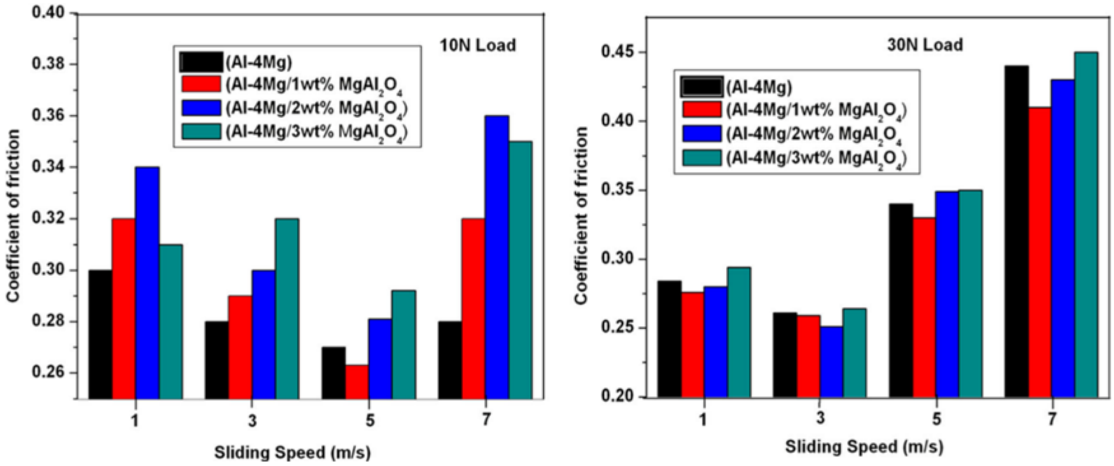

Figure 2:24 Coefficient of Friction [95]**.**

The findings suggest that the in-situ synthesis technique enhances adhesion between the particle-matrix interface, thereby enhancing the mechanical properties and wear resistance of the composite. The research underscores the potential applicability of in-situ composites comprising Al–4Mg alloy and $MgAl_2O_4$ for various applications that demand superior wear resistance and mechanical performance [95].

Sam et al. employed the horizontal centrifugal casting technique to fabricate a functionally graded Cu–Sn–Ni/Al_2O_3 metal matrix composite, focusing on its mechanical and tribological properties for bearing applications. The composite's microstructure was examined at different radial distances from the outer periphery. Tensile strength testing was conducted on samples from both the outer and inner zones of the casting, revealing higher tensile strength in the inner zone. Fractographic analysis of fractured surfaces in the inner zone indicated a combination of brittle and ductile failure mechanisms. Wear rate was found to increase with sliding distance and load, with a non-linear trend initially decreasing and subsequently increasing with sliding velocity. Scanning electron microscope analysis of worn surfaces revealed the formation of a mechanically mixed layer (MML) and the influence of various factors on wear mechanisms [96].

Marami et al. aim to enhance the mechanical properties of commercially pure aluminum by investigating the combined effects of several parameters. This research explores the impact of factors such as the temperature of melt overheating, the positioning of the gating system, and the application of grain refiners in both bar and micro-powder forms on the mechanical properties of pure aluminum. The study reveals that increasing the melt temperature and utilizing a gating system with high heat transfer can boost pure aluminum's ultimate tensile strength by up to 7%. Moreover, the addition of 2 wt% Al–5Ti–1B grain refiner in bar form doubles the ultimate tensile strength, while the micro-powder form achieves a 32% higher UTS, attributed to the elimination of the brittle Al_3Ti phase, as confirmed by SEM images and XRD patterns. This research underscores the importance of these variables in optimizing the mechanical properties and microstructure of pure aluminum, offering valuable insights for applications in sectors like automotive manufacturing, where high strength, weldability, and corrosion resistance are crucial [97].

Kathiravan et al. studied the development of sustainable aluminum metal-matrix composites (AMCs) by incorporating ground granulated blast furnace slag (GGBS) into aluminum 6061 alloy. The microstructural and machinability characteristics of these composites are studied to optimize their performance for various applications.

The study concludes that incorporating GGBS into aluminum 6061 results in a uniform distribution and effective bonding at the interface between the particles and the matrix, thereby enhancing the material properties of the composite. Additionally, the Taguchi technique demonstrated its effectiveness in determining optimal cutting parameters for milling operations, thereby improving the efficiency and quality of the machining process for these advanced metal composites (AMCs) [98].

Luo et al. studied the mechanisms of strengthening aluminum matrix composites reinforced with high-entropy alloy particles (HEAp) ranging from 1-6 wt% Al0.5CoCrFeNi through stir casting. According to the results, the ultimate tensile strength of the AMCs steadily rises, and the grains get finer as the HEAp concentration increases. With an elongation of 32.1% and a UTS of 115 MPa, the composite containing 3 wt% HEAp has the best mechanical characteristics. The theoretical values of the yield strength prediction model, which is based on the indirect reinforcing effect of HEAp in AMCs, correspond well with experimental findings [99].

Abishini et al. focused on employing multicriteria decision-making (MCDM) techniques to select the most suitable aluminum alloy material for sheet metal forming. These methods included AHP, TOPSIS, EDAS, VIKOR, and the Taguchi-based super ranking concept. Using the Taguchi super ranking principle, the study assessed various aluminum alloys based on parameters such as surface expansion ratio (SER) and indentation depth (IE, mm). The results demonstrate that MCDM and the Taguchi-based super ranking concept offer an innovative and systematic approach to material selection in sheet metal forming processes. Among the aluminum alloys studied, AA2024 emerged as the most suitable material for sheet metal forming operations. Additionally, the study suggests that MCDM approaches like TOPSIS, VIKOR, and EDAS can be utilized to determine the optimal alternative material for sheet metal forming. The combination of MCDM approaches with process simulation provides a methodical approach to material selection and process parameter optimization [100].

By employing the accumulative roll bonding (ARB) method, Medjahed et al. developed composite strips reinforced with titanium-carbide (TiC) microparticles, based on an Al-Li-Cu-Mg-Zr alloy. Through experimental investigation and comparison with the as-hot-rolled and unreinforced states, the microstructure, mechanical characteristics, and thermal conductivity of the treated composites were examined. The reinforced sheets showed good reinforcement dispersion following the second ARB cycle. Enhancements in the overall characteristics of the ARBed strips were seen upon increasing the TiC concentration to 2 wt% percent. After two ARB cycles, the composites containing 2 wt% TiC showed better tensile and bending strengths of 380.79 MPa and 623.69 MPa, respectively. These values were substantially greater than those of the as-hot-rolled and unreinforced sheets during the same cycle.

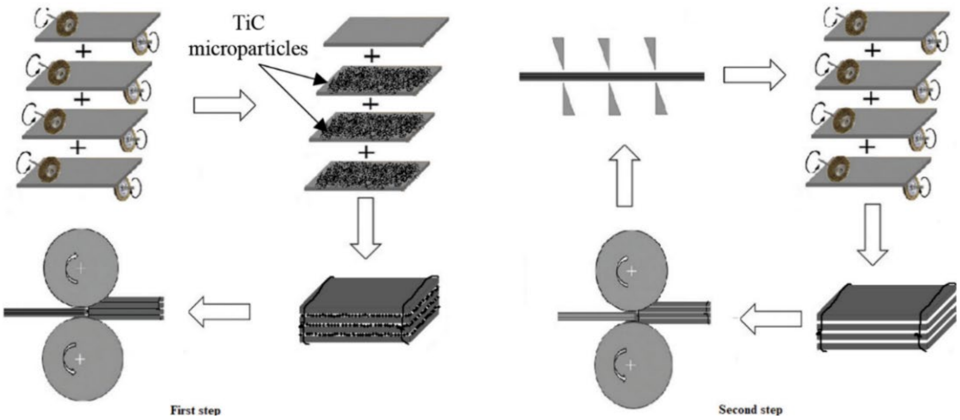

Figure 2:25 Schematic illustration of the ARB Process [101]

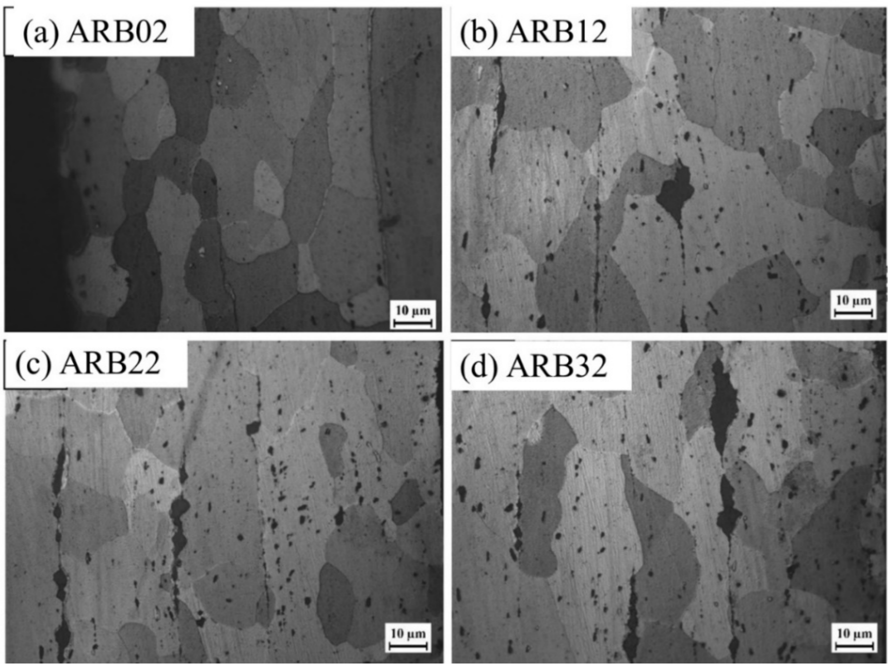

Figure 2:26 Microstructure of fabricated samples [101]

Additionally, the tensile elongation and thermal conductivity of these composites were adequate. The specimens' excellent elongations were shown by the fracture morphologies, which showed a ductile-shear mixed fracture [101].

2.1 RESEARCH GAPS

After conducting an extensive review of the existing literature on metal matrix composites, including the types of reinforcements commonly used in their development and the various processes employed for their fabrication, a comprehensive understanding of the subject matter was achieved. Through this rigorous examination, the following specific gaps in the literature were identified.

- Few relevant literatures are available regarding Graphite/TiC/B_4C/WC being used as a reinforcement in AA6351 matrix.
- Few Comparative study is available for different carbides reinforcement.
- There is a lack of proposed application of these four reinforcements.

2.2 RESEARCH OBJECTIVES

To address the identified research gaps in the field of hybrid metal matrix composites, the following research objectives were defined:

i. To develop a hybrid metal matrix composite of AA6351 reinforced with (B_4C + Gr), (TiC + Gr), (WC + Gr) and (B_4C +TiC + WC) using stir casting method.

ii. Structural behavior of AA6351/Graphite/B_4C/ TiC/WC Hybrid Metal Matrix Composite will be carried out using XRD for phase detection and SEM along with EDX for microstructural and elemental analysis.

iii. Mechanical behavior of AA6351/Graphite/B_4C/ TiC/WC Hybrid Metal Matrix Composites will study using Hardness test, Impact test, Tensile test and benchmarked with AA6351.

iv. Wear Study of above fabricated composites using variable load, sliding distance, sliding time and interfacial conditions benchmarked with AA6351.

These objectives aim to enhance understanding of the structural, mechanical, and wear properties of hybrid metal matrix composites, providing valuable insights for potential applications of developed hybrid metal matrix composite.

Chapter 3: Experimental Work

This chapter provides a comprehensive overview of the fabrication process employed for creating diverse specimens, along with a detailed analysis of their structural and mechanical attributes. The widely utilized stir casting technique serves as the foundation for producing three distinct hybrid composites: AA6351/Gr/B_4C, AA6351/Gr/TiC, AA6351/Gr/WC and AA6351/B_4C/TiC/WC.

To explore the complexities, a variety of essential characterization techniques are utilized. X-ray diffraction (XRD) is employed to delve into the crystallographic structure of the composites. Scanning electron microscopy (SEM) provides insight into the microstructure of the prepared specimens, allowing for a thorough examination of the organization and dispersion of reinforcement materials within the aluminum matrix. By utilizing energy dispersive spectroscopy (EDS), the elemental composition of the fabricated composites is identified, enhancing understanding of their chemical makeup.

Physical attributes are studied through density measurements, while hardness testing assesses the resistance of the composites to indentation. The capacity of the materials to withstand abrupt forces is evaluated through impact strength assessments. Tensile strength testing is undertaken to quantify the maximum stress threshold the composites can withstand before experiencing failure. Additionally, wear analysis investigates the wear resistance of the hybrid composites, a vital consideration for applications encountering friction and abrasion. TOPSIS technique is used for finding the ranking of the developed hybrid metal matrix composite metal matrix based on the mechanical characterization.

Based on the mechanical characteristics, one sample was selected from each batch and wear test was performed to check the wear rate and coefficient of the friction.

Subsequently, SEM examination of worn surfaces brings forth invaluable visual evidence elucidating wear mechanisms and surface transformations during wear testing. This enlightens us about the composite's response to wear-induced conditions, offering a wealth of insights into its behavior under wear-induced circumstances.

3.1 MATERIAL

For this research work, AA6351 is chosen as the primary material, serving as the matrix. It was procured in the form of aluminum ingots as shown in Figure 3.1. The chemical composition of AA6351 used for the fabrication, is as follows: 97.9 wt% Aluminum, 0.7 wt% Silicon, 0.5 wt% Magnesium, 0.5 wt% Manganese, 0.1 wt% Ferrous, 0.1 wt% Copper, 0.1 wt% Titanium, and 0.1 wt% Zinc. The density of aluminium was measured as 2.73 gram/cc. These ingots served as the fundamental building blocks for the subsequent fabrication of the composite materials. In a concerted effort to augment the mechanical attributes of the metal matrix, an array of reinforcing materials was introduced. These encompass B_4C, TiC, WC, and Graphite.

The physical appearance of these reinforcement is shown in Figure 3.2. The unique characteristics of these reinforcing materials are concisely outlined in Table 3.1.

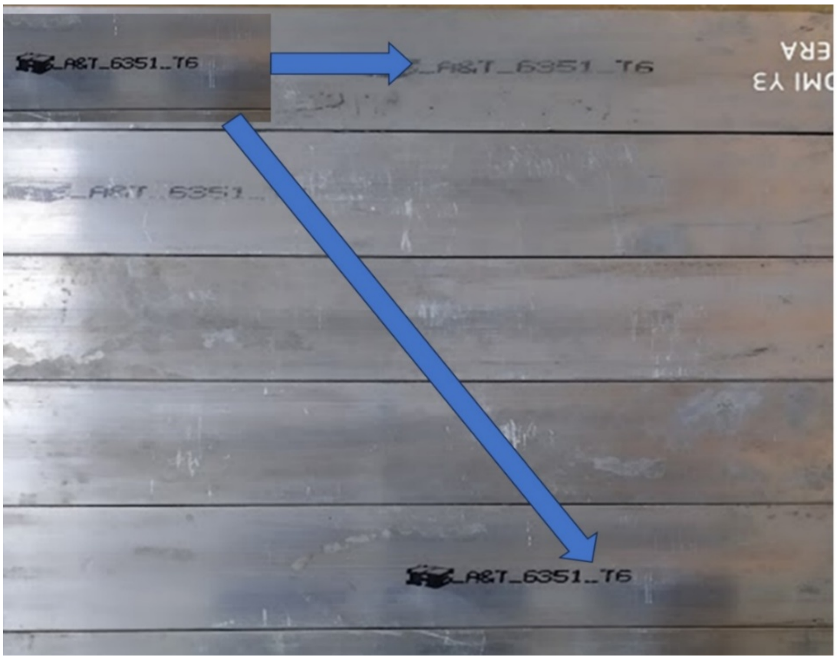

Figure 3:1 AA6351 Ingot

Table 3:1 Physical Characteristics Reinforcement

S.N	Reinforcement	Properties
1	Graphite (Gr)	Good natural lubricity. with excellent thermal, electrical and chemical resistance
2	B_4C	Highly hard and wear resistant material
3	TiC	High micro hardness, wear resistance, and compressive strength.
4	WC	Highly hard, thermally stable and good wear resistance

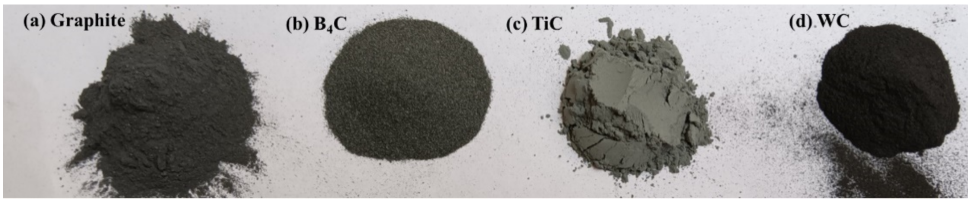

Figure 3:2 Reinforcement Used

The specified reinforcements mentioned above were employed in the development of the hybrid metal matrix. The fabrication process for the composites was conducted in different set. The first set of composites was developed by reinforcing with Graphite and B_4C. The nomenclature for these hybrid MMCs is detailed in the Table 3.2.

Table 3:2 Nomenclature of AA6351/Gr/B_4C

Sample No.	AA6351 (wt %)	Gr (wt %)	B_4C (wt %)	Sample Code
1	100	0	0	AA6351
2	99	0.5	0.5	AlGrB02
3	98	1	1	AlGrB03
4	97	1.5	1.5	AlGrB04
5	96	2	2	AlGrB05

The second set of hybrid metal matrix composites was formulated employing AA6351 as the fundamental metal matrix. In this set, both graphite and TiC were used as reinforcement materials. The nomenclature for these hybrid MMCs is detailed in the Table 3.3.

Table 3:3 Nomenclature of AA6351/Gr/TiC

Sample No.	AA6351 (wt %)	Gr (wt %)	TiC (wt %)	Sample Code
1	100	0	0	AA6351
2	99	0.5	0.5	AlGrT02
3	98	1	1	AlGrT03
4	97	1.5	1.5	AlGrT04
5	96	2	2	AlGrT05

The third set of hybrid metal matrix composites was generated using AA6351 as the foundational metal matrix. In this batch, the reinforcement materials comprised both graphite and WC. The nomenclature designating these specific hybrid MMCs is provided in the Table 3.4.

Table 3:4 Nomenclature of AA6351/Gr/WC

Sample No	AA6351 (wt %)	Gr (wt %)	WC (wt %)	Sample Code
1	100	0	0	AA6351
2	99	0.5	0.5	AlGrW02
3	98	1	1	AlGrW03
4	97	1.5	1.5	AlGrW04
5	96	2	2	AlGrW05

The fourth set of hybrid metal matrix composites was developed with AA6351 as the core metal matrix. This batch integrated a combination of reinforcement materials including TiC, B_4C, and WC. The nomenclature for these distinct hybrid MMCs is shown in table 3.5.

Table 3:5 Nomenclature of AA6351/B_4C/TiC/WC

Sample No	AA6351 (wt %)	B_4C (wt %)	TiC (wt %)	WC (wt %)
1	100	0	0	0
2	99	0.5	0.5	0.5
3	98	1	1	1
4	97	1.5	1.5	1.5
5	96	2	2	2

3.2 WEIGHING

The hybrid metal matrix composite specimens were meticulously developed using the mechanical stir casting process. Before casting, all raw materials underwent precise weighing, facilitated by an electronic weighing balance with an accuracy of 0.0001 gm and a capacity of 150 gm, obtained from Weightism Instruments Private Limited. Figure 3.3 illustrates the electronic weighing balance employed for this purpose.

Figure 3:3 Weighing Scale.

3.3 DEVELOPMENT OF HYBRID METAL MATRIX COMPOSITE

HMMCs are developed by adding reinforcement particles in molten metal by stir casting, which is referred to as the liquid metallurgy route. During the addition of the reinforcing particles, the molten metal is stirred. The hybrid metal matrix composite was developed in two stages. Figure 3.4 displays the stir casting setup utilized for the development of hybrid metal matrix composites. Figure 3.5 outlines the procedural flow for creating hybrid metal matrix composites.

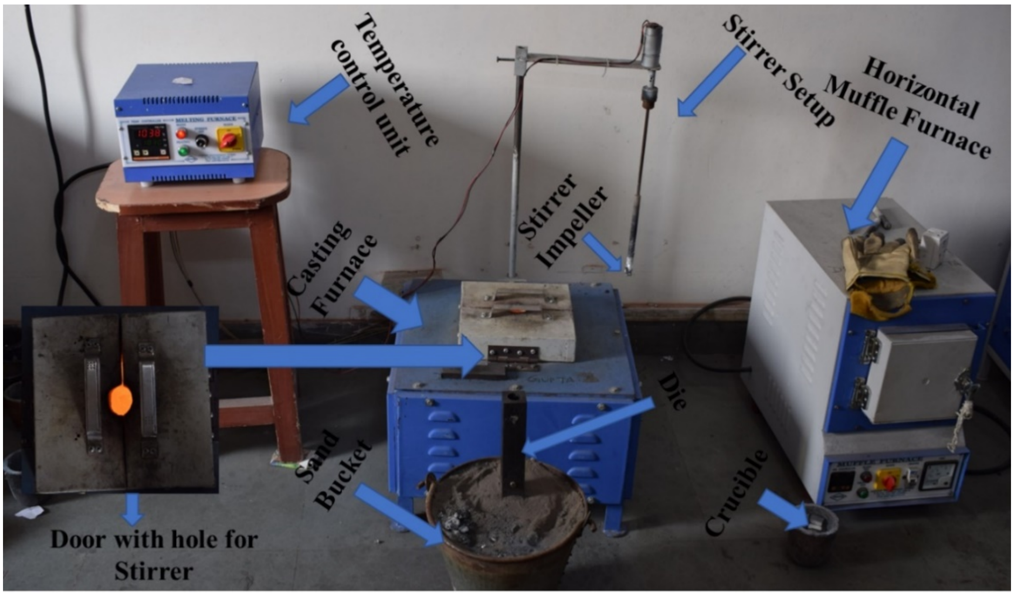

Figure 3:4 Stir Casting Setup.

3.3.1 Casting

The AA6351 bar was initially cut into small pieces, followed by weighing its weight using an electronic weighing scale. These small pieces of AA6351 were put in a crucible that had been dry-cleaned before being put into a muffle furnace with a programmed temperature control. The configuration for stir-casting is shown in Figure 3.4. The furnace includes a heating chamber measuring 200 x 200 x 300 mm, equipped with four heating lamps capable of sustaining temperatures up to 1200°C. The furnace was initially set to a temperature of 930°C, which it achieved within 30 minutes. At 650°C, the AA6351 alloy began to melt, and this temperature was sustained for 50 minutes. In addition, reinforcement weighted according to AA6351 was simultaneously placed in a horizontal muffle furnace and heated to 300°C in order to reduce moisture content and avoid oxidation during mixing.

Subsequently, the temperature of the furnace was increased to 960°C in order to compensate for the heat loss caused by the furnace door opening. Prior to adding reinforcement to the molten metal, the AA6351 was first stirred for five minutes at 300 RPM[102]. The heated reinforcement particles were mixed while being continuously stirred. In order to minimize splashing during stirring, a specially constructed impeller was employed for mixing. The blending procedure lasted around 20 minutes. Following the addition of the reinforcement, the molten mixture of AA6351, graphite, and B_4C was stirred for five minutes. This process was completed by closing the furnace door and heating the molten mixture of reinforcement and AA6351 for a further 10 minutes at a temperature of 960°C.

3.3.2 Solidification

A die with a rectangular cross-section measuring 30x30x75 mm, as shown in Figure 3.6, was manufactured using a CNC Vertical Milling Centre. The die was made from Die Steel and is intended for use in the solidification process of molten metal.

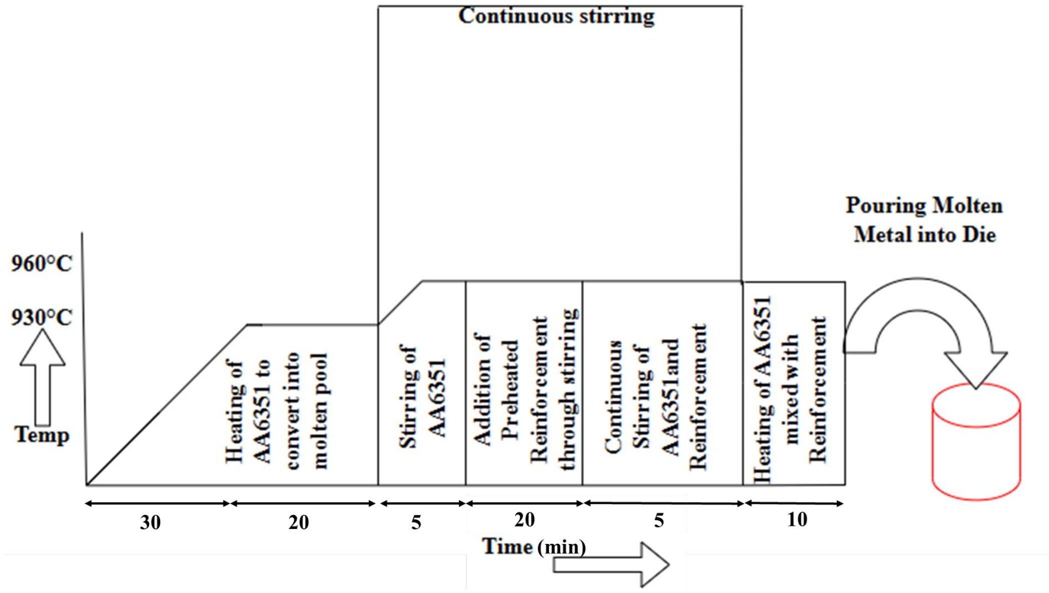

Figure 3:5 Process Flow Chart

The die was heated before use to reduce the temperature gap between the hot molten metal and the die, as well as to regulate the solidification process rate. The molten metal was then carefully poured into the preheated die. Subsequently, the die was allowed to gradually cool to room temperature. After approximately two hours, the workpiece was removed from the die, and initial machining operations were performed to eliminate surface defects.

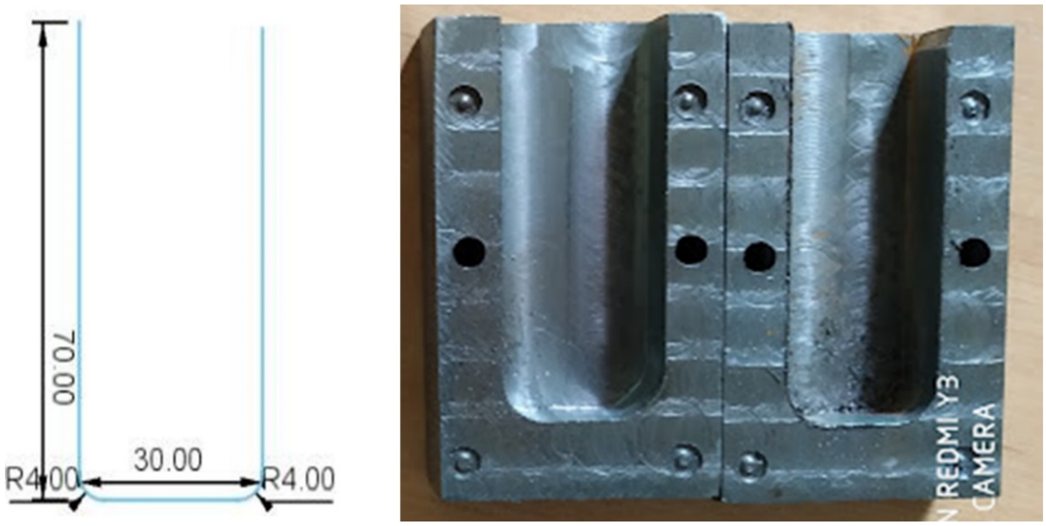

Figure 3:6 Die For Solidification.

The top of the casting was cut out by power hacksaw, as most defects were observed on the top of the casting.

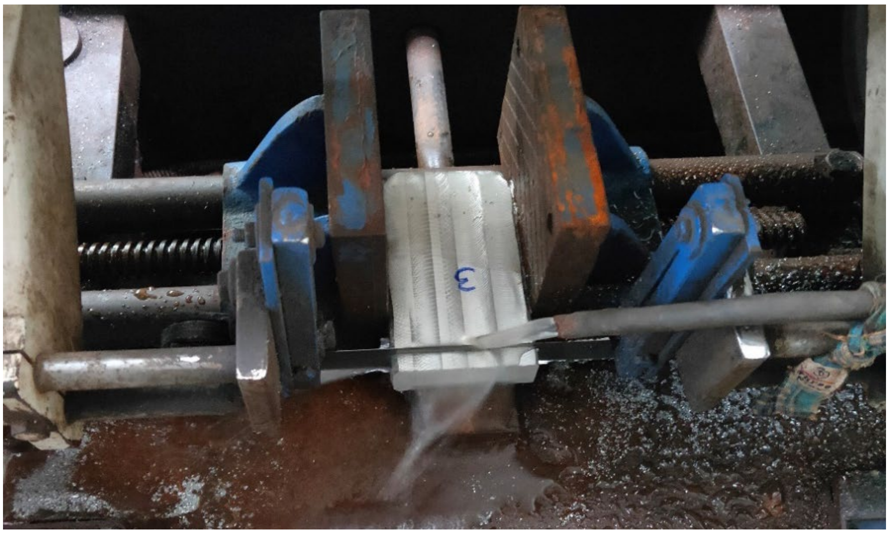

Figure 3:7 Cutting of HMMCs on Power Hacksaw

The procedure was replicated to generate hybrid metal matrix composite samples as per the Tables 3.2,3.3,3.4 and 3.5. The developed hybrid metal matrix composite samples after primary machining process are shown in Figure 3.8.

Figure 3:8 Fabricated Composites

3.4 CHARACTERIZATION OF AA6351 HMMCs

The hybrid metal matrix composite that was developed underwent a thorough examination of its microstructural and mechanical attributes. This evaluation included the analysis of phase composition, microstructure, density, Rockwell hardness, impact strength, tensile strength, and wear resistance. Additionally, a detailed examination of the microstructure of the worn surface was conducted to ascertain its response to wear and potential mechanisms of damage. This comprehensive assessment provided valuable insights into the operational behavior and performance of the hybrid metal matrix composite, thereby enhancing its potential for use across a wide range of engineering and industrial applications.

3.4.1 SEM and EDS Analysis

Energy Dispersive Spectroscopy (EDS) in conjunction with an Oxford Instruments scanning electron microscope (SEM) was used to conduct morphological examinations on specimens made of aluminum hybrid metal matrix composites. Energy Dispersive Spectroscopy (EDS) and a scanning electron microscope (SEM-ZEISS) were utilized to study the morphology of a hybrid composite material. SEM combined with EDS is shown in Figure 3.9. The components and proportion of elements present at random points in a material are analysed using energy dispersive spectroscopy (EDS).

Figure 3:9 EDS coupled SEM

Samples for SEM, EDS, and XRD analysis were prepared. Sample preparation start from cutting of the specimen in 10x10x30 mm cube. The first process was to remove the major surface scratches by using vertical milling centre. After this the specimen's smoothness was improved by using emery paper. The procedure was initiated with the of grit sizes of P500 and P1000, each phase spanning a duration of 15 to 30 minutes. Following this preliminary step, the polishing process continued with emery paper possessing a grit size of P1500, carried out for a timeframe of 15 to 20 minutes. After this stage, the polishing machine fitted with emery paper featuring a grit size of P2000, was used for approximately 15-20 minute. After this the workpiece were polished on polishing machine by using Nylon cloth and Alumina gel for a duration extending from 30 to 40 minutes.

Upon the completion of the polishing sequence, the polished samples underwent a drying process within a muffle furnace, set at a temperature of 150°C, for a period of 20 minutes. After this the samples were packed using soft cloth and cotton, to prevent from any kind of dirt or oxidation.

3.4.2 X-Ray Diffraction

The developed hybrid composite samples were carefully subjected to X-ray diffraction (XRD) examination. The analysis's angular range was 10° to 90°, which made it possible to thoroughly examine the phases that were present in the specimens. Cu-Kα radiation was used in the diffractometer, and a Ni-filter was purposefully included to the experimental setup to improve accuracy.

The sophisticated X-ray diffractometer utilized in this analysis operated at a voltage of 40 kV. This configuration ensured optimal conditions for determining and characterizing the crystalline structures within the hybrid composite materials. The detailed XRD analysis using these advanced tools contributes significantly to the understanding of the composition and structural characteristics of the developed composite samples [103]. The X-Ray Diffractometer of Rigaku is shown in Figure 3.10.

Figure 3:10 X-Ray Diffractometer

3.2.3 Density

AA6351/Gr/B_4C, AA6351/Gr/TiC, AA6351/Gr/WC and AA6351/B_4C/TiC/WC are the developed hybrid metal matrix composites whose densities were measured using Archimedes' principle. According to the principle, when an object is submerged in a fluid, it experiences a buoyant force that is equal to the weight of the fluid displaced by the object. This buoyant force acts upward, making the object feel lighter while submerged in the liquid. For density measurements using Archimedes' principle, the steps typically involve:

Weighing the Object in Air: Measure the weight of the object when it is suspended in the air. This provides the mass of the object (m_1).

Immersing the Object in a Fluid: Immerse the object in a fluid of known density, such as water. The object should be completely submerged. The buoyant force acting on the object reduces its apparent weight.

Weighing the Object in the Fluid: Measure the weight of the object while it is immersed in the fluid. This provides the apparent weight of the object in the fluid (m_2).

Computing the Buoyant Force: The buoyant force (B) acting on the object in the fluid is given by the difference in weight between the object in air and the object in the fluid.

Calculating the Density: The density (ρ) of the object can be computed using the formula:

$$\rho = \frac{m_1}{m_1 - m_2} * \rho_{fluid}$$

Where ρ_{fluid} is the density of the fluid. Setup for density measurements is shown in Figure 3.11.

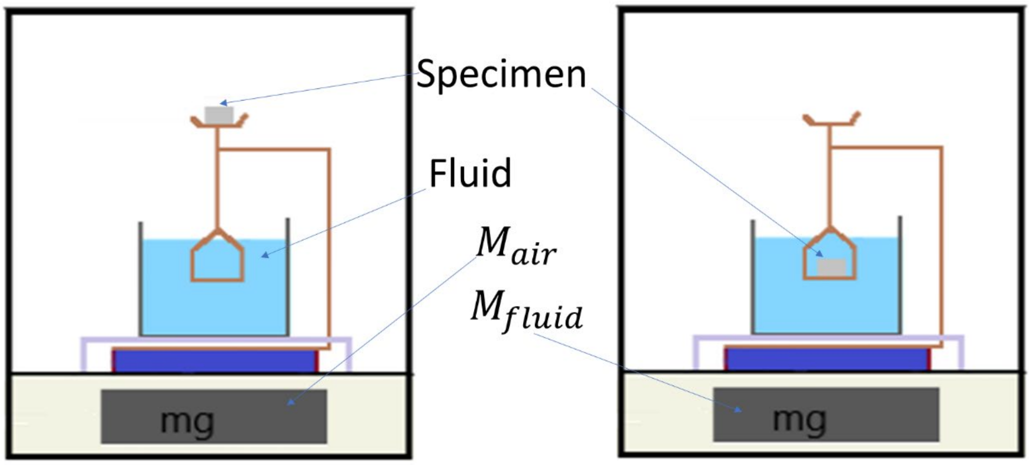

Figure 3:11 Density Measuring Instrument

3.4.3 Hardness

Using a Rockwell Hardness Tester made by Mechatronics Control System, the hardness of the AA6351/Gr/B_4C, AA6351/Gr/TiC, AA6351/Gr/WC and AA6351/B_4C /TiC/WC hybrid metal matrix composite was evaluated. This aluminum-based composite material-specific Rockwell hardness tester has two major loads of 150 kg and a minor load of 10 kg. It also requires the usage of a 1/16-inch-diameter steel ball indenter. The HRC scale was used to quantify Rockwell Hardness. An illustration of the Rockwell Hardness Tester may be seen in Figure 3.12. Samples used for hardness testing is shown in Figure 3.13.

Figure 3:12 Rockwell hardness testing machine

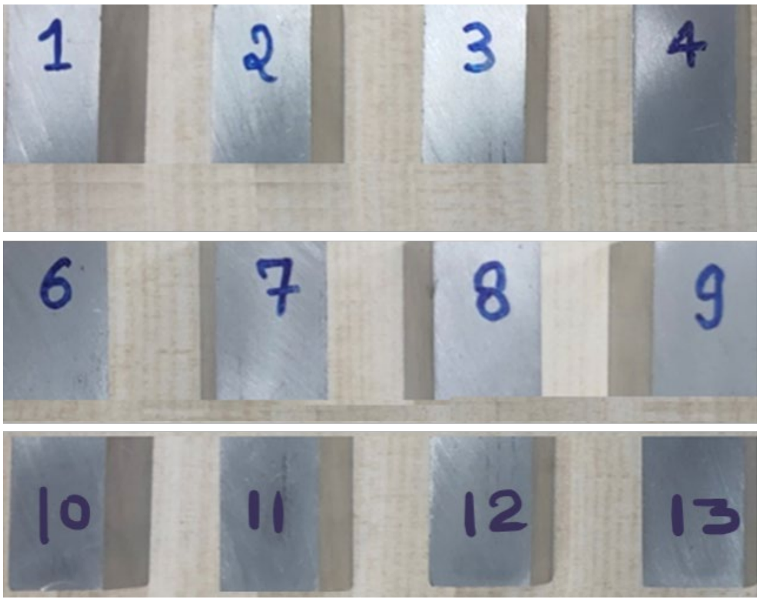

Figure 3:13 Specimen for Hardness

3.4.4 Impact Test

The impact test serves as an essential tool for assessing a specimen's ability to absorb energy upon impact. This assessment employs two specific techniques to measure impact strength: the Izod test and the Charpy test. The impact testing apparatus, depicted in Figure 3.14, is manufactured by “Precision Systems & Innovations.” For this research, the Charpy test method is exclusively utilized to determine the specimen's impact strength.

A striking hammer weighing 21 kg is positioned in the Charpy test setup at an anticlockwise angle of 140˚ from vertical axis. The opposing side of the notch is struck by the hammer in the Charpy test. Figure 3.15 shows the fabricated samples according to ASTM standard.

Figure 3:14 Impact testing machine

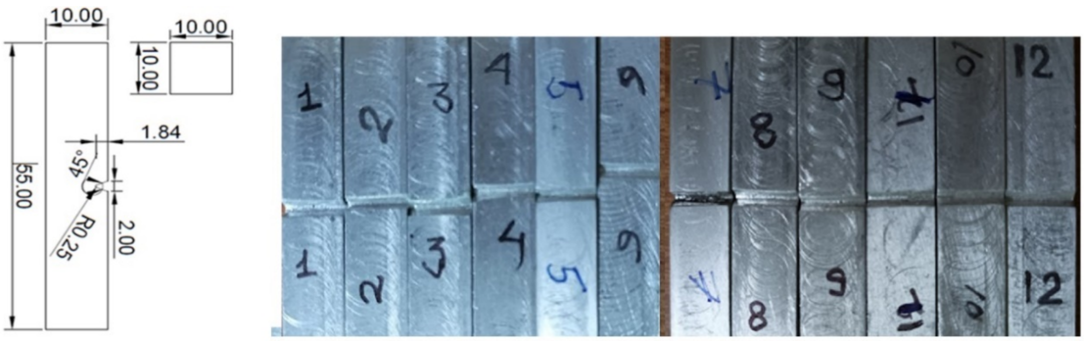

Figure 3:15 Charpy Test specimen as per ASTM Standard

3.2.6 Tensile Test

Tensile testing is a fundamental method used to determine mechanical strength and to obtain stress-strain curve. Three samples of each configuration were prepared according to ASTM E8M standards for the tensile test. The specimen's dimensions are shown in Figure 3.16. To get the arc's precision and lessen the concentration of stress on the shoulders, these samples were made using a vertical milling machine. Following preparation, the samples were examined using a PC 2000 tensiometer with a 20 kN load capacity. Tensiometer speed was calibrated at 0.5 mm/min with 0.1 mm increments. Tensiometer used for testing PC2000 is shown in Figure 3.17.

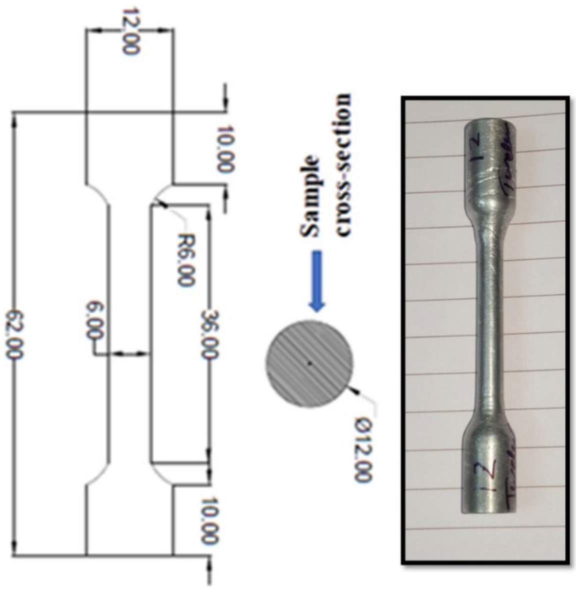

Figure 3:16 Tensile Test Specimens

Figure 3:17 Computerized Tensiometer

3.2.7 Wear Analysis

Wear is the gradual damage or deterioration of a material through use, often caused by friction, abrasion, or other external factors. Wear tests are conducted to evaluate the durability and resistance of materials under simulated conditions, providing crucial insights into their performance and lifespan.

3.2.7.1 Wear Test

A pin-on-disc setup, in conjunction with a data acquisition system, was employed to examine the wear properties. The sample with the most favourable mechanical characteristics in each group was chosen, and the fabrication and testing of the wear samples were carried out following the ASTM G99-95a procedure. The test setup utilized in the investigation is depicted in Figures 3.18 and 3.19. An EN31 steel disc was used for the wear test, and the sample's weight loss was calculated after it had travelled 1000 meters. With a pin diameter of 10 mm and a length of 30 mm, a sliding velocity of 1.0 m/s was maintained.

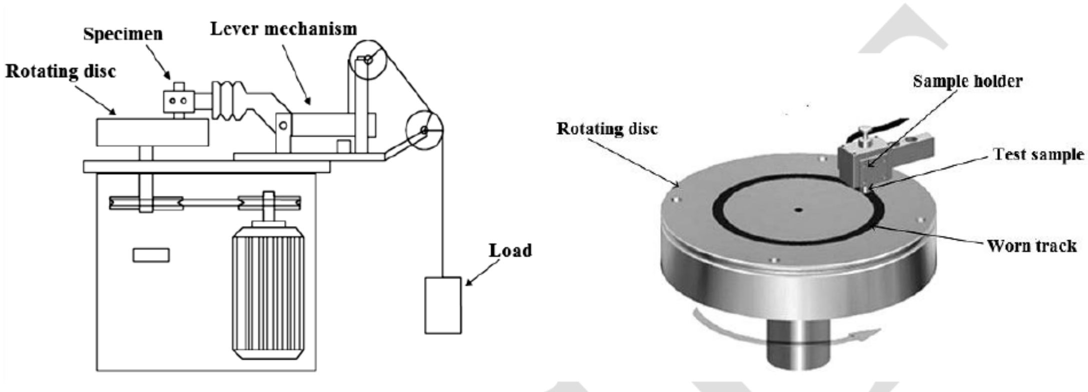

Figure 3:18 Pin on Disc Setup [93]

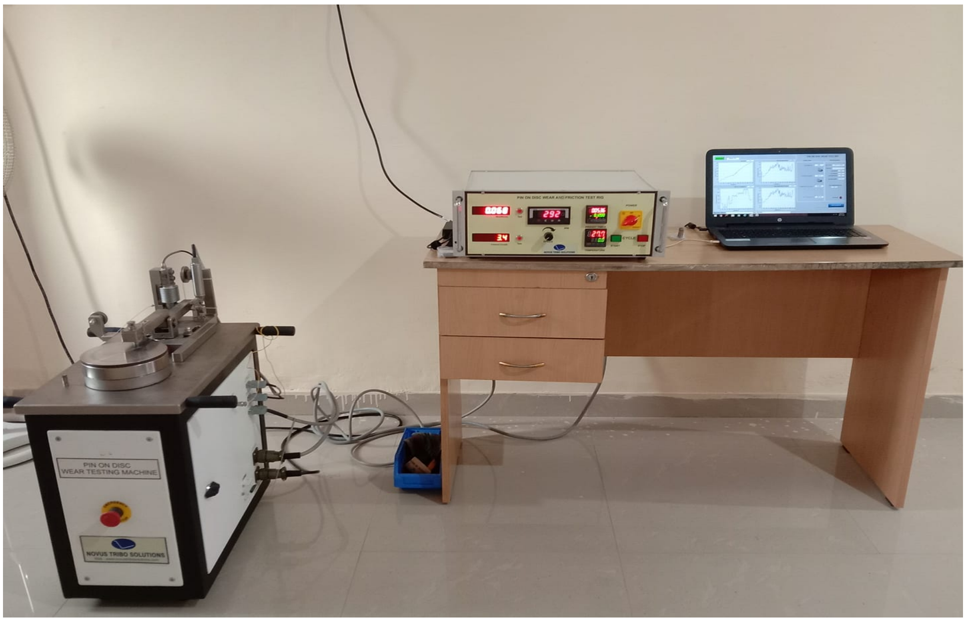

Figure 3:19 Pin on Disc Wear Testing Machining Setup

The samples were polished for around ten minutes each using sandpapers with grit levels of P300, P1000, and P1500 before being subjected to wear testing. An additional ten minutes were spent polishing the samples using P2000 emery paper. Once the polishing process was completed, the samples were ready for wear testing.

Following the wear test, each specimen's weight loss was calculated using the formula below:

Weight loss of the specimen = Initial weight of the specimen – Final weight of the specimen

The wear rate (mm^3/m) of the specimen was measured by given expression.

$$\text{Wear rate of the sample} = \frac{\text{Total wear volume (V)}}{\text{Sliding distance (s)}}$$

Chapter 4: Physical and Structural Analysis

This chapter explores the detailed examination of various physical characteristics of the fabricated hybrid metal matrix composite. Specifically, it focuses on examining the density, porosity, and microstructure of the composite. The goal is to thoroughly understand the composite's inherent physical properties, including how its density is distributed, identifying any present porosity, and analysing its microstructure in detail. By highlighting these aspects, the chapter aims to provide valuable insights into the overall physical behavior and composition of the hybrid metal matrix composite.

4.1 DENSITY AND POROSITY

B_4C and Graphite reinforcements demonstrate lower density than the base Al matrix, while TiC and WC have higher density. The determination of the density of solid materials, including composites, can be accomplished using Archimedes' principle. This concept is applicable to complicated or asymmetrical geometry. It says that a body experiencing submersion in a fluid experiences buoyant force equivalent to the weight of the displaced fluid. When the body is completely immersed, this buoyant force is likewise equal to the body weight.

The following formula may be used to determine the analytical density of a hybrid metal matrix composite:

$$\rho_t = \rho_m \phi_m + \rho_{r1} \phi_{r1} + \rho_{r2} \phi_{r2}$$

Where:

ρ_m = Density of Matrix material (AA6351)

ϕ_m = Weight proportion of Matrix material (AA6351)

ρ_{r1} = Density of Reinforce Material 1

ϕ_{r1} = Weight proportion of Reinforce Material 1

ρ_{r2} = Density of Reinforce Material 2

ϕ_{r2} = Weight proportion of Reinforce Material 2

Reinforcement density and proposition are used for computing the theoretical density of hybrid metal matrix composite samples.

Porosity in the fabricated sample is calculated based on the density of the fabricated sample and the theoretical density of the fabricated samples.

$$porosity\ \% = \left(1 - \left(\frac{\rho}{\rho_t}\right)\right) * 100$$

Where ρ is the experimental density of hybrid MMC.

The theoretical density, average experimental density along with porosity for the developed composites of set-01 in Figure 4.1. For every composition, the experiment was conducted five times. Error bars are included in the figure to show the error in experimental density. The porosity of a material is the discrepancy between its theoretical and experimental densities. In AA6351/Gr/B_4C hybrid MMCs, the density of HMMCs decreases with the incorporation of reinforcement because both reinforcements are lighter than the matrix material. Due to the porosity in HMMCs, a difference in theoretical and experimental densities is observed. Lowest experimental density is observed in sample AlGrB05 having 2 wt% of each reinforcement.

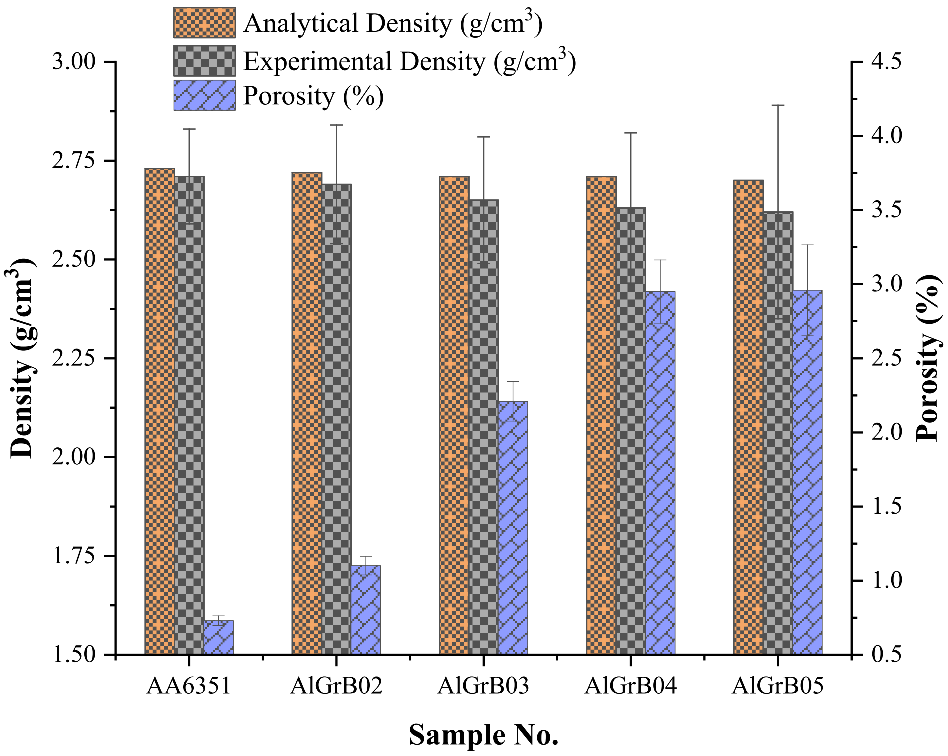

Figure 4:1 Density and Porosity of AA6351/Gr/B_4C

In set-02, the theoretical density of the developed HMMCs increases due to the higher density of TiC. However, the experimental density of the HMMCs decreases because of the presence of porosity in the composites. Sample AlGrT05 exhibits the lowest density and highest porosity. Figure 4.2 illustrates the variation in density and porosity with changes in reinforcement proportion for set-02. In set-03, there is a rapid increase in density due to the high density of the WC reinforcement. Additionally, as the proportion of reinforcement increases, both porosity and density increase in set-03, with AlGrW05 showing the highest density and porosity. Figure 4.3 illustrates the variation in density and porosity with changes in reinforcement proportion for set-03. In set-04, a similar pattern is evident in the trends of density and porosity. The excessive amount of carbide led to improper mixing of the reinforcement, resulting in higher porosity compared to other hybrid composite sets. In set-04, ABTW05 shows the highest density and porosity. Figure 4.4 depicts the changes in density and porosity as the reinforcement proportion varies in set-04. Among all the developed samples, AlGrB05 shows lowest theoretical density, while AlGrT05 shows lowest experimental density due to porosity.

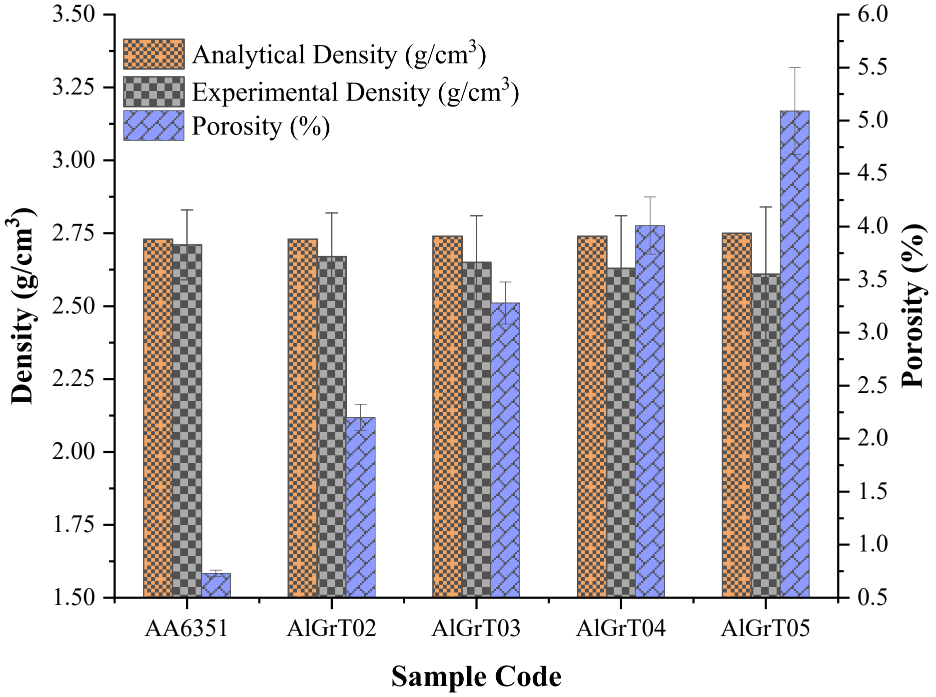

Figure 4:2 Density and Porosity of AA6351/Gr/TiC

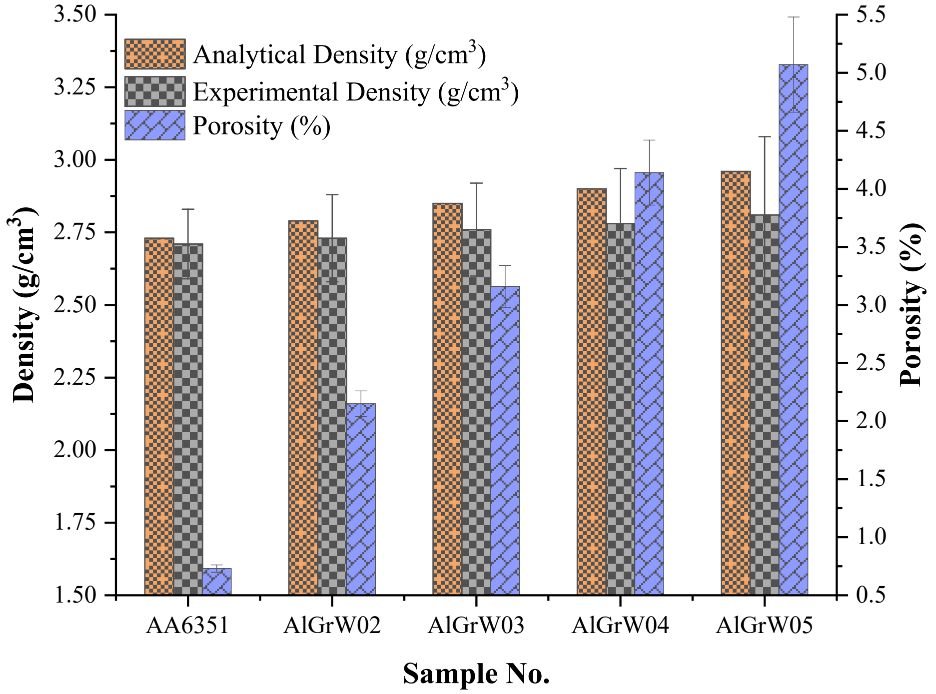

Figure 4:3 Density and Porosity of AA6351/Gr/WC

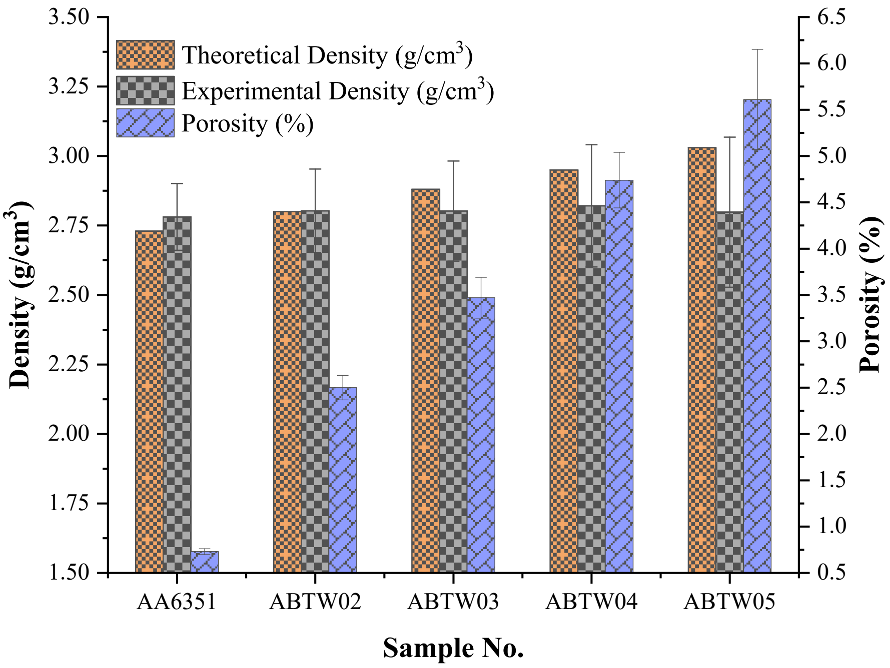

Figure 4:4 Density and Porosity of AA6351/B_4C/TiC/WC

4.2 MICROSTRUCTURAL ANALYSIS OF AA651/Gr/B_4C

Microstructural analysis involves examining the microscopic features, arrangement, and composition of materials. It utilizes techniques like microscopy and imaging methods to study the fine details, such as grain structure and phases, influencing a material's properties. In the context of materials science, it provides insights into how the microstructure influences the behavior of a material. Microstructural analysis for the fabricated hybrid metal matrix composite involved the use of various techniques, including XRD, SEM, and EDS tests. These methods were employed to examine and characterize the microscopic features, crystal structures, and elemental composition of the material, providing a comprehensive understanding of its microstructure and properties.

X-ray diffraction (XRD) patterns can offer valuable insights into a material's crystal structure, level of crystallinity, composition, and even the presence of defects or impurities. In this analysis, "Match" application is used to process the raw XRD data and generate the XRD patterns. These patterns are typically plotted with the X-axis representing the 2θ values, spanning from 10˚ to 90˚, and the Y-axis showing the intensity.

4.2.1 SEM Analysis of AA651/Gr/B_4C

When analysing the morphological behavior of a developed hybrid composite, microstructure plays a crucial role. Figure 4.5 shows the microstructure of the AA6351/Gr/B_4C matrix at 1000X magnification. Figure 4.5(a) presents the microstructure of AlGrB02 reinforced with 0.5wt% of each reinforcement. This image illustrates the detailed composition and structure of the composite material, showcasing the distribution and arrangement of the reinforcements within the matrix. The hybrid metal matrix composite showed a consistent dispersion of reinforcement.

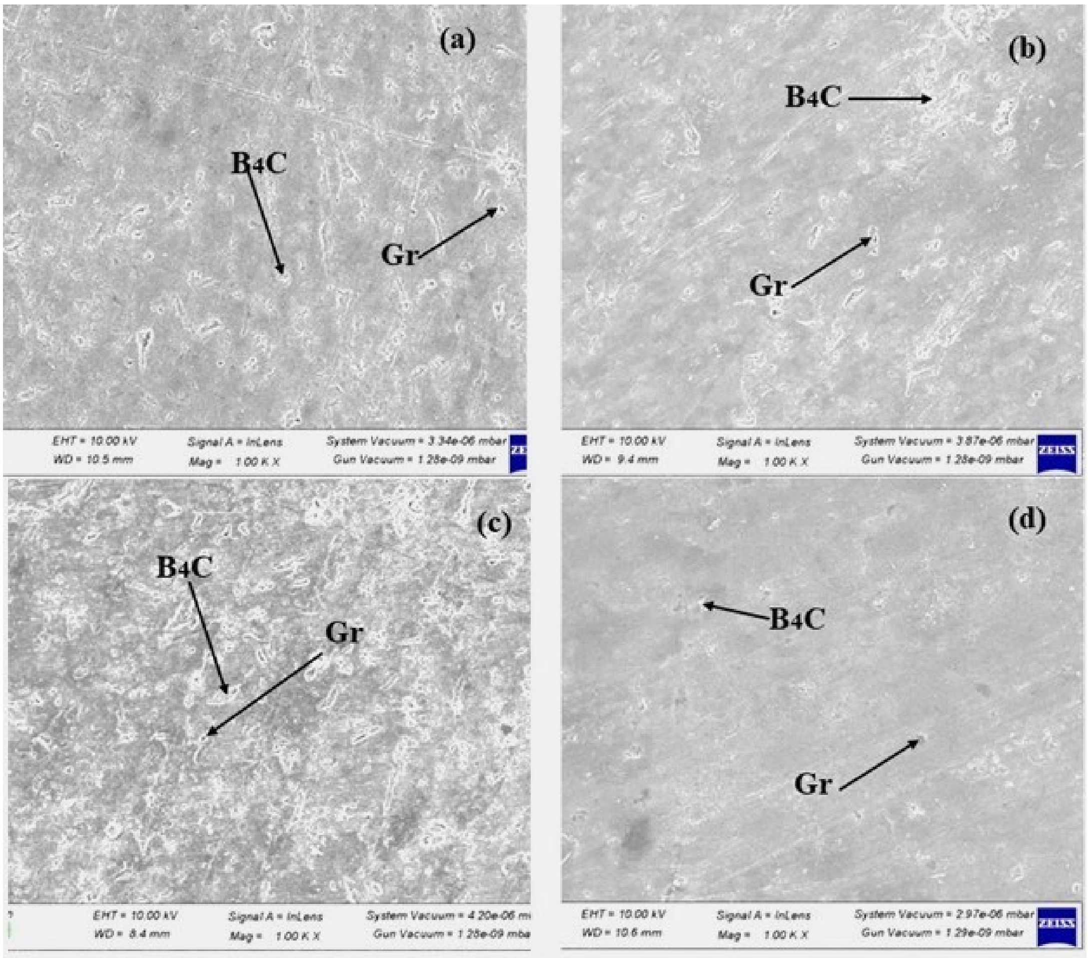

Figure 4:5: SEM of AA651/Gr/B_4C HMMCs

Denser reinforcement clusters are shown in Figure 4.5(b) as compared to Figure 4.5(a) when the proportion of reinforcements rises to 1wt% Gr and 1wt% B_4C. Figure 4.5(c) shows the emergence of minor particle accumulations upon increasing the reinforcement content to 1.5wt% Gr and 1.5wt% B_4C. This buildup may also be shown in Figure 4.5(d). Notably, enhancing a small amount of reinforcement during the stir-casting process tends to ensure that the material disperses uniformly. On the other hand, an uneven distribution and particle accumulation among other particles happen when the proportion of reinforcements proportion increases a certain range. Because the reinforcement is insoluble in the matrix, a considerable proportion of particles tend to settle on top when a high percentage of reinforcement is incorporated in the AA6351 metal matrix.

4.2.2 XRD analysis of AA651/Gr/B_4C

Figure 4.6 illustrates an X-ray diffraction pattern of AA651/Gr/B_4C. This pattern provides a visual representation of the intensity of peaks associated with various elements, each marked with their corresponding miller indices.

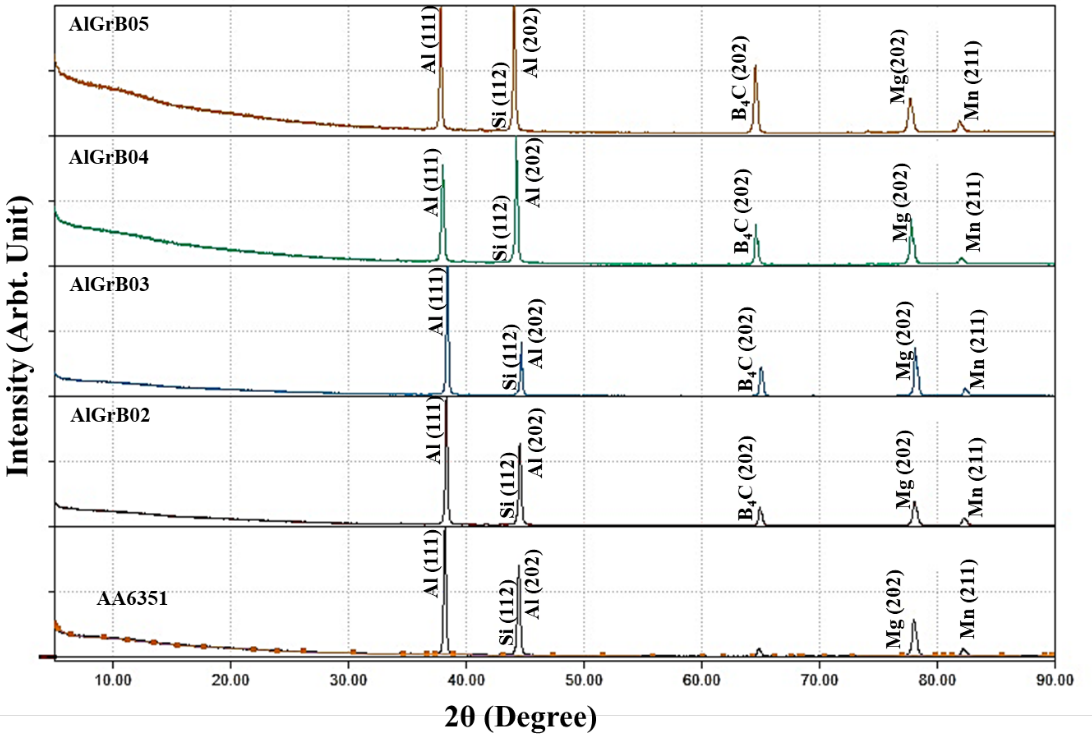

Figure 4:6: XRD Pattern of AA651/Gr/B_4C HMMCs

On close examination, it can be noted that the low-intensity peak corresponds to the reinforcement particles, while the high-intensity peak is due to aluminum. The XRD analysis reveals specific findings for each sample as follows: In Sample AA6351, the XRD pattern exhibits a higher intensity peak for aluminum compared to magnesium (Mg) and manganese (Mn). Moving on to Sample AlGrB02, a notable difference is observed from AA6351, as this sample displays an additional peak attributed to B_4C reinforcement. The pattern showcases both the low-intensity B_4C peak and the high-intensity aluminum peak. Sample AlGrB03, with an increased concentration of B_4C reinforcements, demonstrates a more pronounced B_4C peak compared to AlGrB02. Similarly, Sample AlGrB04 displays a higher B_4C peak intensity, indicating a greater concentration of B_4C reinforcements in the hybrid metal matrix. Among all the samples, AlGrB05 stands out with the maximum reinforcement proportion, lead to the highest peak intensity for the composition. It's important to note that the XRD patterns did not indicate any chemical reactions occurring between the reinforcements and the aluminum matrix particles. Each sample maintained distinct peaks for individual elements, and no new compound formation was observed. To verify the crystal plane index for specific elements, we referred to JCPDS card numbers: 04-0787 for aluminum (111), 35-0798 for B_4C (104), and 78-0430 for Mg (202) [104][105].

4.2.3 EDS analysis of AA651/Gr/B_4C

The hybrid metal matrix composite was elementally analysed by EDS. Table 4.1 gives the chemical composition of sample AA6351, and Figure 4.7 shows the EDS spectrum.

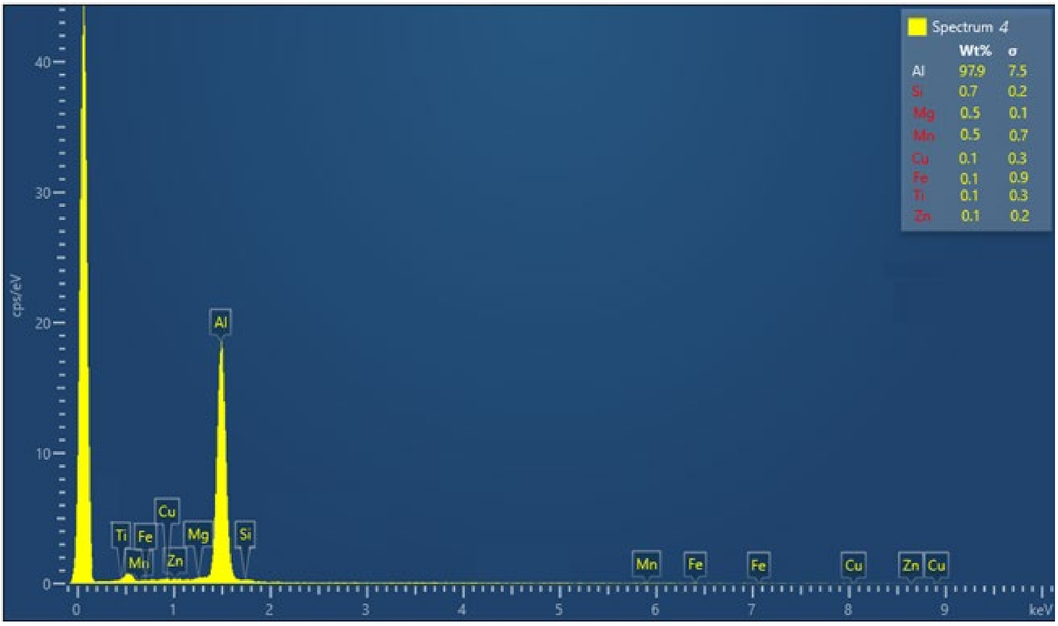

Figure 4:7: EDS spectrum of AA6351

Table 4:1 Weight percentage of different elements in AA6351

Element	Al	Si	Mg	Mn	Fe	Cu	Ti	Zn
wt%	97.9	0.7	0.5	0.5	0.1	0.1	0.1	0.1

The EDS analysis of specimen AlGrB02, AlGrB03, AlGrB04 and AlGrB05 are shown in Figures 4.8 and 4.9 respectively. The Table 4.2 represent weight percentages of different elements present in AlGrB02, AlGrB03, AlGrB04 and AlGrB05. The EDS spectrum shows both the elements of B_4C, B and C. Remarkably, no oxygen content was detected in any sample, which can be attributed to effective protection from environmental factors during the fabrication process. Due to its larger wt %, aluminum has a noticeably high peak in the EDS spectrum. In contrast, elements with lower weight percentages, such as magnesium, silica, and manganese, have smaller peaks.

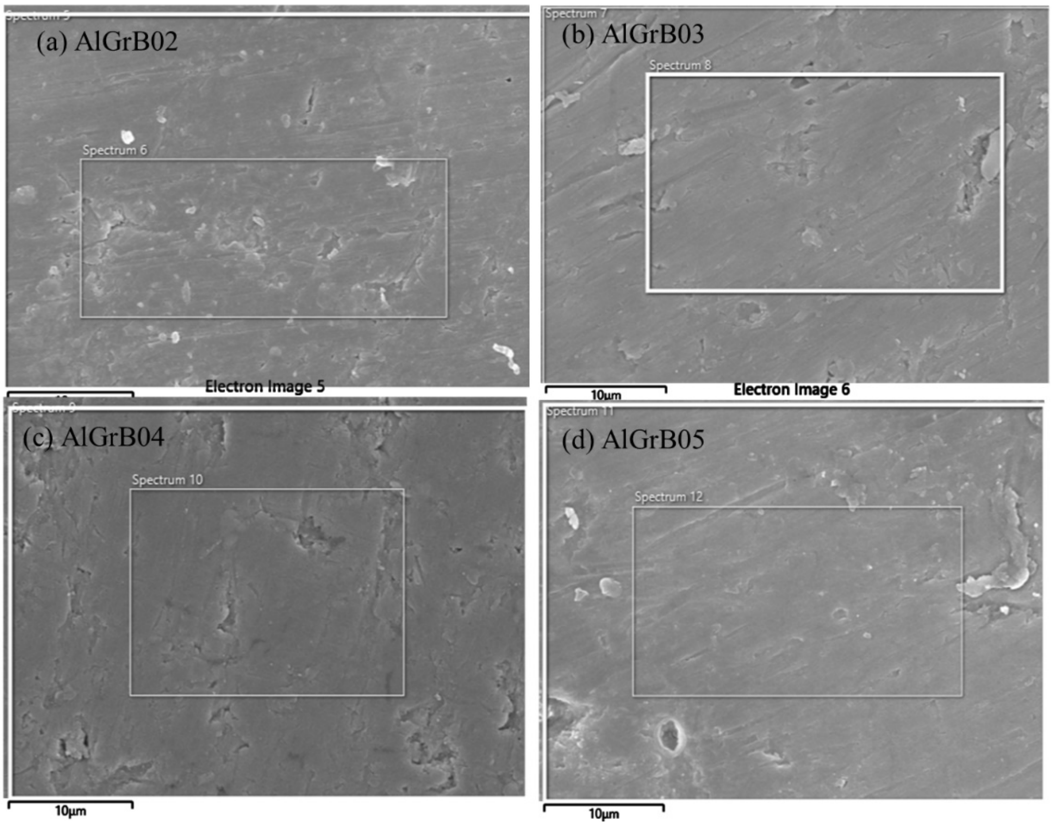

Figure 4:8 SEM for EDS of AA6351/Gr/B_4C HMMCs

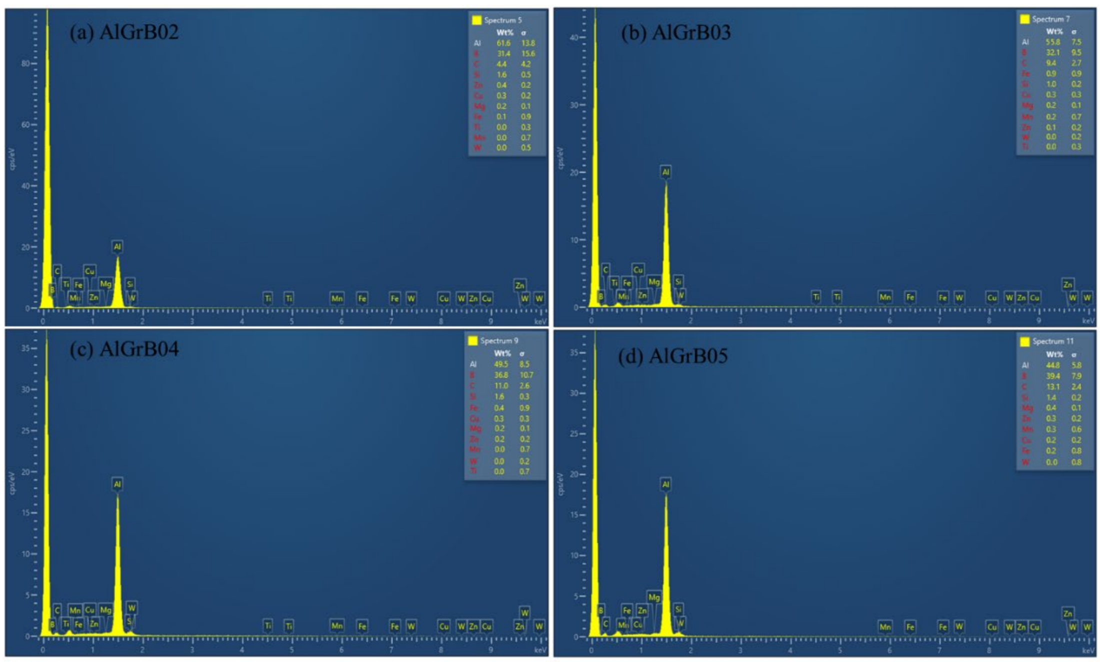

Figure 4:9 EDS of AA6351/Gr/B_4C HMMCs

Table 4:2 Weight percentage of different elements AA6351/Gr/B_4C

Element (%)	Al	B	C	Si	Zn	Cu	Mg	Fe	Total
AlGrB02	61.6	31.4	4.4	1.6	0.4	0.3	0.2	0.1	100
AlGrB03	55.8	32.1	9.4	1	0.1	0.3	0.2	0.9	100
AlGrB04	49.5	36.8	11	1.6	0.2	0.3	0.2	0.4	100
AlGrB05	44.75	39.36	13.1	1.4	0.3	0.2	0.4	0.2	100

The Table 4.2 highlights an evident increase in the weight proportion of Boron and graphite with the rise in reinforcement. Notably, Sample AlGrB05 exhibits the highest concentration of Boron and Graphite. Figure 4:9 provides evidence that no intermediate reactions occurred between the Al matrix and the reinforcements (Gr-B_4C).

4.3 MICROSTRUCTURAL ANALYSIS OF AA6351/Gr/TiC

4.3.1 SEM analysis of AA6351/Gr/TiC

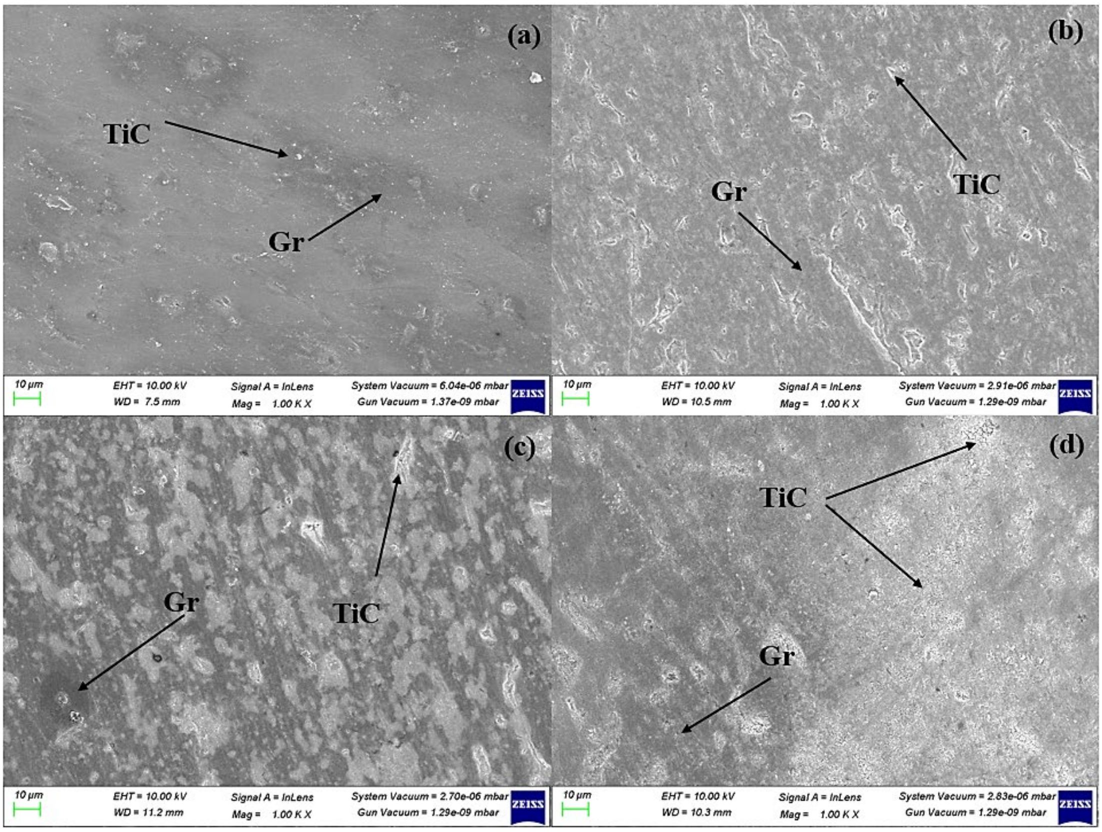

Figure 4:10 SEM of AA6351/Gr/TiC

Figure 4.10 shows the microstructure of AA6351 reinforced with Titanium Carbide (TiC) and graphite (Gr). The micrograph presented in Figure 4.10 depicts the consistent distribution of these reinforcements in the hybrid metal matrix composite at a low reinforcement fraction. The SEM of 0.5 weight percent Gr and TiC in Figure 4.10(a) illustrates the homogeneous distribution of reinforcement.

As the weight proportion of reinforcements increases, denser clusters of reinforcement become evident in Figure 4.10(b) when compared to Figure 4.10(a). Further elevating the proportion of reinforcements to 1.5 wt% Graphite and 1.5 wt% Titanium Carbide, some areas of accumulation between particles can be observed in Figure 4.10(c), which is also noticeable in Figure 4.10(d). It is important to note that a better dispersion is often the outcome of adding ceramic reinforcement in smaller amounts. On the other hand, when the proportion of reinforcements rises, the particles become more unevenly distributed and accumulate. Since the reinforcement materials are insoluble in the AA6351 metal matrix, a sizable portion of the particles tend to settle on top when a larger proportion of reinforcement is incorporated into the metal matrix during the stir-casting process.

4.3.2 XRD analysis of AA651/Gr/TiC

Figure 4.11 shows the XRD pattern of AA651/Gr/TiC hybrid metal matrix composite developed by reinforcing Graphite and TiC. In this configuration, the aluminum matrix dominates the hybrid metal matrix sample, constituting the highest proportion among the components.

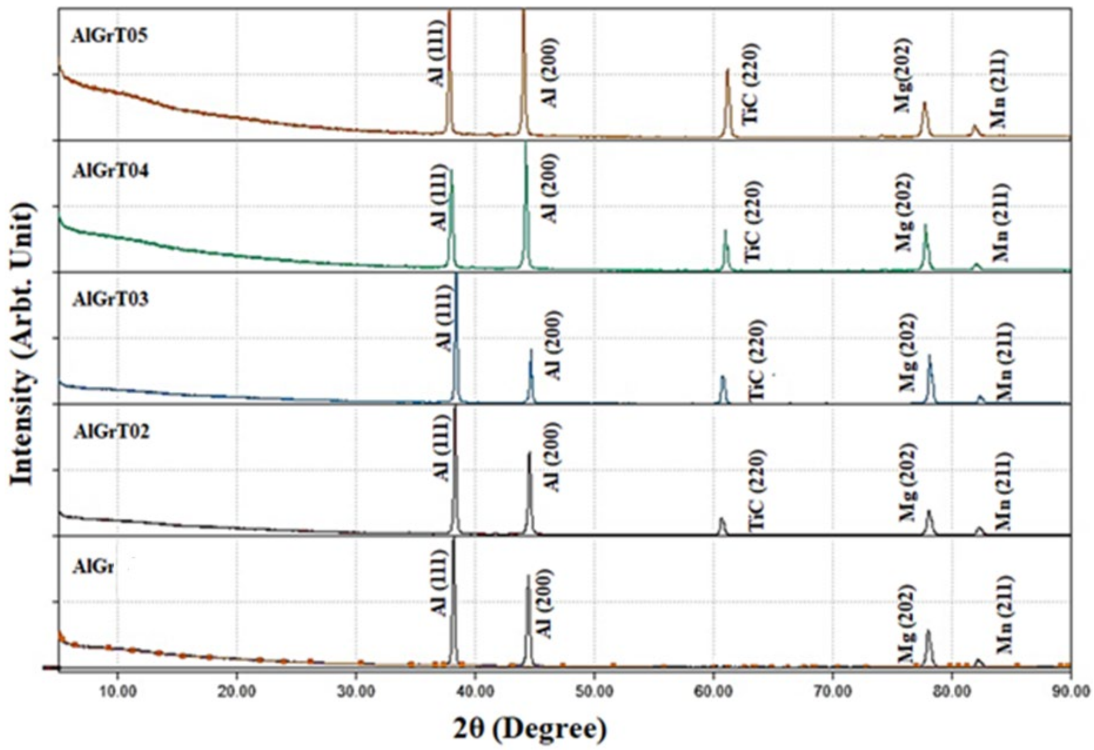

Figure 4:11: XRD Pattern of AA6351/Gr/TiC

Analysing the XRD pattern of AlGrT02, an additional low-intensity peak appears at an angle of 60.76° (2θ), indicating the presence of TiC reinforcement in the hybrid metal matrix composite. As the concentration of reinforcement increases in hybrid metal matrix composites (as seen in AlGrT05, which contains the highest reinforcement percentage), the peak intensity of TiC also significantly increases. However, the peak intensities of Mg, Mn, and Si remain relatively unchanged.

These diffraction patterns provide evidence that no chemical reactions occurred between the reinforcement materials and the aluminum alloy in the hybrid MMCs. Each composition demonstrates distinct peaks subsequent to all the elements, without any noticeable peaks indicating the formation of new compounds.

To confirm the crystallographic orientation and structure of aluminum and TiC within the composite, JCPDS card numbers 04-0787 and 32-1383 were utilized for indexing. This indexing process ensures that the crystallographic properties of these materials are accurately identified. Understanding these properties is crucial for comprehending how the different components interact within the composite and how they contribute to its overall performance [67].

4.3.3 EDS analysis of AA651/Gr/TiC

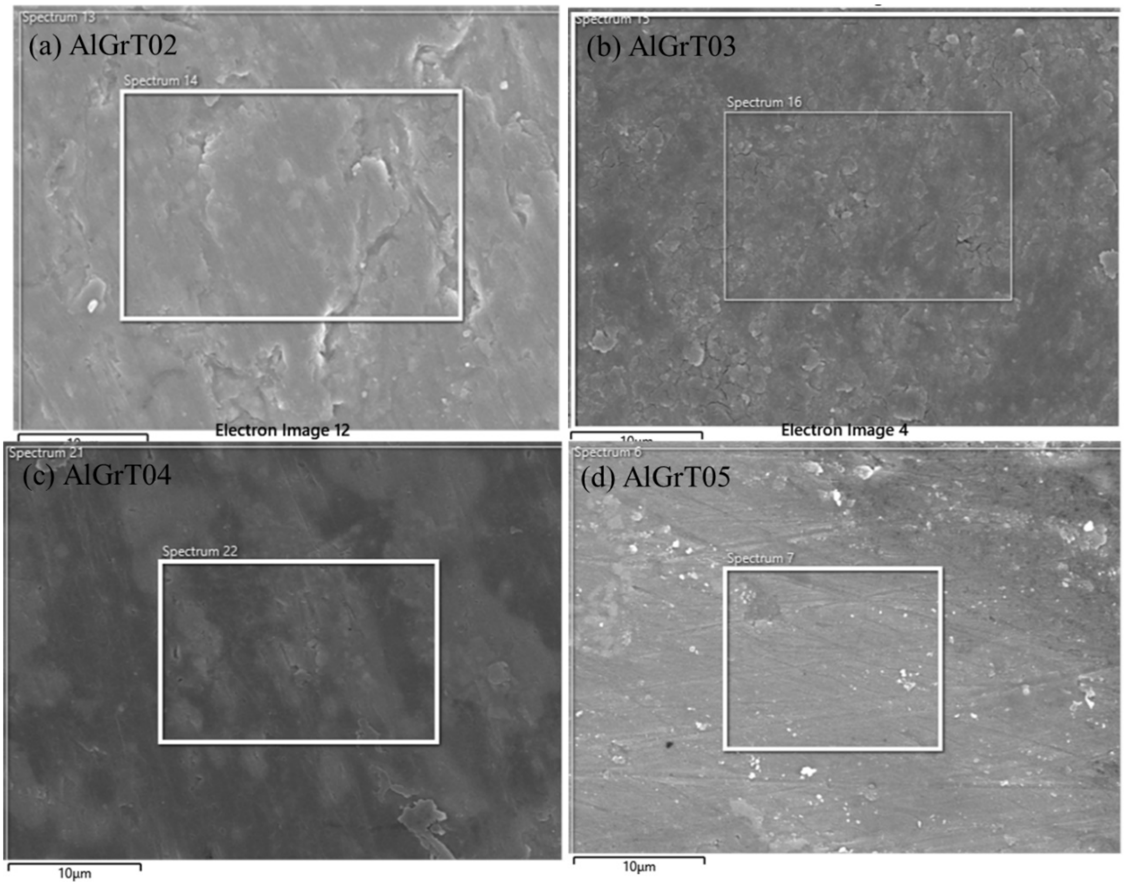

Figure 4:12 SEM for EDS AA651/Gr/TiC

The SEM and EDS spectra of AlGrT02, AlGrT03, AlGrT04, and AlGrT05 are shown in Figures 4.12 and 4.13, respectively. The presence of Ti and C in the hybrid metal matrix composite indicates the existence of reinforcing material TiC, which is amply confirmed by the EDS analysis. It is important to note that Titanium's peak intensity is quite low since these elements have a comparatively low weight %. The chemical composition of the produced composite, including the weight % distribution of the different constituents, is shown in Table 4.3.

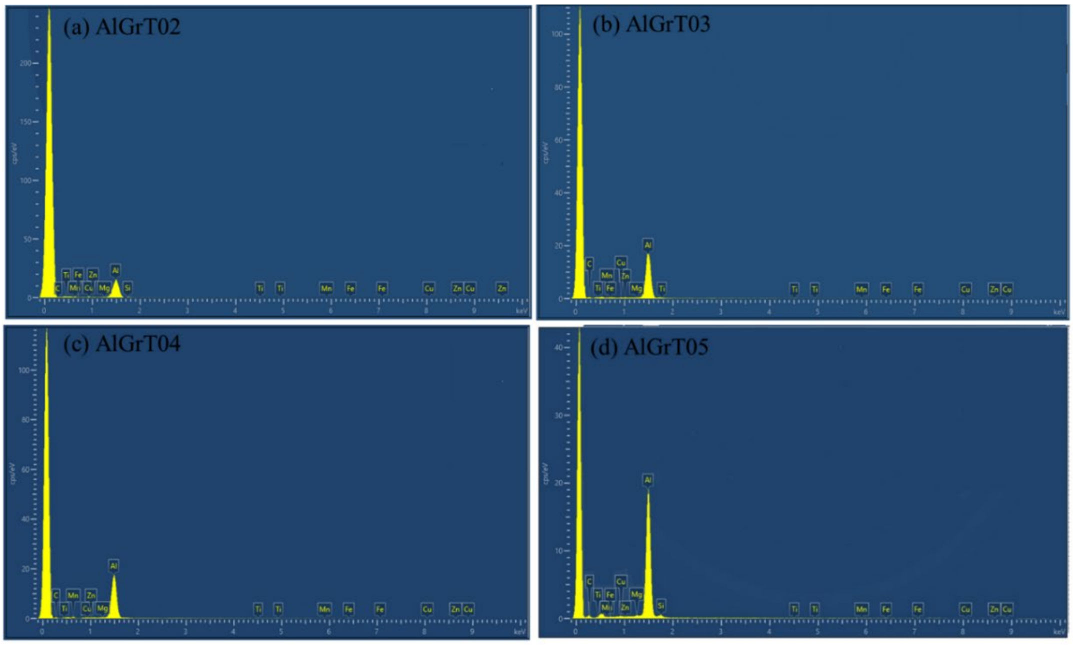

Figure 4:13 EDS of AA651/Gr/TiC

Table 4:3 Weight Percentage of Different Elements in AA651/Gr/TiC

Sample Code	Al	Gr	Si	Mg	Mn	Fe	Cu	Ti	Zn
AlGrT02	96.7	0.7	0.7	0.5	0.5	0.1	0.1	0.6	0.1
AlGrT03	95.9	1.1	0.7	0.4	0.5	0.1	0.1	1.1	0.1
AlGrT04	94.7	1.7	0.6	0.5	0.6	0.1	0.1	1.6	0.1
AlGrT05	94.1	2.2	0.6	0.5	0.4	0.1	0.1	1.9	0.1

The table highlights an evident increase in the weight proportion of Titanium and Graphite with the rise in reinforcement. Notably, Sample AlGrT05 exhibits the highest concentration of Boron and Graphite.

4.4 MICROSTRUCTURAL ANALYSIS OF AA6351/Gr/WC

4.4.1 SEM analysis of AA6351/Gr/WC

Figure 4.14 shows the microstructure of the AA6351/Gr/WC metal matrix composite. Figure 4.14(a) show the microstructure of a hybrid metal matrix composite containing 0.5 wt% of the reinforcement. Uniform dispersion of the reinforcement was observed at low proportion of the reinforcement.

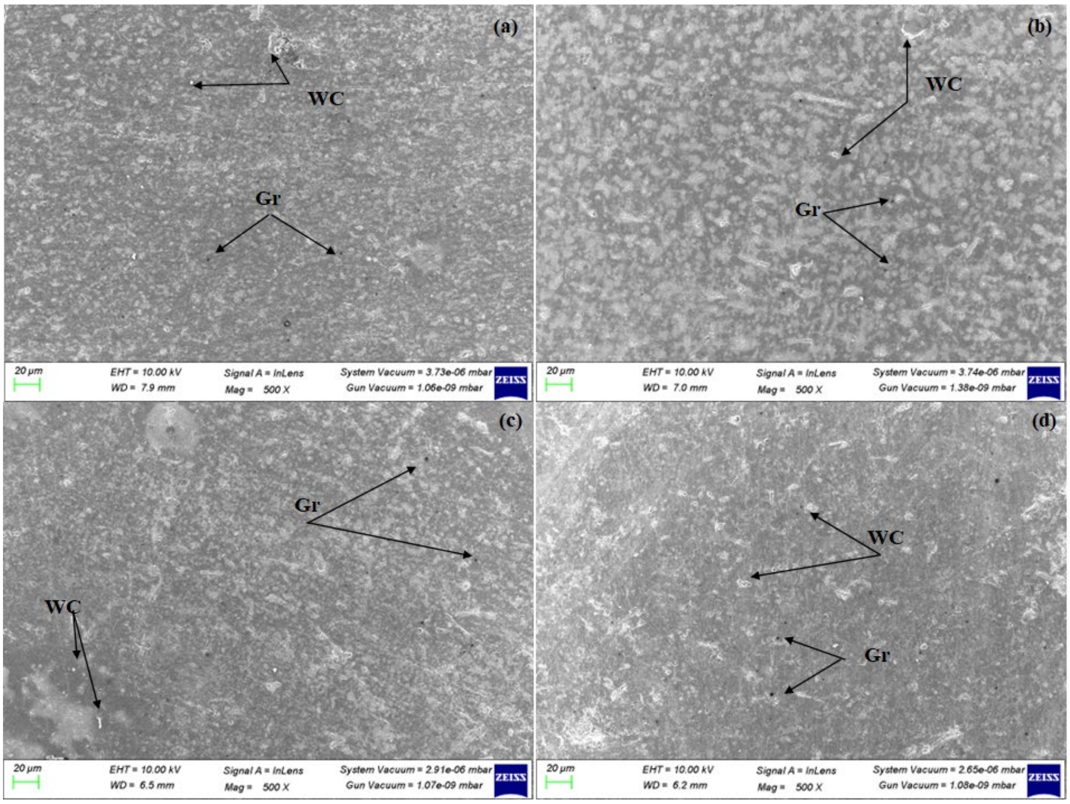

Figure 4:14 SEM analysis of AA6351/Gr/WC

Compared to Figure 4.14(a), Figure 4.14(b) depicts denser reinforcement patches when the reinforcements proportion (1 wt% of Gr and WC) is raised. A few areas of particle buildup are shown in Figure 4.14(c) following the extension of reinforcements to 1.5 wt% of each Gr and WC. The least amount of ceramic that is blended produces uniform dispersion; on the other hand, a rise in the percentage of reinforcements causes uneven dissemination and buildup between the various particles. When a larger percentage of reinforcement is incorporated during the stir-casting process, many particles rise to the surface because the reinforcement is insoluble in the Al6351 metal matrix. This uneven mixing was seen in Figure 4.14(d).

4.4.2 XRD analysis of AA6351/Gr/WC

The XRD patterns of AA6351 reinforced with graphite and WC in different ratios are shown in Figure 4.15. Finding the crystal structure, crystallinity, composition, and any potential flaws or contaminants in the samples may be accomplished with the use of the XRD analysis.

Aluminum has the highest peak in sample AA6351, with smaller peaks showing up for Mg, Mn, and Si. In contrast, AlGrW02 had an extra low-intensity WC peak at 66° (2θ), suggesting that hybrid metal matrix composites contain reinforcement. The peak intensity of WC rose significantly along with the fraction of reinforcement. AlGrW05 had the highest peak intensity of WC and the highest % of reinforcement. Peak intensities for Mg, Mn, and Si did not significantly alter. The hybrid composite's graphite, WC, and aluminum matrix particles did not develop any new phases in the hybrid MMC, according to the diffraction patterns.

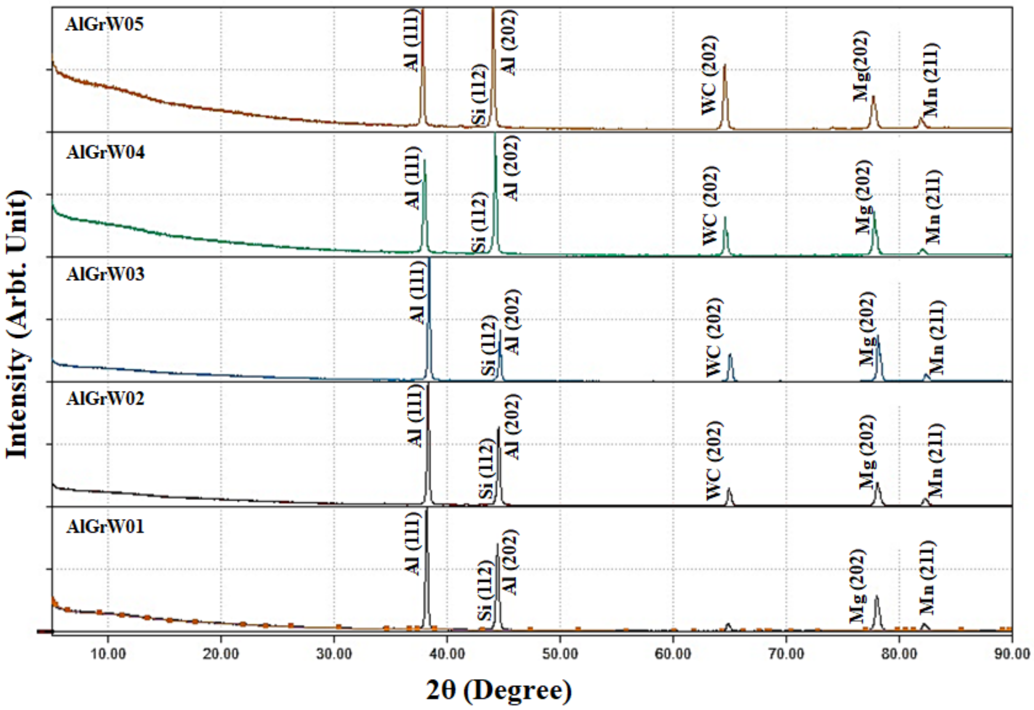

Figure 4:15 XRD for Fabricated Composite AA6351/Gr/WC

4.4.3 Energy Dispersive Spectroscopy of AA6351/Gr/WC

The EDS spectrum is shown in Figure 4.17, and the chemical constituent of the AA6351/Gr/WC HMMCs is shown in Table 4.4. Figure 4.16 shows SEM images of the manufactured Hybrid MMCs samples, AlGrW02, AlGrW03, AlGrW04, and AlGrW05. Energy Dispersive Spectroscopy (EDS) was used in combination with these SEM pictures for analysis. Energy Dispersive Spectroscopy (EDS) verifies the existence of tungsten (W) and graphite. It is important to note, that the peak intensity of tungsten looks comparatively faint in the EDS spectrum because of their low weight percentage.

Table 4:4 Weight wise Proportions in AA6351/Gr/WC HMMCs

Sample Code	Al	Gr	Si	Mg	Mn	Fe	Cu	Ti	Zn	W
AlGrW02	97.29	0.62	0.53	0.51	0.12	0.10	0.10	0.11	0.11	0.51
AlGrW03	96.29	0.89	0.52	0.50	0.50	0.10	0.10	0.10	0.10	0.90
AlGrW04	95.42	1.12	0.53	0.51	0.52	0.12	0.11	0.11	0.10	1.46
AlGrW05	94.67	1.30	0.52	0.50	0.50	0.10	0.10	0.11	0.10	2.10

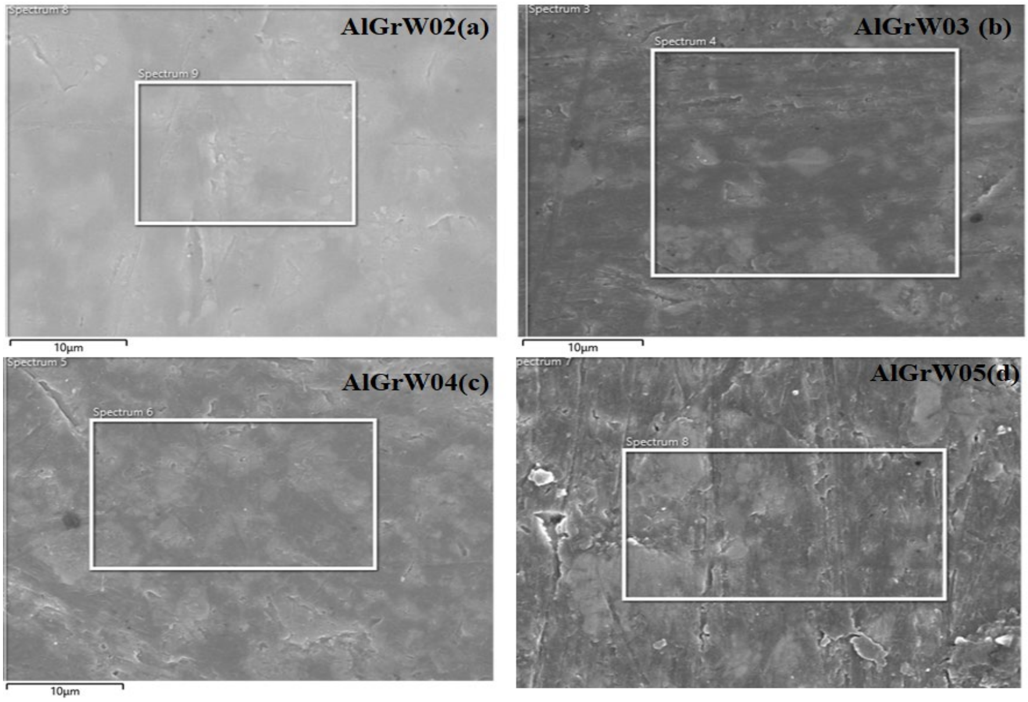

Figure 4:16 SEM for EDS of AA6351/Gr/WC Hybrid MMCs

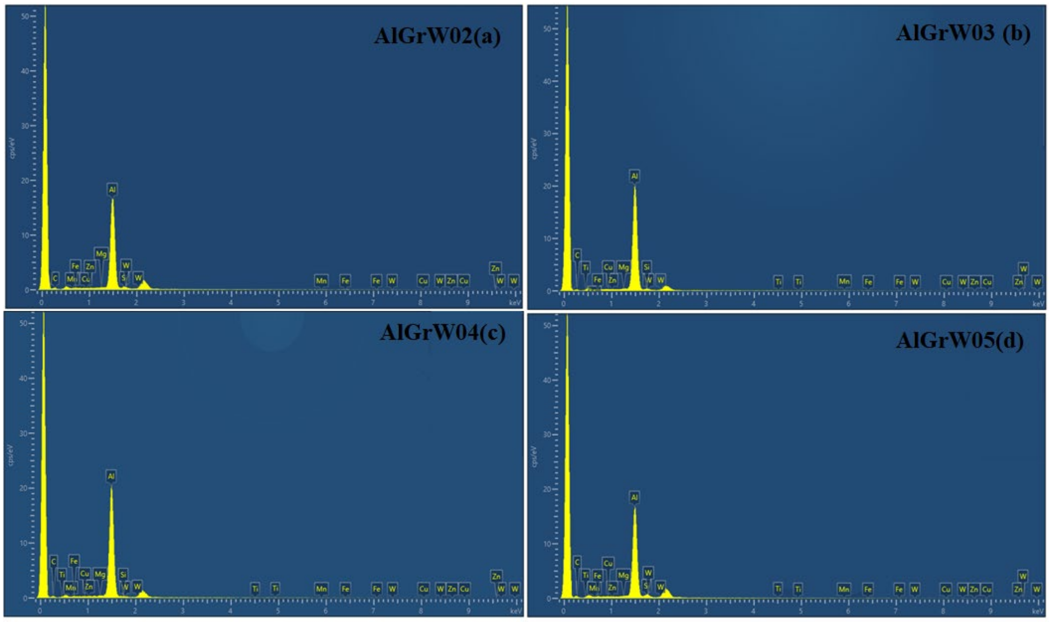

Figure 4:17 EDS of AA6351/Gr/WC Hybrid MMCs

In Figure 4.17(b), the EDS spectrum of sample AlGrW03 exhibits a noticeable similarity to that of AlGrW02. However, the chemical composition reveals an increase in the weight percentage of tungsten and graphite, indicating a higher concentration of these elements in AlGrW03 compared to AlGrW02.

Continuing with Figure 4.17(c), the EDS analysis of sample AlGrW04 displays a similar spectrum to that of AlGrW03. The chemical composition further demonstrates an incremental rise in the weight percentage of tungsten and graphite, indicating a higher concentration of these elements in AlGrW04 in comparison to both AlGrW03 and AlGrW02.

Figure 4.17(d) showcases the EDS spectrum of sample AlGrW05. The EDS analysis reveals distinct peaks corresponding to different elements. Notably, AlGrW05 exhibits the highest weight percentage of reinforcements in comparison to all the other samples.

4.5 AVERAGE PARTICLE SIZE

The particle size of the reinforcement in AA6351/Gr/B4C, AA6351/Gr/TiC, and AA6351/Gr/WC hybrid metal matrix composites (HMMCs) was analysed using ImageJ software. A distinct pattern was observed in each set. Initially, the particle size was relatively larger. However, when the reinforcement proportion reached 1 wt% for each reinforcement, the average particle size reduced significantly. Beyond this proportion, the particle size started to increase again.

Average particle size for each combination is shown in Figures 4.18, 4.19 and 4.20. Lowest particle size is obtained in AlGrB03 and highest particles obtained in AlGrW02.

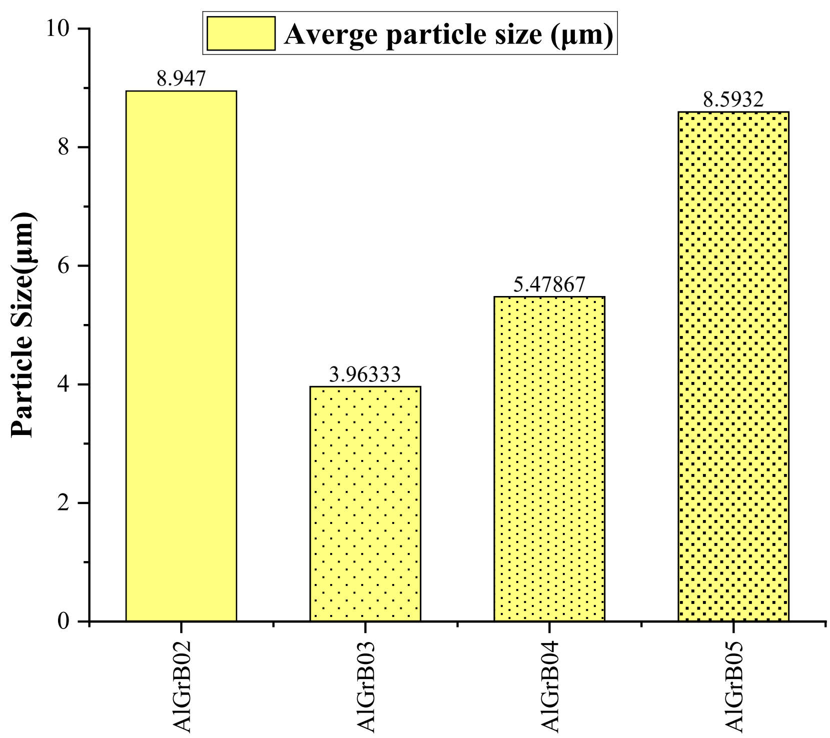

Figure 4:18 Average Particle Size AA6351/Gr/B_4C

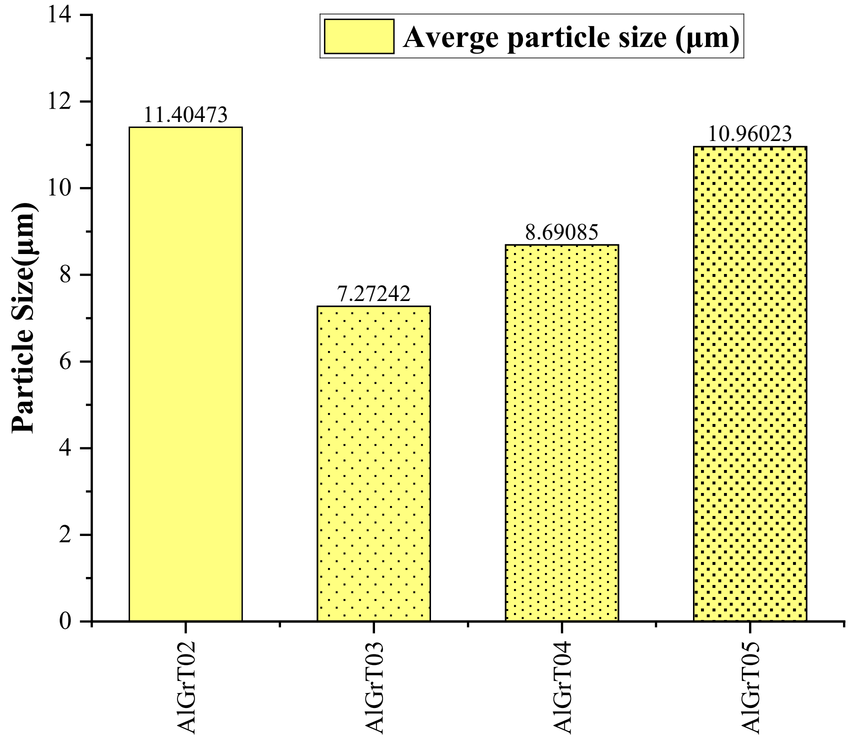

Figure 4:19 Average Particle Size AA6351/Gr/TiC

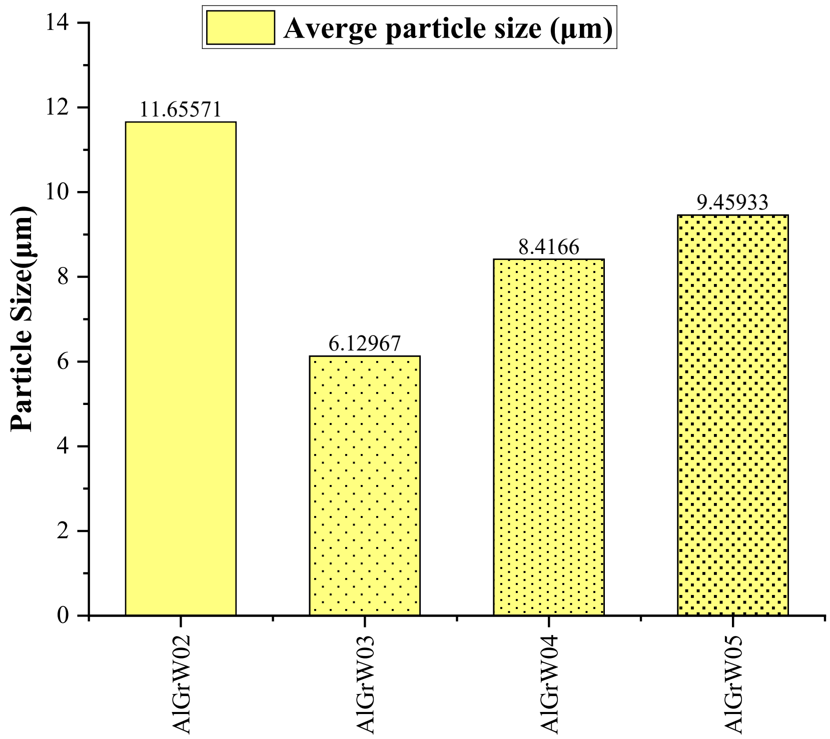

Figure 4:20 Average Particle Size AA6351/Gr/WC

Chapter 5: Mechanical Behaviour of AA6351Gr/B_4C/TiC/WC

This chapter aims to investigate and scrutinize the mechanical characteristics of developed hybrid metal matrix composites. This composite consists of AA6351 aluminum alloy reinforced with various combinations of B_4C, TiC, WC, and Graphite. A comprehensive set of tests was carried out to thoroughly evaluate these properties. The results obtained from these tests were then utilized to discern potential applications for this hybrid metal matrix composite.

5.1 HARDNESS

To assess sample hardness, a hardness testing machine was used. Five reading were taken on each specimen to take the average hardness of the specimen. Harness was measured using e "C" scale. Figure 5.1 displays the average hardness and experimental error for set-01. Pure AA6351 shows the hardness of 70 HRC. In set-01 hybrid MMCs, AlGrB03 exhibited the highest hardness at 82 HRC, with a smaller error bar due to uniform mixing. The increase in hardness is attributed to B_4C expansion in the hybrid metal matrix, while AlGrB04 and AlGrB05 shows decreased hardness in compare of AlGrB03, due to the uneven mixing of reinforcement, lower density and delicate nature of Graphite.

Figure 5.2 shows the hardness of Set-02. In Set-02 Hybrid MMCs, AlGrT03 recorded the highest hardness of 85 HRC, with the lowest experimental error. The hardness increase is attributed to the incorporation of TiC reinforcement in the hybrid metal matrix. However, AlGrT04 and AlGrT05 showed decreased hardness, likely due to the non-uniform mixing of the reinforcement and soft nature of Graphite.

Within set 3, AlGrW03 demonstrates the highest hardness at 76 HRC. The rise in hardness is less in comparison to other developed hybrid metal matrices. Despite tungsten carbide (WC) being the second hardest material after diamond, the lower hardness is attributed to the poor bonding and inadequate mixing of WC in the HMMCs. The results of Set-03 are reported in Figure 5.3.

Figure 5.4 shows the hardness of Set-04. In Set-04, AlBTW04, with 1.5 wt% of B_4C, TiC, and WC, displayed the highest hardness, but results were less impressive, possibly due to excessive amount of carbide and poor bonding between reinforcement and matrix materials.

Among all developed hybrid metal matrix composites, AlGrT03 demonstrated the best hardness, attributed to the hard nature of TiC and good bonding. The second-highest value was observed in sample AlGrB03.

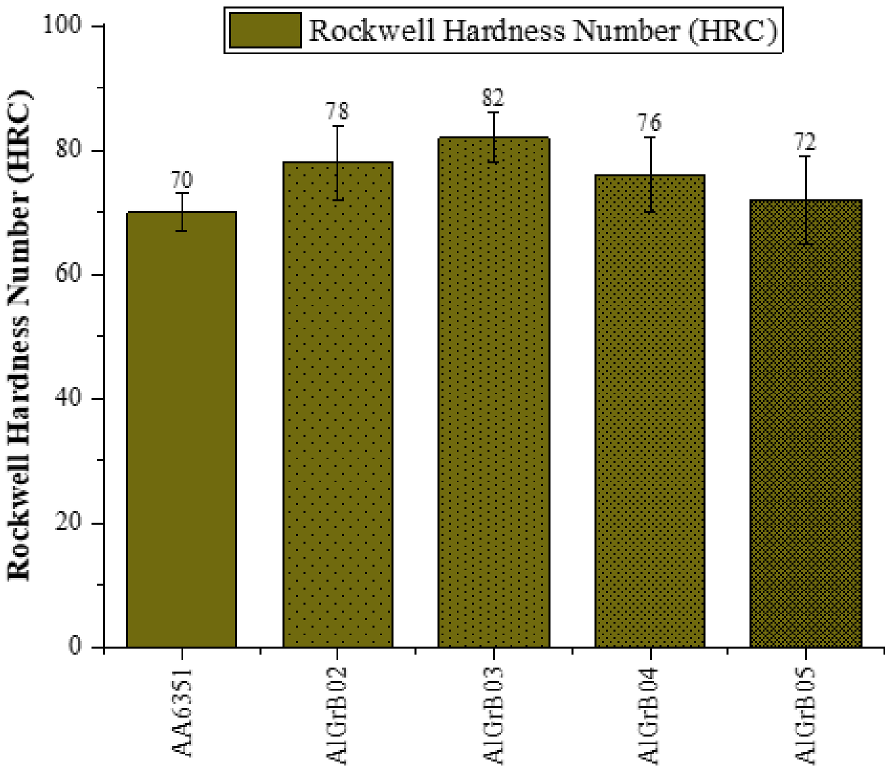

Figure 5:1 Hardness of AA6351/Gr/B_4C

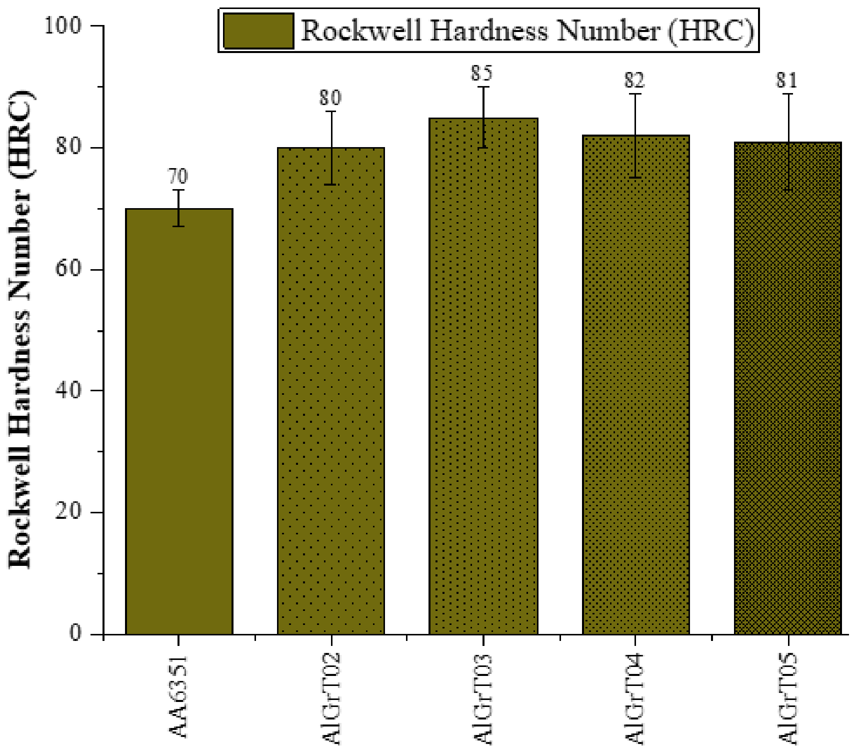

Figure 5:2 Hardness of AA6351/Gr/TiC

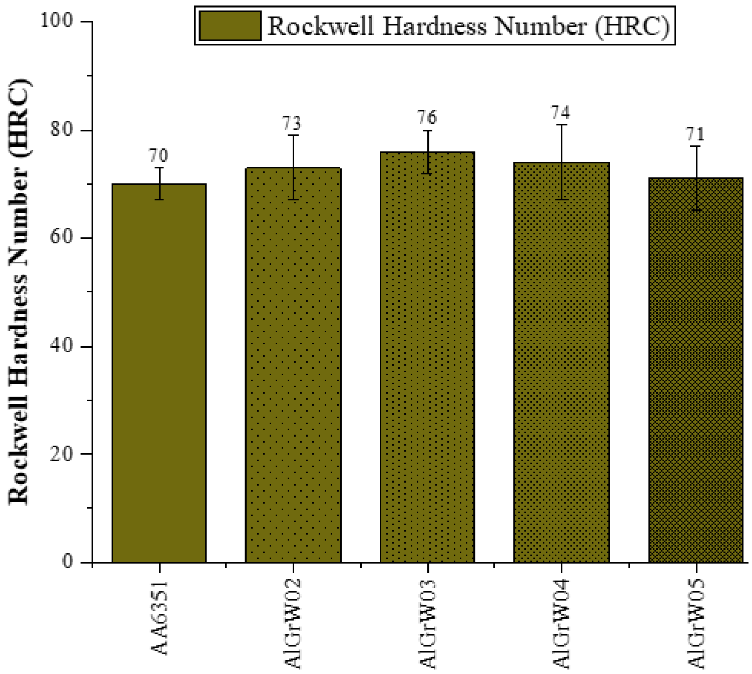

Figure 5:3 Hardness of AA6351/Gr/WC

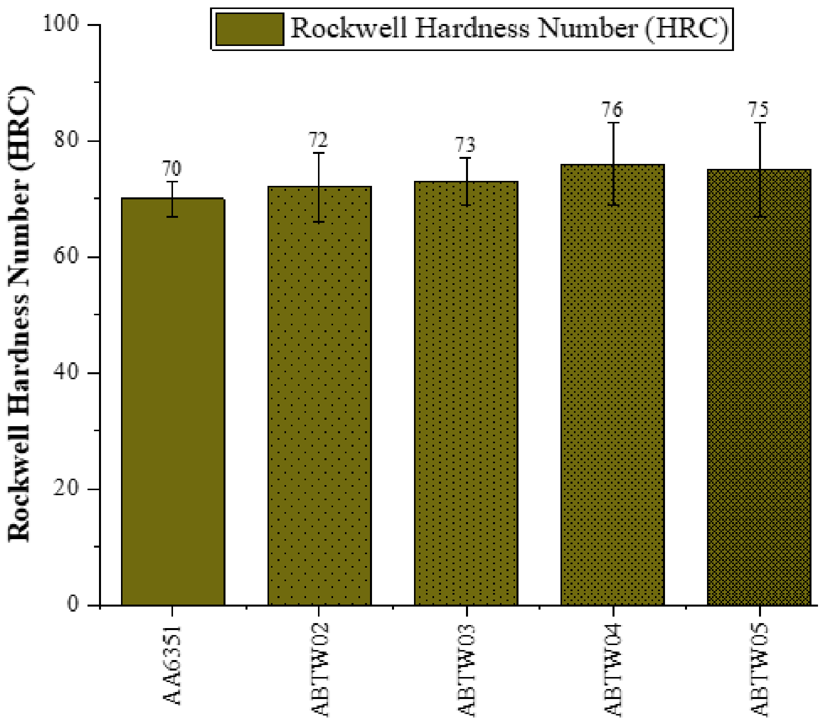

Figure 5:4 Hardness of AA6351/B_4C/TiC/WC

5.2 IMPACT STRENGTH

Impact strength is a crucial measurement used to assess a material's capacity to absorb energy before experiencing fracture or breakage. It measures the amount of energy needed to fracture a notched specimen under high-speed impact conditions. This parameter provides valuable insights into the durability and toughness of a material, making it a pivotal factor in the selection and design of materials for a wide array of applications, including but not limited to construction, transportation, and industrial equipment.

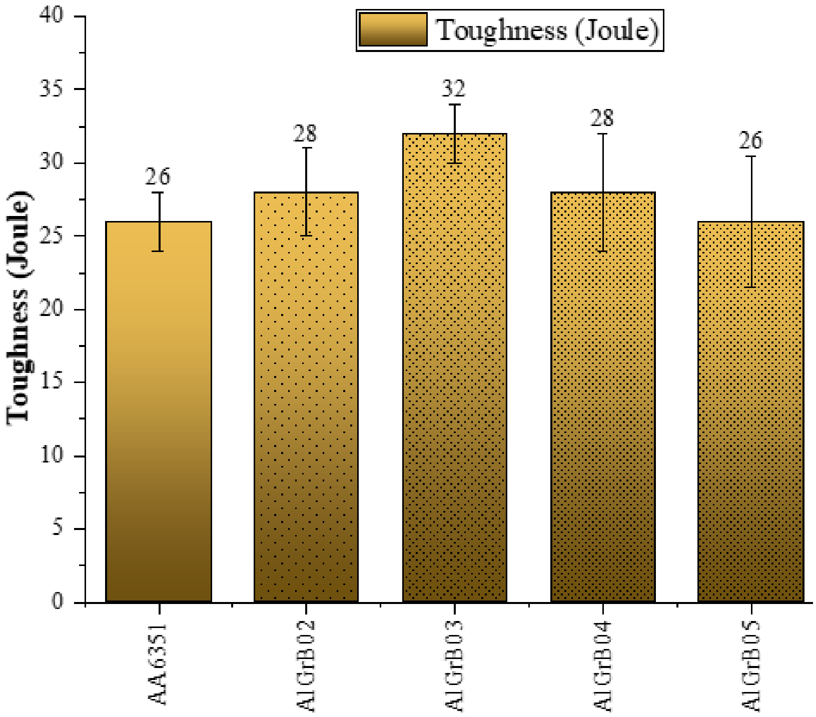

Figure 5:5 Impact Strength of AA6351/Gr/B_4C

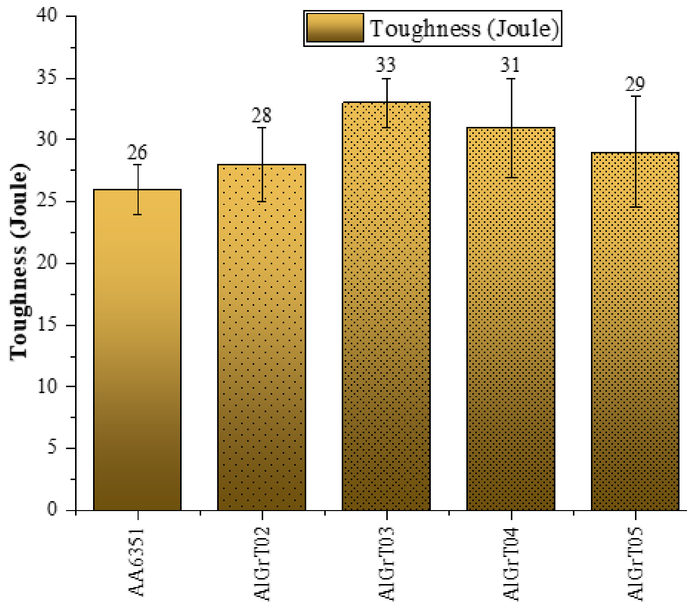

Figure 5:6 Impact Strength of AA6351/Gr/TiC

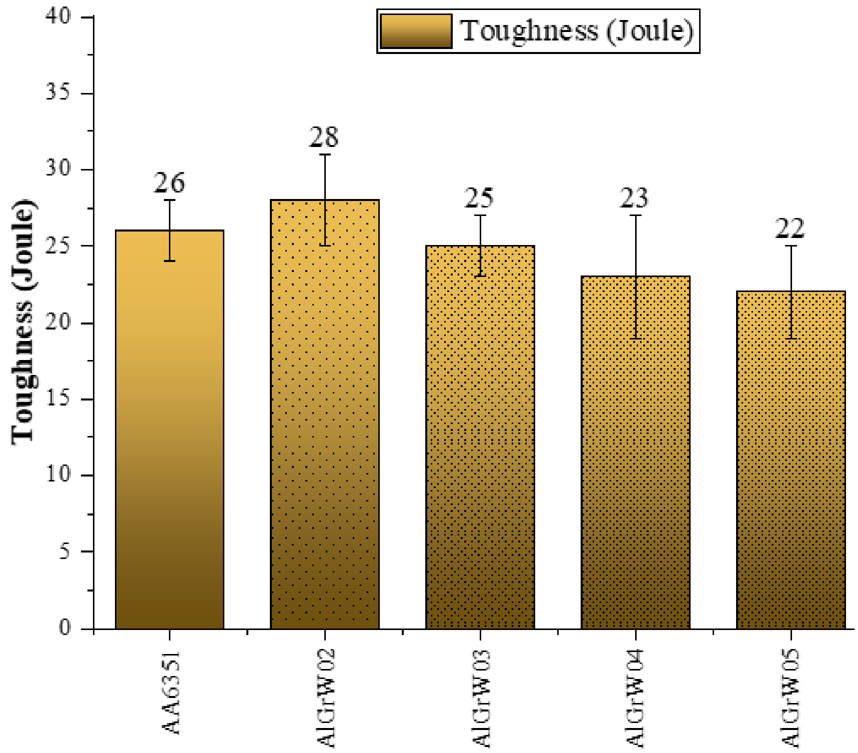

Figure 5:7 Impact Strength of AA6351/Gr/WC

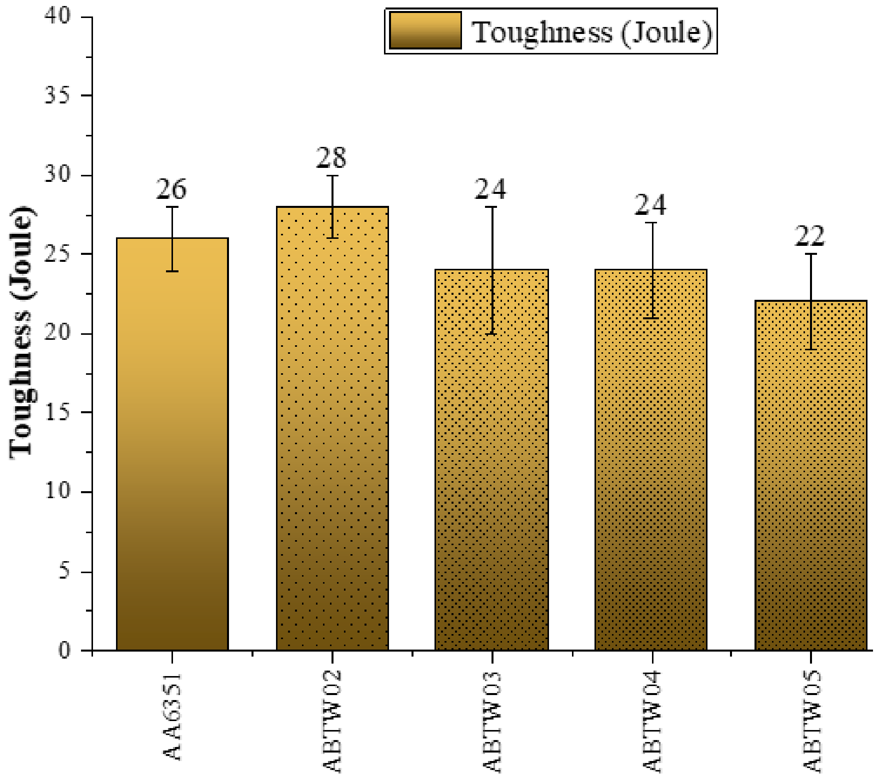

Figure 5:8 Impact Strength of AA6351/B_4C/TiC/WC

Figure 5.5 illustrates how the inclusion of B_4C and Graphite reinforcements in AA6351 significantly affects the hybrid metal matrix composites' impact strength. Impact strength first shows a rising trend, reaching its maximum for both B_4C and graphite at 1.0 wt% for reinforcement. However, the impact strength decreases when the reinforcement percentage is increased further. In Set-01, AlGrB03 had the highest impact strength, measuring 32 Joules. This increment in toughness is due to soft nature of Graphite, proper bonding and even mixing of reinforcement.

In Set-02, Shown in Figure 5.6, With an initial rising trend in impact strength as the reinforcing proportion increases, AlGrT03 exhibits the maximum impact strength at 33 joules. The peak impact strength is achieved at 1.0 wt% for both graphite and TiC. However, due to the brittleness introduced by TiC and the uneven distribution of reinforcement, the impact strength diminishes as the percentage of reinforcement increases.

Within Set-03, AlGrW02 exhibits the highest strength at 28 joules. However, the impact strength is observed to be lower compared to other developed hybrid composites. This decreased impact strength is attributed to the inadequate bonding of WC with the matrix. The relationship between impact strength and reinforcement proportion is illustrated in Figure 5.7.

In Set-04, AlBTW02 demonstrates the most favourable impact characteristics, while AlBTW05 displays the weakest. The excessive carbide content, which induces brittleness in the developed hybrid composite and improper bonding, leads to a subpar impact strength result. Figure 5.8 depicts the correlation between impact strength and the proportion of reinforcement.

Among the 17 tested samples, AlGrT03, containing 1 wt% of each reinforcement, shows the best result, followed by AlGrB03. The lowest impact strength is observed in sample AlBTW05.

5.3 TENSILE STRENGTH

Measuring tensile strength is of paramount importance for various purposes, including material selection, quality control, safety assurance, and research and development. It aids in gaining a deeper understanding of material behavior, developing novel materials, and optimizing manufacturing processes.

The graphs of stress Vs strain for AA651 is shown in Figure 5.9. Hook's law is followed by the specimen in a tensile test up to a proportionate point. Curve can be separated in to two parts: elastic zone and plastic zone. After removal of the applied force, the specimen can revert to its initial state within the elastic zone. The material, however, experiences persistent deformation inside the plastic zone.

The stress versus strain graph for casted AA6351 is depicted in Figure 5.9. It is evident from Figure 5.10 that as the proportion of reinforcement increases, the strain in the component decreases. This same pattern is noticeable in AA6351/Gr/TiC, AA6351/Gr/WC, and AA6351/B_4C/TiC/WC, illustrated in Figures 5.11, 5.12, and 5.13, respectively. The consistent decrease in strain indicates the introduction of brittleness in the hybrid metal matrix composite.

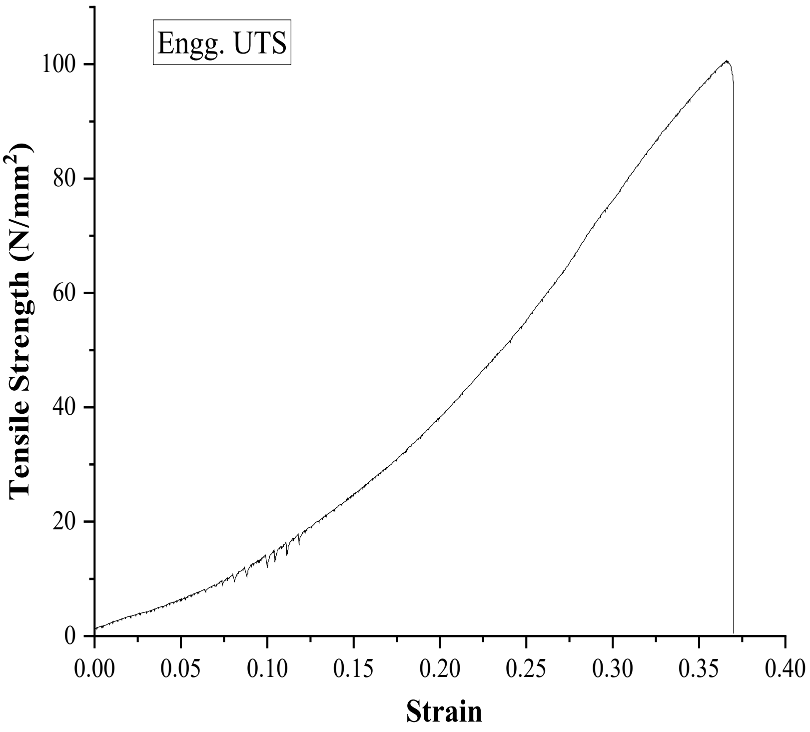

Figure 5:9 Engg. Stress Vs Strain Plot for AA6351

Figure 5.14 shows ultimate tensile strength of AA6351/Gr/B_4C along with experimental error. During a tensile test, when a specimen undergoes low stress, the atomic bonds stretch, and upon removing the load, the atoms return to their original state. In this phase, materials adhere to Hooke's law. With an increase in the applied load, the stress planes slide against each other, resulting in permanent material stretching, termed as plastic deformation. From figure it can be observed that on elevating the reinforcement weight percentage initially enhances the tensile strength. Notably, Sample AlGrB03, containing 1.0 wt% B_4C and 1.0 wt% reinforcement, demonstrates the highest tensile strength. Nevertheless, surpassing these percentages results in a decline in the ultimate tensile strength of the produced hybrid metal matrix composite.

Figure 5.15 shows the UTS of AA6351/Gr/TiC with experimental error. Notably, among the various configurations, sample AlGrT03, containing 1.0 wt% TiC and 1.0 wt% Graphite, demonstrates superior results. However, as the proportion of reinforcement is increased beyond this point, there is a decrease in the engineering ultimate tensile strength. This indicates the presence of an optimal balance between the proportion of reinforcement and the properties of the hybrid metal matrix composite.

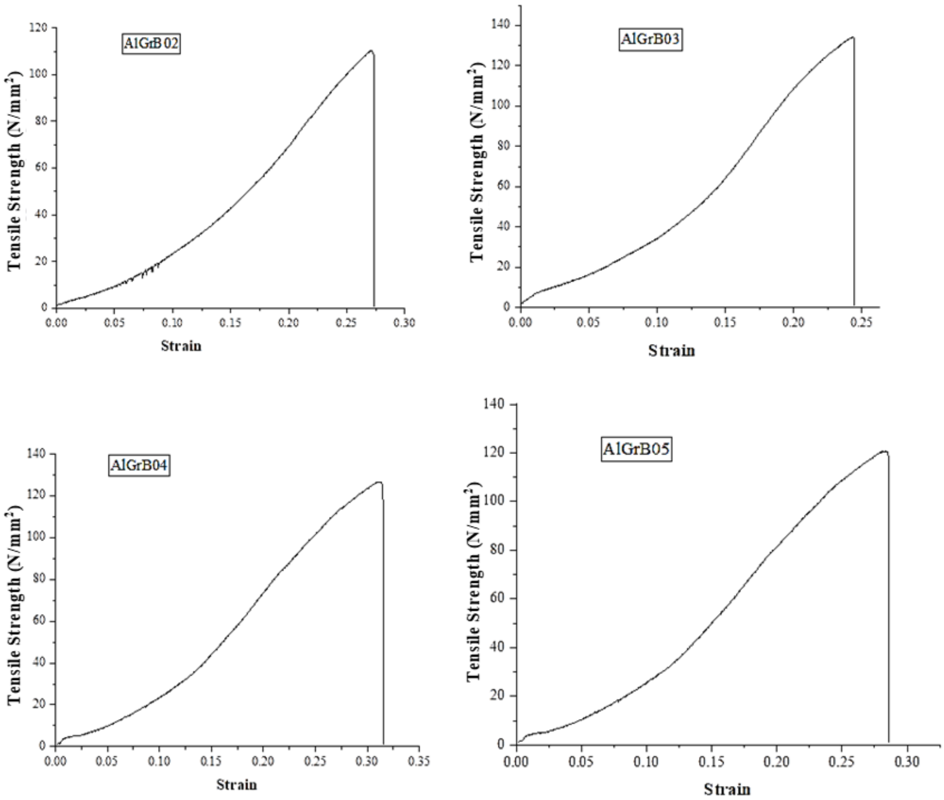

Figure 5:10 Engg. Stress Vs Strain AA6351/Gr/B$_4$C

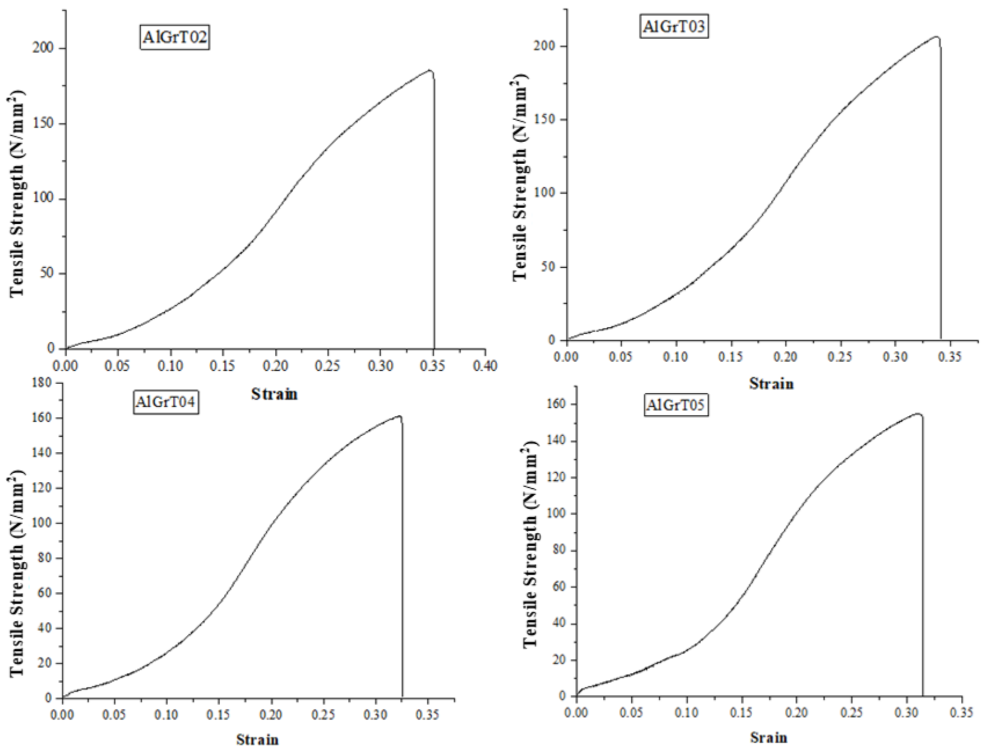

Figure 5:11 Engg. Stress Vs Strain AA6351/Gr/TiC

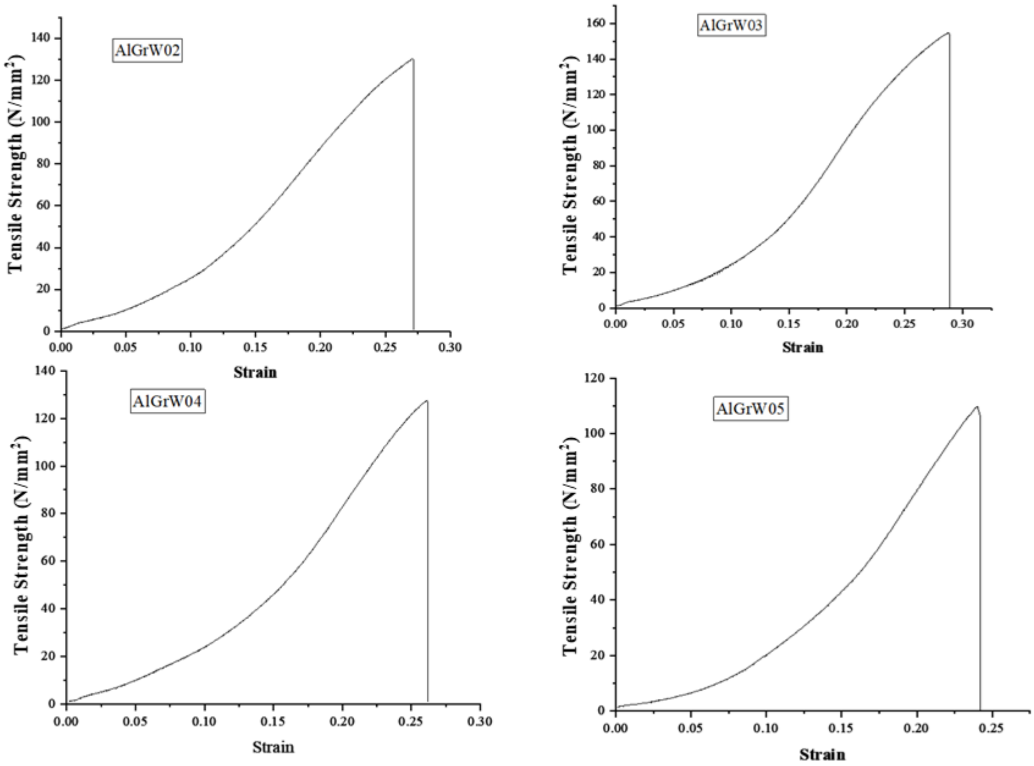

Figure 5:12 Engg. Stress Vs Strain AA6351/Gr/WC

Figure 5.16 shows the ultimate tensile strength for AA6351/Gr/WC. The figure demonstrates a rise in ultimate tensile strength up to the point where the reinforcement proportion reaches 1.0 wt% Gr and 1.0 wt% WC. Notably, among the samples, the AlGrW03 sample, containing 1.0 wt% WC and 1.0 wt% Graphite, showcases superior performance compared to other configurations. Nevertheless, with a further increase in the reinforcement proportion, there is a subsequent decrease in the engineering ultimate tensile strength.

The diagram in Figure 5.17 depicts the ultimate tensile strength of AA6351/B_4C/TiC/WC HMMCs. Upon closer examination of the figure, it becomes evident that initially, there is an increase in ultimate tensile strength with the increase in reinforcement proportion. However, beyond a certain point, further increases in reinforcement lead to a decrease in the ultimate tensile strength of the developed hybrid metal matrix composite. This phenomenon can be linked to the non-uniform mixing observed in the SEM graph. The combination of AA6351 with B_4C, TiC, and WC does not yield promising results. While there was some improvement, it was not as significant as observed in other cases. Notably, AlBTW04 demonstrates the best result in this context.

Among all samples, pure AA6351 exhibits the lowest strength but the highest ductility. A consistent trend is observed across all batches: as the reinforcement weight percentage increases, both peak load and break load increase, but at the expense of the ductility of the hybrid composite materials. Subsequently, there is a decrease in both peak load and break load after reaching a certain point. In batches 1 and 2, the increase in peak load and break load is noted up to a reinforcement weight percentage of 1% each, beyond which both parameters decline. Similarly, in batches 3 and 4, a decrease in peak load and break load is observed after the reinforcement weight exceeds 0.5% each.

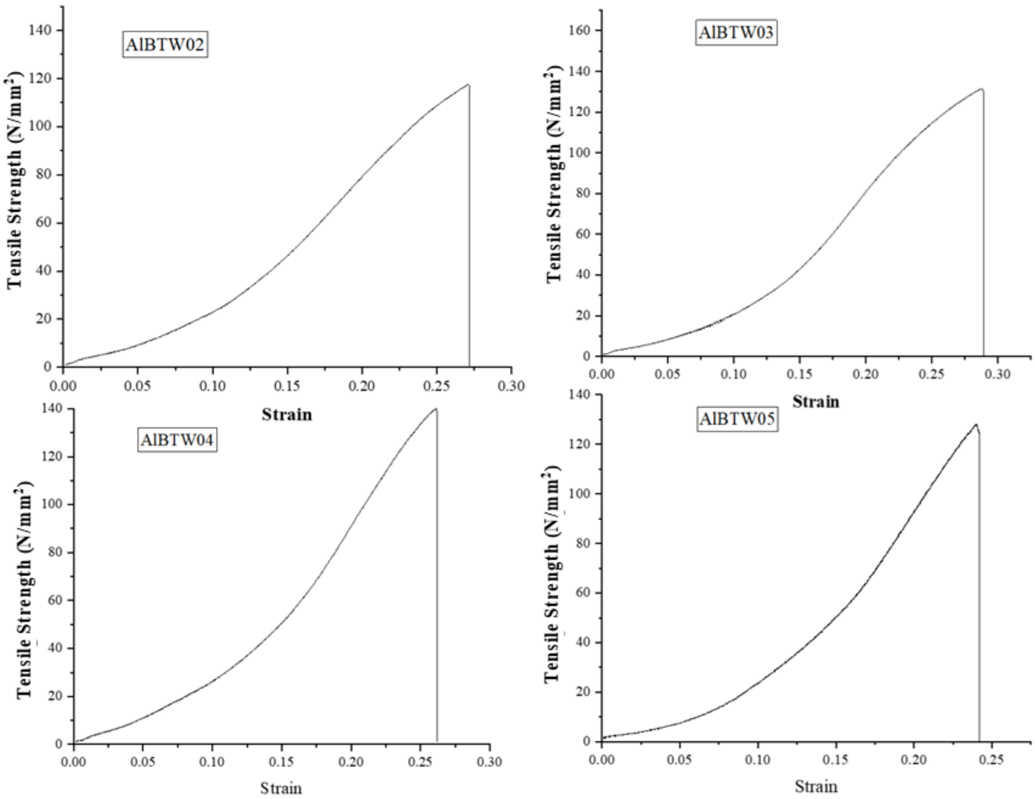

Figure 5:13 Engg. Stress vs Strain of AA6351/B_4C/TiC/WC

Out of all the developed hybrid composite samples, AlGrT03, reinforced with 1 wt% each of Graphite and TiC, exhibits the highest Engineering Ultimate Tensile Strength at 206.7 MPa, followed by AlGrT04 at 161.3 MPa. The lowest Engineering UTS is observed in AlGrB02, reinforced with 0.5 wt% Graphite and 0.5 wt% B_4C.

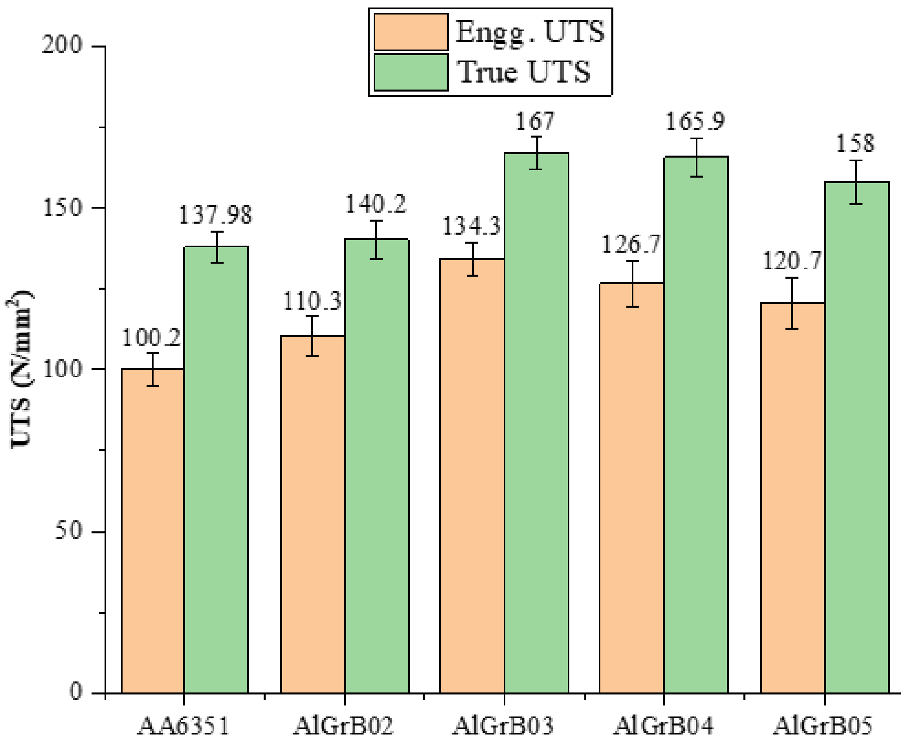

Figure 5:14 UTS of Developed AA6351/Gr/B_4C

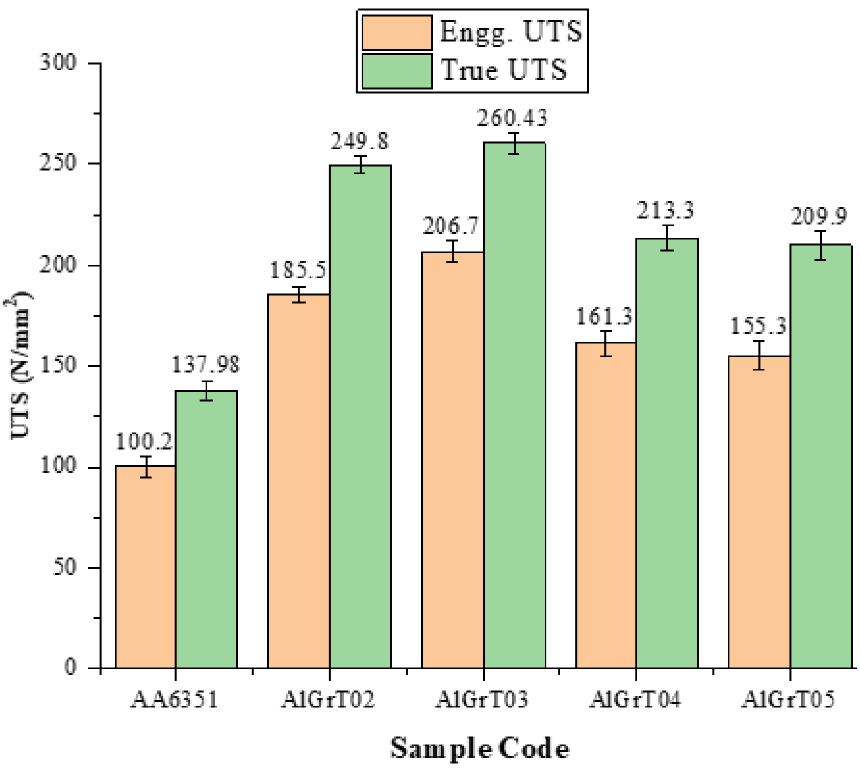

Figure 5:15 UTS of Developed AA6351/Gr/TiC

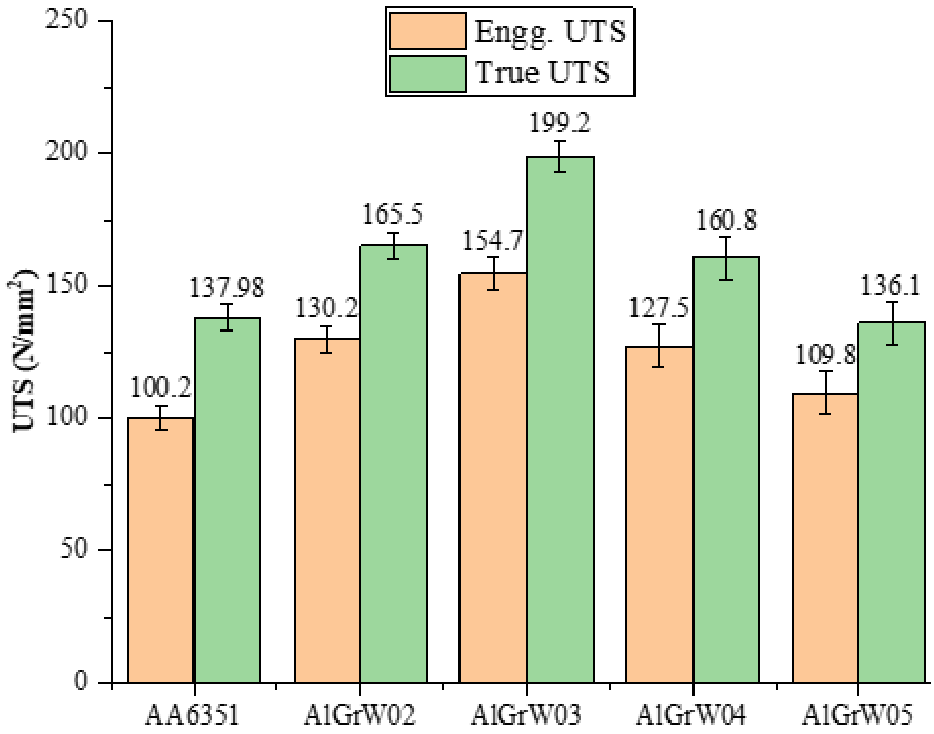

Figure 5:16 UTS of Developed AA6351/Gr/WC

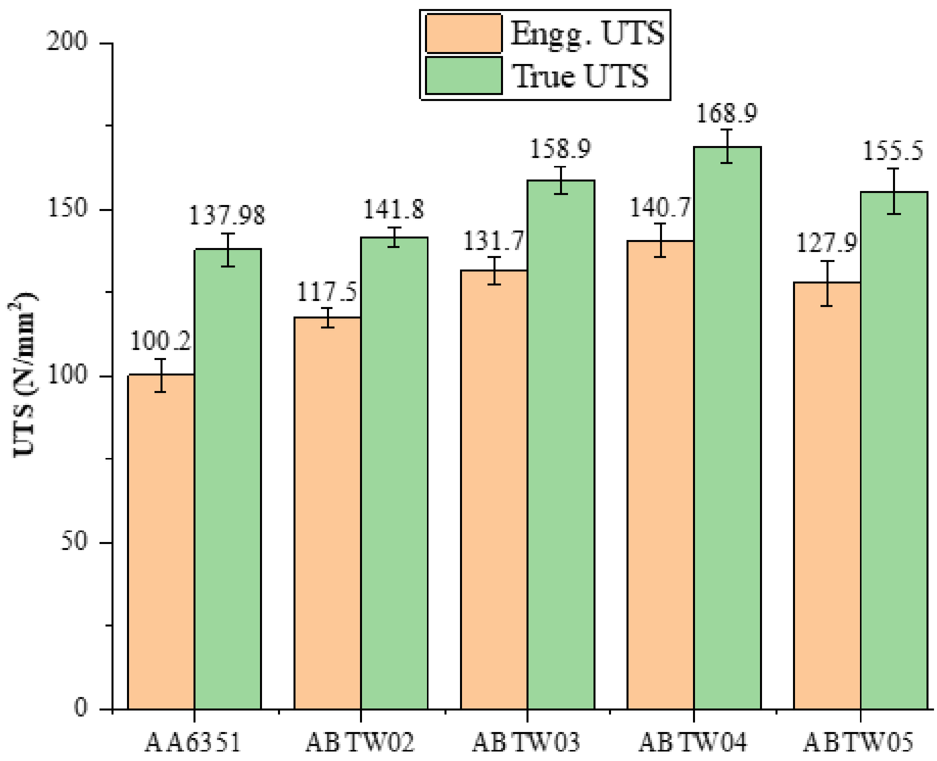

Figure 5:17 UTS of Developed AA6351/B_4C/TiC//WC

5.4 STATISTICAL ANALYSIS

Ranking techniques like TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) are integral tools in decision-making processes, particularly in multi-criteria analysis scenarios. TOPSIS operates on the principle of identifying the alternative that is closest to the ideal solution while simultaneously being farthest from the negative ideal solution in a multidimensional space defined by criteria. By calculating the Euclidean distances of alternatives from these ideal points, TOPSIS provides a systematic approach to rank alternatives based on their overall performance across multiple criteria. This method allows decision-makers to effectively prioritize alternatives, considering various factors simultaneously, thereby aiding in informed decision-making and facilitating efficient resource allocation across diverse contexts ranging from project selection to supplier evaluation.

5.4.1 TOPSIS Procedure

The TOPSIS method is employed to assign rankings to samples based on their performance scores within a dataset. This technique comprises several sequential steps, which include:

Step 1:

The normalised matrix is prepared with the help of given formula in equation (1)

$$\overline{X}_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \quad \text{....(1)}$$

Step 2:

To find out the ideal best mechanical properties value V^+ (maximum value in true UTS, hardness, and toughness respectively as well as minimum value in theoretical density) and ideal worst mechanical properties value V^- (minimum value in true UTS, hardness, and toughness respectively as well as minimum value in theoretical density).

Step 3: The Euclidean distance (e^-) is determined with the help of given equation (2)

$$S_i^+ = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^+\right)^2\right]^{0.5} \quad \text{... (2)}$$

Step 4: The Euclidean distance (e^-) is determined with the help of given equation (3).

$$S_i^- = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^-\right)^2\right]^{0.5} \quad \text{... (3)}$$

Step 5: The performance score (P_i) is determined with the help of given formula in equation

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad \text{... (4)}$$

5.4.2 Optimization of data using TOPSIS technique

The normalised matrix table 4 prepared with the help of given formula in equation 1.

Table 4: Normalised matrix

Sample Code	True UTS	Hardness	Toughness	Theoretical Density
AA6351	0.1863	0.2223	0.2329	0.2359
AlGrB02	0.1893	0.2478	0.2508	0.2352
AlGrB03	0.2255	0.2605	0.2867	0.2345
AlGrB04	0.2240	0.2414	0.2508	0.2338
AlGrB05	0.2134	0.2287	0.2329	0.2331
AlGrT02	0.3373	0.2541	0.2508	0.2362
AlGrT03	0.3517	0.2700	0.2956	0.2366
AlGrT04	0.2880	0.2605	0.2777	0.2369
AlGrT05	0.2835	0.2573	0.2598	0.2373
AlGrW02	0.2235	0.2319	0.2508	0.2409
AlGrW03	0.2690	0.2414	0.2240	0.2459
AlGrW04	0.2171	0.2351	0.2060	0.2509
AlGrW05	0.1838	0.2255	0.1971	0.2559
ABTW02	0.1915	0.2287	0.2508	0.2419
ABTW03	0.2146	0.2319	0.2150	0.2488
ABTW04	0.2281	0.2414	0.2150	0.2549
ABTW05	0.2100	0.2382	0.1971	0.2618

TOPSIS result is shown in table 5 which is calculated with the help of above given steps and equations. The rank of the samples is decided on the basis of performance score (P_i) as display in table 5. The composite sample AlGrT03 has higher performance score (0.9941) and other composites have lower performance score, so rank one is assigned for composite sample AlGrT03.

Table 5: TOPSIS result

Sample Code	True UTS	Hardnes s	Toughness	Density	Si+	Si-	Pi	Rank
AA6351	0.1863	0.2223	0.2329	0.2359	0.1832	0.0443	0.1947	13
AlGrB02	0.1893	0.2478	0.2508	0.2352	0.1699	0.0654	0.2779	9
AlGrB03	0.2255	0.2605	0.2867	0.2345	0.1269	0.1094	0.4630	5
AlGrB04	0.2240	0.2414	0.2508	0.2338	0.1383	0.0752	0.3522	7
AlGrB05	0.2134	0.2287	0.2329	0.2331	0.1574	0.0550	0.2588	10
AlGrT02	0.3373	0.2541	0.2508	0.2362	0.0497	0.1677	0.7713	2
AlGrT03	0.3517	0.2700	0.2956	0.2366	0.0035	0.2020	0.9831	1
AlGrT04	0.2880	0.2605	0.2777	0.2369	0.0669	0.1394	0.6757	3

AlGrT05	0.2835	0.2573	0.2598	0.2373	0.0782	0.1252	0.6155	4
AlGrW02	0.2235	0.2319	0.2508	0.2409	0.1413	0.0707	0.3334	8
AlGrW03	0.2690	0.2414	0.2240	0.2459	0.1138	0.0927	0.4490	6
AlGrW04	0.2171	0.2351	0.2060	0.2509	0.1663	0.0384	0.1875	15
AlGrW05	0.1838	0.2255	0.1971	0.2559	0.2010	0.0067	0.0324	17
ABTW02	0.1915	0.2287	0.2508	0.2419	0.1716	0.0582	0.2531	12
ABTW03	0.2146	0.2319	0.2150	0.2488	0.1643	0.0391	0.1922	14
ABTW04	0.2281	0.2414	0.2150	0.2549	0.1519	0.0519	0.2547	11
ABTW05	0.2100	0.2382	0.1971	0.2618	0.1778	0.0307	0.1470	16
V+	0.3517	0.2700	0.2956	0.2331				
V-	0.1838	0.2223	0.1971	0.2618				

The minimum performance score (P_i) is found in composite sample AlGrW05 (0.0324), so its rank is 17. The composite sample AlGrT03 has maximum mechanical properties due to higher performance score (P_i). On comparing both the methods i.e. ANOVA and TOPSIS, it is observed.

that both methods have separate techniques for optimization and TOPSIS method provide much closer result as compared to ANOVA method. In ANOVA, study the effect of reinforcements on mechanical properties in terms of different types of samples. In TOPSIS, the maximum mechanical properties found in sample AlGrT03 on the basis of rank and rank of the specimen is decided with the help of performance score (P_i).

5.5 DISCUSSION

The developed samples of hybrid metal matrix composites show that the matrix and reinforcement have an efficient interfacial bonding. The mechanical characteristics of the composite, such as its stiffness, toughness, and tensile strength, are heavily influenced by this strong interfacial bonding. Tensile strength and impact resistance are two mechanical qualities that are improved by a strong interfacial binding, which makes it easier for stress to propagate from the matrix to the reinforcement. Additionally, it serves as a barrier to stop the initiation and spread of cracks.

The hybrid metal matrix composite experiences strain hardening as a result of the addition of reinforcing components to the metal matrix. The tensile strength and toughness of the composite are further enhanced by this strain hardening.

The hybrid metal matrix composite's theoretical and experimental densities are less affected by the weight fraction of reinforcements. The main causes of this tendency are the hybrid metal matrix composite's porosity and the reinforcements' low density. Upon closer examination of Table 8, it can be observed that the percentage of porosity inside the composite grows in tandem with the weight % of reinforcement.

The introduction of graphite particles into the metal matrix leads to a substantial reduction in wear and friction among the metal particles. Graphite functions as a solid lubricant. Conversely, the composite's hardness is augmented by the inclusion of B_4C, TiC, and WC, which are ceramic materials known for their notable hardness and resistance to wear. The collaborative action of graphite, B_4C, TiC, and WC results in the formation of a composite with outstanding hardness.

In AA6351/Gr/B_4C, AA6351/Gr/TiC and AA6351/Gr/WC surpassing a weight percentage beyond 1% for both reinforcement materials does not result in additional improvement in the hardness of the developed hybrid metal matrix composite. Similarly, in batch 4, exceeding a weight percentage beyond 1.5% for each reinforcement materials do not yield further improvement in hardness. This phenomenon is attributed to the agglomeration of reinforcement particles, creating regions with high-stress concentration, and weakened points within the composite. These weakened areas are susceptible to the formation of cracks and other defects, ultimately reducing the overall strength and durability of the composite.

The incorporation of Graphite along with B_4C, TiC, and WC reinforcements in the composite leads to improvement in impact strength. These reinforcements serve as obstacles, hindering the propagation of cracks and absorbing energy during impact loading. The enhanced strength and hardness resulting from these reinforcements play a crucial role in elevating the resistance to impact. However, surpassing a certain concentration of reinforcement leads to a further decline in impact strength. In AA6351/Gr/B_4C and AA6351/Gr/TiC, the maximum impact strength is observed in the sample containing 1.0 wt% for each reinforcement. In batches AA6351/Gr/TiC and AA6351/B_4C/TiC/WC, the highest impact strength is observed in the sample containing 0.5 wt% of each reinforcement. This decrease is attributed to the potential clustering or agglomeration of reinforcing particles, which compromises the overall impact resistance of the composite. Additionally, weak interfacial bonding between the reinforcing particles and the matrix material impedes load transfer, limiting energy absorption during impact loading. This inadequate interfacial bonding also contributes to the reduction in impact strength.

Upon a more detailed analysis of Figure 5:15, it becomes apparent that the hybrid metal matrix composite, comprising 1.0 wt% Graphite and 1.0 wt% TiC, displays the lowest standard deviation. This indicates that this particular composition of the hybrid metal matrix composite showcases a notable level of consistency and uniformity in its mechanical properties, with the highest impact strength observed. Conversely, samples AlGrW05 and AlBTW05 exhibit the lowest impact strength, likely due to inadequate bonding.

The tensile strength of hybrid metal matrix composites rises with increased proportions of reinforcement. HMMCs incorporating higher amounts of reinforcement demonstrate superior mechanical properties when compared to the unreinforced Al6351 alloy. The enhanced mechanical characteristics are primarily ascribed to the reinforcement particles, which hinder the movement of dislocations and improve load transfer within the material. Among the developed composites, in batches AA6351/Gr/B_4C, AA6351/Gr/TiC, and AA6351/Gr/WC, the highest engineering ultimate tensile strength and true tensile strength were observed in samples containing

1.0 wt.% of each reinforcement. However, an escalation in the weight percentage of reinforcement beyond this point leads to a decrease in tensile strength. The decline in strength observed at higher reinforcement proportions can be attributed to the agglomeration of reinforcement particles. Agglomeration pertains to the clustering of reinforcement particles, diminishing the effectiveness of load transfer between the particles and the matrix. Consequently, this phenomenon ultimately results in a decline in the overall tensile strength of the Hybrid Metal Matrix Composite (HMMC). The stress- strain graphs consistently indicate a reduction in break displacement data as the proportion of reinforcement increases. This trend implies a growing brittleness characteristic in the composite material, as noted by Mohanavel et al. in 2016[106].

AA6351/B_4C/TiC/WC demonstrates distinct trends; the highest tensile strength is observed in the sample containing 1.5 wt% of each reinforcement. Upon a detailed analysis of the data from all 17 samples, it becomes apparent that the hybrid composite incorporating graphite and TiC exhibits significant improvements in strength.

In addition to this, grain size plays a crucial role in strengthening the bond between the reinforcement and the matrix in hybrid metal matrix composites. A finer grain size increases the overall surface area of the grains, thereby enhancing the interfacial bonding between the matrix and the reinforcement particles. This stronger bond leads to improved load transfer and mechanical properties. Samples with a lower grain size exhibit better strength due to their ability to resist deformation more effectively, as the finer grains act as barriers to dislocation movement, a phenomenon known as grain boundary strengthening. Thus, controlling and refining grain size is critical for achieving optimal strength and performance in these composites.

The results indicate that the mechanical strength achieved with this lower weight proportion is comparable to, or potentially surpasses, the strength obtained with higher weight proportions in previous research. This unexpected outcome underscores the potential advantages and effectiveness of utilizing lower-weight proportions of Graphite (Gr) and Titanium Carbide (TiC) as reinforcement materials, as suggested by Ahamad et al. in 2020[39] and Mohanavel et al. in 2015[107].

Chapter 6: Wear Characterization

After the mechanical testing phase, the best sample from each set was chosen for further evaluation of wear behavior. Wear testing is a crucial step in understanding how materials perform under conditions that simulate real-world usage, helping to identify potential weaknesses or strengths in the materials.

The results obtained from the tensile test, hardness test, and impact test are consolidated in the Table 6.1 below.

Table 6:1 Mechanical Characterization of Selected Samples

Sample	Engg. UTS (MPa)	Hardness (HRC)	Toughness (Joules)
AA6351	100.2	70	26
AlGrB03	134.3	82	32
AlGrW03	154.7	76	25
AlGrT03	206.7	85	33

Sample AlGrT03 shows the best mechanical characteristics among all the fabricated samples due to uniform proper mixing and lower defects.

6.1 WEAR TEST

The wear behavior of the fabricated hybrid MMCs was evaluated using a pin-on-disk wear testing machine. The composite sample, in the form of a pin, was brought into contact with the rotating disk under controlled conditions. Below explained parameters and test conditions were considered for wear experiments:

Applied Load: The load or force applied to the composite material during wear testing is an important parameter. Load in the range of 10 to 40 N varied with equal intervals of 10N to simulate different levels of contact pressure and determine the load-bearing capacity and wear resistance of the composite.

Sliding Speed: The sliding speed or rotational speed of the test setup is a crucial factor, as it signifies the relative motion between the composite sample and the counterface material. Depending on the intended application, sliding speeds can vary from low-speed conditions to higher speeds. For this particular test, the relative linear speed was fixed at 1*m/s,* and the disc R.P.M was adjusted accordingly.

Sliding Distance: The sliding distance represents the cumulative distance travelled by the sliding contact. It is an essential parameter for assessing the wear resistance and durability of the composite. The workpieces were subjected to a sliding distance of 1000 m to achieve a noticeable weight loss in the specimens.

Counterface Material: The choice of counterface material, which encounters the composite sample, is crucial. It should represent the intended application or the typical wear conditions that the composite will encounter. Based on the recommendation of ASTM, EN31 steel was selected due to its hardness and compatibility with the composite material.

6.2 EXPERIMENTAL PROCEDURE

To conduct a wear test on the fabricated hybrid MMCs, the following steps were implemented. Firstly, the experimental setup was prepared by meticulously cleaning the specimen pin and eliminating any burns on the circumference using fine-grade emery paper. The disc was also thoroughly cleansed with a solvent and allowed to dry to assess wear on the disc surface. The weight of the specimen was then accurately measured using a highly precise weighing machine. Subsequently, the sample pin was securely clamped to the loading lever tip using hardened jaws of appropriate size. To establish a wear radius of 65 mm, the sliding plate was adjusted by unscrewing and shifting it to the desired position, aligning it with the graduated scale, and then securing it in place with the clamp screw. The machine operated at a speed of 295 RPM, and the process continued for the remaining duration while monitoring for any fluctuations.

sliding velocity and sliding distance were calculated by using below equation:

$$\text{Sliding speed in m/sec} = \frac{\pi DN}{60000}$$

$$\text{Sliding distance in meters} = \frac{\pi DNT}{60000}$$

Where D is the diameter of the wear track in mm, N is the disc speed in rpm and T is the test duration in seconds.

After setting the rotation of the machine, the normal load was applied slowly without shaking. The experiment was conducted for all the specimens, and the data was observed. During and after experimentation weight loss and coefficient of friction data were collected to analyze the wear behavior of the hybrid MMCs.

6.3 RESULT AND ANALYSIS

The specimens were subjected to a wear testing machine to assess their performance. Initially, a low load of 10N was applied to each specimen. After traveling a distance of 1000 m, the weight losses and coefficients of friction were measured. Subsequently, the load was incrementally increased to 20N, 30N, and 40N, and the corresponding weight losses and coefficients of friction were recorded and presented in Figure 6.1.

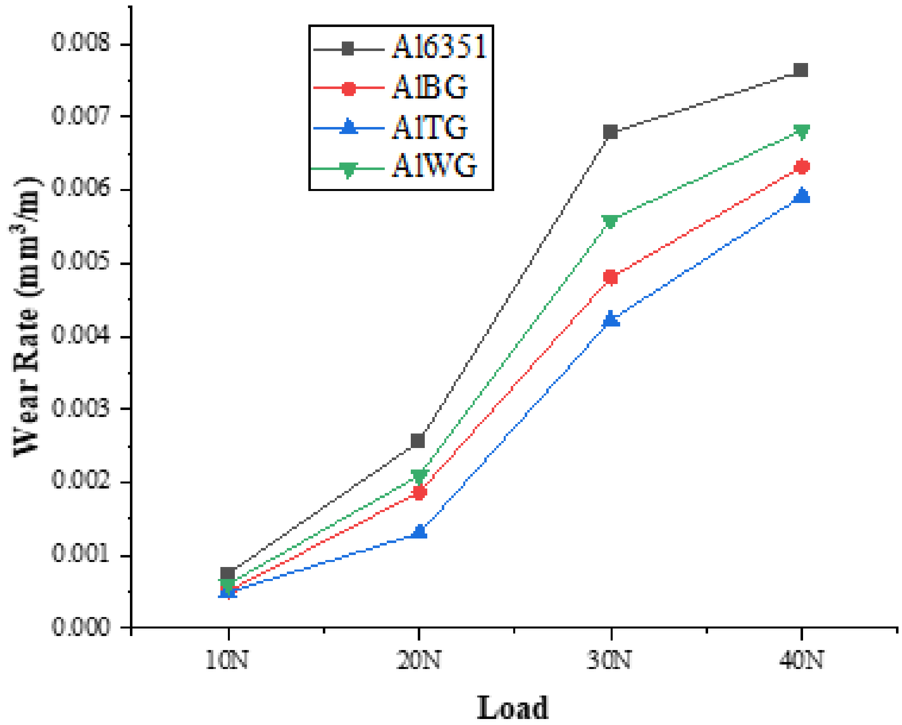

Figure 6:1 Wear Rate of Fabricated Samples

Figure 6.2 displays the coefficient of friction along with the respective load.

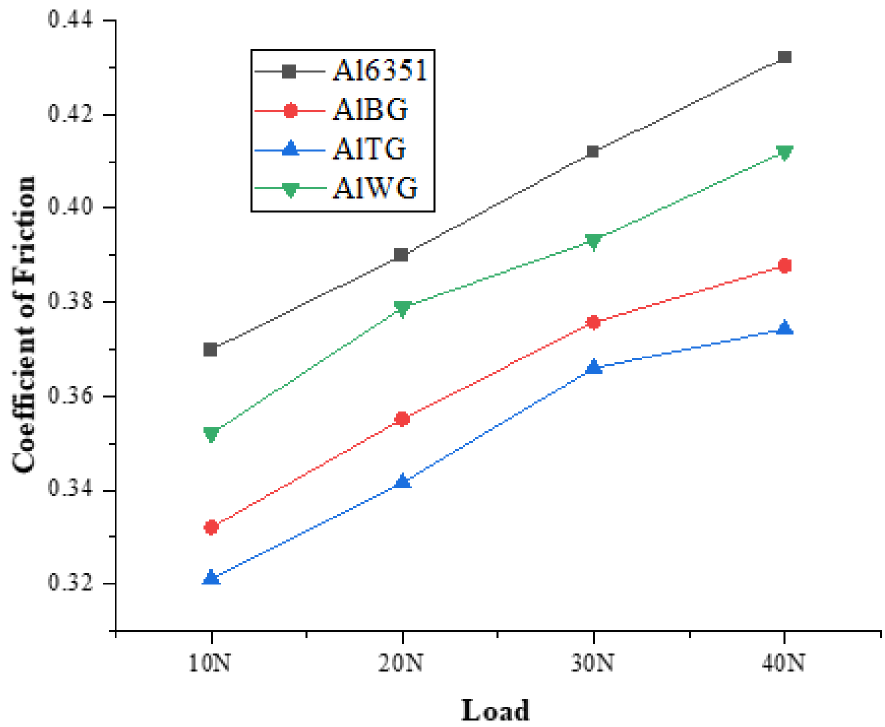

Figure 6:2 Variation of friction with load

In accordance with Archard's equation, the wear resistance of a material is inversely related to its hardness. By increasing the hardness of composite material, its ability to withstand sliding wear is improved. The addition of reinforcement particles, which are inherently hard, reduces the effective contact area between Al6351 and the disc. This redistribution of contact area, where some of it is occupied by the ceramic's particles, enhances the wear resistance of the composite. Furthermore, the strong bond between the matrix and the ceramics particles prevents their separation during sliding, further enhancing the wear resistance of the hybrid MMC compared to the monolithic alloy. Figure 6.1 and Figure 6.2 illustrate the impact of load on the wear rate of the unreinforced Al alloy and Hybrid MMCs. Notably, the Al6351 matrix reinforced with 1 wt% TiC and 1 wt.% consistently exhibits a lower wear rate under all load conditions.

6.4 WORN SURFACE ANALYSIS

Following the experimentation, the worn surfaces were studied using a high-resolution microscope (SEM). These detailed images serve as a valuable tool for identifying wear mechanisms, observing wear tracks, and analysing wear debris. Fig. 6.3 showcases the impact of reinforcement content on the worn microstructure of the composites under a normal load of 40 N. The worn surface microstructure of the Al6351 alloy displays noticeable plastic deformation. Heat is generated between the specimen to be tested and the countersurface due to their relative motion and friction between them. The wear mechanism is predominantly adhesive. In Figure 6.3 (b, c, d), the worn surface micrographs of the composites display narrower grooves and a smaller number of pits. The presence of reinforcement particles reduces the depth of the grooves and minimizes plastic deformation along the groove edges. The wear mechanism in this case is primarily abrasive.

In Fig. 6.3(a), the observed microstructure reveals several grooves and scratches that are oriented along the sliding direction. This observation provides significant insights into the predominant wear characteristics, which are primarily attributed to adhesion and delamination.

The presence of multiple grooves suggests the occurrence of adhesive wear, where the contact surfaces experience strong forces leading to material transfer and subsequent formation of grooves. This phenomenon is often associated with the intimate contact and bonding between the mating surfaces, resulting in material removal and the formation of wear debris.

Additionally, the presence of scratches further indicates the involvement of delamination wear. Delamination occurs when layers of material separate or peel off from the surface due to shear forces during sliding. These scratches can be considered evidence of localized material detachment and failure, which contributes to the overall wear process.

Figures 6.3(b), 6.3(c), and 6.3(d) showcase the impact of adding reinforcement particles on the worn surface characteristics. These figures reveal that adding the reinforcement particle restricts plastic deformation and minimizes the formation of grooves on the worn surface. Notably, the movement of metal on the worn surfaces of the hybrid Metal Matrix Composites (MMCs) is substantially reduced compared to the unreinforced Al6351 alloy.

Among the different hybrid MMC compositions investigated, the hybrid MMC with a 1wt% reinforcement particle content exhibits the least number of debris and a smoother worn surface when compared to the other hybrid MMC variants. This indicates that a 1wt% reinforcement particle content effectively mitigates wear and results in improved surface quality.

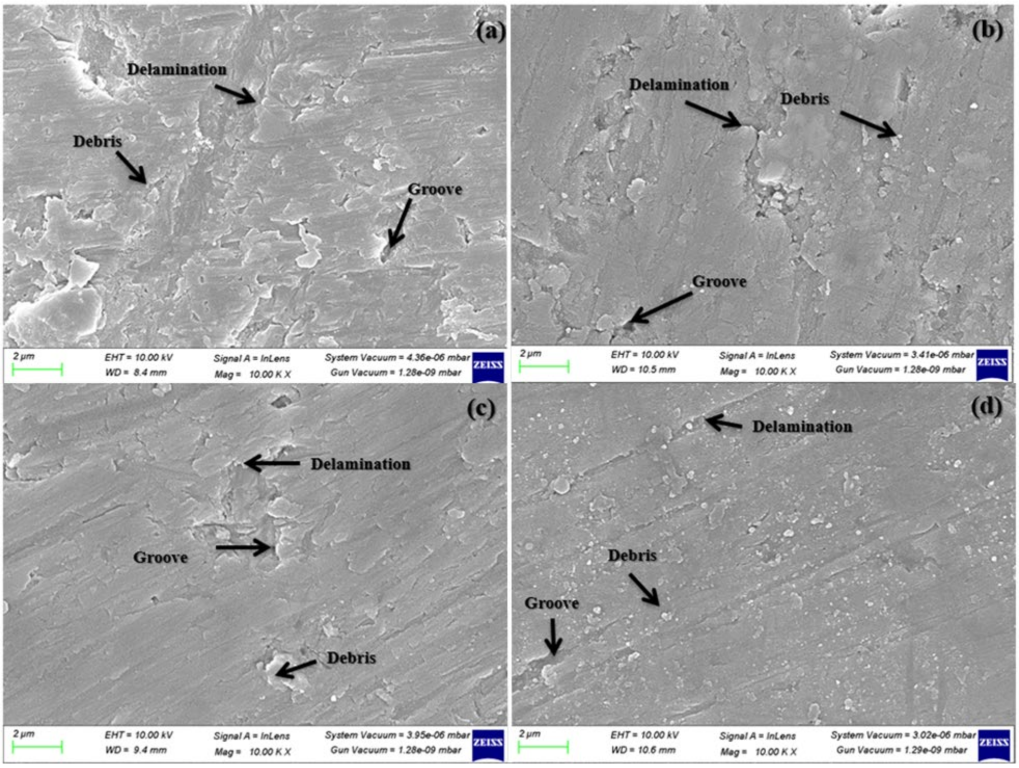

Figure 6:3 SEM of Worn Surfaces

Based on the improved corrosion and wear resistance of the Gr-TiC-Al6351 alloy matrix hybrid composites, potential applications include marine and aerospace industries, where corrosion and wear resistance are critical. Composites can also be used in automotive and mechanical engineering applications, where improved performance is desired.

Chapter 7: Conclusion and Scope of Future Work

The fabrication of the hybrid MMCs AA6351/Gr/B_4C, AA6351/Gr/TiC, AA6351/Gr/WC, and AA6351/B_4C/TiC/WC through liquid metallurgy have been successfully achieved. Various aspects of the fabricated samples, including phase composition, microstructure, EDS analysis, density, hardness, and tensile strength, have been thoroughly investigated. Ranking of the fabricated samples was done by statistical techniques. Wear studies were conducted on selected samples. Below are the key concluding remarks and future scope of this study.

7.1 CONCLUSIONS

XRD Analysis

XRD and EDS Analysis: The XRD and EDS analyses of the fabricated hybrid metal matrix composite confirm the presence of the reinforcement particles and also indicate that no chemical reaction occurred between the Al metal matrix and the reinforcements. Notably, the peak height of reinforcement increased with a rise in the proportion of reinforcement.

Microstructural Analysis

i. Scanning Electron Microscopy (SEM) revealed a uniform distribution of reinforcement particles throughout the Al matrix at a lower proportion of reinforcement, highlighting good interfacial bonding between the matrix and ceramic materials. This strong interfacial bonding is crucial for the mechanical properties of the composite.
ii. Particle agglomeration occurs when the reinforcement fraction is raised over 1.5 wt% percent of each reinforcement.
iii. This agglomeration caused the porosity in developed hybrid MMCs.
iv. Grain size shows a pattern of initially decreasing and then increasing.

Density Analysis

i. In the case of AA6351/Gr/B_4C, the sample AlGrB05 exhibited the lowest density at 2.62 g/cc. The introduction of Graphite into the Al matrix is a contributing factor to this decrease in density, rendering it advantageous for lightweight applications. Furthermore, the density of the composite is noticeably influenced by the shape, size, and proportion of ceramic particles.
ii. In the composite AA6351/Gr/TiC, the density decreases with higher proportions of reinforcement. This phenomenon is attributed to the presence of porosity in the developed hybrid Metal Matrix Composites. The sample AlGrT05 exhibited the lowest density at 2.61 g/cc. The incorporation of Graphite (Gr) in the Aluminum matrix contributes to this reduction in density,

making it advantageous for applications where lightweight materials are desirable.

iii. The density of AA6351/Gr/WC increases with the proportion of reinforcement. Based on density measurements, the lowest recorded density, at 2.73 g/cc, was achieved by incorporating 0.5 wt% of Graphite and 0.5 wt% of WC. In contrast, the highest density was observed when using 2.0 wt% of Graphite and 2.0 wt% of WC, reaching 2.81 g/cc. Among the hybrid Metal Matrix Composite (MMC) samples, AlGrW05 displayed the highest porosity.

iv. The density of AA6351/B_4C/TiC/WC increases with the proportion of reinforcement. The lowest recorded density, at 2.73 g/cc, was achieved by incorporating 0.5 wt% of each reinforcement. Conversely, the highest density was observed when using 2.0 wt% of each reinforcement, reaching 2.86 g/cc. Among the hybrid Metal Matrix Composite (MMC) samples, AlBTW05 exhibited the highest porosity.

Hardness Assessment

i. The hybrid metal matrix composite AA6351/Gr/B_4C, containing 1 wt% Gr and 1 wt% B_4C, exhibited the highest hardness of 82 HRC compared to the AA6351 matrix. However, it was observed that hardness decreases with an increase in reinforcement beyond 1 wt% Gr and 1 wt% B_4C.

ii. The hardness of the AA6351/Gr/TiC, reinforced with 1.0 wt% Gr and 1.0 wt% TiC recorded the highest of 85 HRC. However, it is found that hardness diminishes with an expansion in reinforcement above 1.0 wt% Gr and 1.0 wt% TiC.

iii. In AA6351/Gr/WC the composite reinforced with 1 wt% graphite and 1 wt% tungsten carbide had the highest hardness. recorded as 76 HRC. On increasing the reinforcement, the hardness starts decreasing due to non-uniform distribution of reinforcement in Hybrid HMMCs.

iv. The AA6351/B_4C/TiC/WC Hybrid MMC sample containing 1.5 wt. % of each reinforcement exhibited the utmost hardness of 76 HRC.

Toughness Assessment

i. The hybrid metal matrix AA6351/Gr/B_4C displayed superior impact strength in contrast to the AA6351. Impact strength improved with varying reinforcement weight percentages in the base material, with sample AlGrB03 exhibiting the highest impact strength at 32 Joules.

ii. Hybrid metal matrix AA6351/Gr/TiC has higher impact strength in contrast to the Al matrix. Impact strength improved with the variation of reinforcement contents in the base material. Sample AlGrT03 has the highest impact strength of 33 Joules.

iii. In AA6351/Gr/WC, The maximum toughness of the composite was obtained for sample AlGrW02 as 28 Joule.

iv. The Hybrid MMC AA6351/B_4C/TiC/WC sample containing 1.5 wt. % of each reinforcement exhibited the utmost toughness as 28 Joule.

Tensile Strength

i. The hybrid metal matrix AA6351/Gr/B_4C containing 1wt% of each reinforcement, showcased the highest engineering ultimate tensile strength and true ultimate tensile strength, measuring 134.3 MPa and 167.0 MPa, respectively, in comparison to the other samples.

ii. In hybrid metal matrix AA6351/Gr/TiC Sample AlGrT03 shows the highest engineering ultimate tensile strength and true ultimate tensile strength as ten 206.7 N/mm2 and 260.43 N/mm2 in comparison to other samples.

iii. AA6351/Gr/WC, When reinforced with 1 wt% graphite and 1 wt% tungsten carbide had the highest tensile strength, yield strength, and hardness. Maximum Engg. UTS strength and hardness recorded as 154.7 N/mm^2.

iv. The AA6351/B_4C/TiC/WC Hybrid MMC sample containing 1.5 wt. % of each reinforcement exhibited the utmost engineering UTS of 140.7 MPa and hardness of 76 HRC. Maximum toughness was observed in Hybrid MMC having 0.5 wt.% of each reinforcement as 28 Joule.

Wear Assessment

i. The wear test revealed a consistent improvement in the wear performance of the fabricated HMMCs in comparison to the base Al6351 alloy.

ii. The highest wear rate was observed in Al6351 as 0.007621 mm^3/m and the lowest in AlGrT03 (1 wt.% Gr& 1 wt.% TiC) as 0.00592 mm3/m.

iii. The coefficient of friction shows an increasing pattern with increasing load. The lowest friction was observed for sample AlGrT03 at 40 N as 0.374286.

iv. In microphotograph, Al6351 shows a large number of debris and plowing. The addition of reinforcement shows a reduction of debris. Sample AlGrT03 shows the least number of debris and plowing.

Among various hybrid development combinations, AA6351, when reinforced with Gr and TiC, exhibits superior mechanical properties, including strength, impact resistance, and hardness. The tribological characteristics of hybrid Metal Matrix Composites reinforced with Gr and TiC surpass others, attributed to the effective bonding between the reinforcement and the AA6351 matrix.

The study on fabricating hybrid metal matrix composites (HMMCs) using AA6351 alloy and reinforcement materials is of great importance and offers promising prospects. It allows for the development of lightweight, high-strength materials with tailored properties for industries like aerospace and automotive industries. Furthermore, this research paves the way for further advancements in composite materials, such as the exploration of new reinforcement combinations that will lead to sustainable and efficient solutions in a variety of industries.

7.2 FUTURE SCOPE

This research can be further expanded to gain deeper insights by considering the following aspects.

Heat Treatment on the Hybrid Metal Matrix: To enhance the microstructure and mechanical attributes of the hybrid metal matrix, implementing heat treatment processes is crucial. Heat treatments such as age hardening, artificial age hardening, and tempering are essential for improving the mechanical properties of Aluminum alloys under severe environmental conditions. Additionally, the influence of heat treatment processes on microstructure evolution and mechanical characteristics is also to be studied.

Further Beyond conventional heat treatment methods exploring advanced techniques such as rapid solidification or cryogenic treatment could enhance the microstructure and mechanical properties of the hybrid metal matrix. Investigating the effects of these techniques on grain refinement, phase distribution, and residual stresses could provide valuable insights into optimizing material performance.

Delving Deeper into Process Parameters: A more comprehensive understanding can be gained by delving deeper into process parameters. A further study on the impacts of stir casting parameters like stirring speed, feed rate of reinforcement, temperature, and shape of stir can be carried out to optimize the process parameters. Cooling rates during solution treatment, show that different cooling rates can optimize hardness, tensile, and tribological properties.

Modifying the Combination of Reinforcements: Modifying the combination of reinforcements B_4C, TiC, and WC along with Graphite, by keeping one constant while increasing the proportion of the other is an area that warrants further exploration.

Undertaking Fatigue Analysis: Undertaking a fatigue analysis of the developed hybrid metal matrix composite can be carried out in the future. This analysis is essential for understanding the long-term performance and durability of the composite material.

Multi-scale Modeling and Simulation: Integrating computational modeling and simulation approaches at various length scales (atomic, microstructural, macroscopic) can offer a deeper understanding of the relationships between process parameters, microstructure evolution, and mechanical behavior. Utilizing techniques like finite element analysis, molecular dynamics simulations, and phase-field modeling could predict material response under different conditions and aid in the design of novel processing routes.

In-situ Characterization Techniques: Employing in-situ characterization methods such as synchrotron X-ray diffraction, electron microscopy, or acoustic emission analysis during processing and mechanical testing can capture real-time changes in microstructure and deformation mechanisms. This real-time monitoring can provide crucial data for optimizing processing parameters and understanding the underlying mechanisms governing material behavior.

Environmental Durability and Sustainability: Assessing the environmental durability and sustainability of the developed hybrid metal matrix composite is becoming increasingly important. Conducting accelerated aging tests, corrosion resistance evaluations, and life cycle assessments can provide valuable data on the material's long-term performance, durability, and environmental impact. Exploring eco-friendly processing routes and recyclability aspects could also contribute to the development of more sustainable materials.

Tailored Reinforcement Architectures: Instead of simply varying the proportion of different reinforcements, investigating novel reinforcement architectures such as gradient structures, hierarchical arrangements, or nanostructured hybrids could lead to superior mechanical properties and enhanced performance under specific loading conditions. Understanding the synergistic effects between different reinforcements and their distribution within the matrix is essential for tailoring material properties to meet specific application requirements.

By exploring these avenues significant contributions can be made to advancing the field of hybrid metal matrix composites and addressing current challenges in materials science and engineering.

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List of Publications and their Proofs

Based on Mechanical characterization and Microstructural characterization of Hybrid metal matrix composite (AA6351/Gr/B4C/TiC/WC), Following research paper are published in SCIE Index journal.

1. Ali, S., Murtaza, Q. and Gupta, P., 2023. Synergetic Effect of Gr-B4C Reinforcement on the Structural and Mechanical Properties of AA6351 Hybrid Metal Matrix Composites. ECS Journal of Solid State Science and Technology, 12(6), p.067002. SCIE

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Synergetic Effect of Gr-B_4C Reinforcement on the Structural and Mechanical Properties of AA6351 Hybrid Metal Matrix Composites

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The purpose of this study is to investigate the effects of Graphite (Gr)-Boron Carbide (B_4C) reinforcement particles on the mechanical characteristics of an aluminium-based hybrid metal matrix composites. Hybrid metal matrix composites (MMCs) were prepared by adding different proportions of Gr and B_4C (0.5–0.5, 1.0–1.0, 1.5–1.5, and 2.0–2.0 wt%) through liquid metallurgy (stir casting) route. The phase, microstructure, EDS, density, hardness, tensile strength of fabricated samples were studied. Through X-ray diffraction analysis, it was established that there was a transitional stage of development between the matrix and reinforcement particles due to interfacial bonding. Furthermore, scanning electron microscopy results indicate a consistent dispersion of reinforcement particles within the aluminium matrix up to the 1 wt% Graphite and 1 wt% B_4C. As the proportion of reinforcement increased, a decrease in density was observed, with the lowest density as 2.62 g cc^{-1} in the sample containing 2 wt% Graphite and 2 wt% B_4C. The best mechanical characteristics of the fabricated hybrid metal matrix were observed with 1 wt% Graphite and 1 wt% B_4C, with a hardness of 82 HRC, impact strength of 32 Joules, and an engineering ultimate tensile strength of 134.3 MPa.
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With difficult requirements and a challenging environment, it becomes necessary to impart the requisite properties into the materials either by alloying or making composite by adding suitable elements. Pure materials are normally soft and do not meet the requirements of the ever-changing industrial demand.[1] Composite materials solve this problem to a certain extent. Aluminium alloys possess good mechanical, electrical, and thermal properties. The properties of these alloys can further be improvised by adding suitable reinforcement in it. A metal matrix composite is made up of a metal or alloy as the base and the reinforcement such as a particle, short fiber, whisker, or continuous fiber.[2] A composite having three or more than three materials as reinforcement is known as a hybrid metal matrix composite. Hybrid metal matrix composites (HMMCs) exhibit tailored superior mechanical and functional performance compared to their metal matrix, thus increasing their potential application in structural engineering and functional device applications.

Common techniques for fabricating metal matrix composite and hybrid metal matrix composite are (a) Liquid Metallurgy (b) Solid State Processing and (c) In situ process.[3] In liquid metallurgy, metal is melted in a furnace by heating it above the melting point and then mixed with the reinforcement through the stirring process.[4] This is the simplest and most widely used liquid route process. The limitation of this process is wetting of surface of the reinforcement which causes problems in the proper mixing of reinforcement with the molten metal pool. In Solid State Processing, Powder metallurgy (P/M) is a widely used process for developing aluminium and other metal matrix composites. Powder metallurgy requires lower temperatures. Many typically shaped parts can be easily manufactured by powder metallurgy in large quantities at low cost. In the powder metallurgy process, a series of steps is followed which includes mixing powders, then shaping them by compacting the mixture in a mould, and finally solidifying it through sintering in a furnace. Additional steps may be necessary for specific desired properties.[5] In the case of In situ process, a metal matrix composite is fabricated in a single step from an alloy. This process avoids the predicament inherited in mixing different constituents. Solidification and its direction can be controlled in this process. This type of processing technique is described as a self-propagating high-temperature synthesis (SHS) process.

Aluminium 6351 is an alloy that can be reinforced with a variety of materials to improve its mechanical and microstructural properties.[6] These materials include metals such as Boron, Nickel, Zinc, Titanium, and Copper, as well as non-metallic materials such as carbon fiber, glass fiber, and ceramic. The specific mechanical properties of an aluminium 6351 alloy reinforced with different materials will depend on the type and amount of reinforcement used, as well as the processing techniques employed. The addition of reinforcement generally results in increased strength, stiffness, and hardness of the alloy. Additionally, it improves the wear resistance and fatigue strength of the alloy. The addition of preheated boron carbide (5 wt%) and SiC (5 wt%) reinforcement to aluminium 6351 by the stir casting process improved the ultimate tensile strength, yield strength, and scratch-resisting capacity of the alloy.[7] Further, increasing the weight-wise % of B_4C to 10 wt% along with 5 wt% SiC has a 10.10% increase in tensile strength, 8.78% increase in yield strength, 7.26% increase in hardness, and a very marginal decrease in density.[8] Dhoria et al. conducted a comprehensive analysis by fabricating a hybrid metal matrix composite of AA6351 using different proportions of Gr and SiC employing a squeeze casting process. The proportion variation of SiC was taken from 0 to 10% and the same for Gr in a reverse manner. An increase in the proportion of SiC and a decrease in the proportion of Gr were found to lead to a corresponding rise in both hardness and tensile strength. Furthermore, as the applied load increased, it was observed that the wear rate of all composites tended to increase as well.[9] In a comparative study, AA6061 reinforced separately with B_4C, SiC, and Al_2O_3, showed that an interfacial reaction product was observed at the Al-SiC interface for longer processing times. However, no such reaction products were found at the Al-B_4C and Al-Al_2O_3 interfaces. In terms of interfacial bonding and particle distribution, the B_4C-reinforced Al composites outperformed the other two composites.[10]

AA6351 reinforced with alumina and graphite shows improvement in mechanical and surface characteristics of hybrid metal matrix composite.[11] Several researchers have explored the influence of synthesized fly ash as a reinforcement on mechanical and structural characteristics of hybrid metal matrix of AA6351. Through wear analysis on fly ash reinforced AA6351 metal matrix composite, M. Uthayakumar et al. discovered that at lower loads, the

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2. Ali, S., Murtaza, Q. and Gupta, P., 2023. Phase, Microstructure, and Tensile Strength of Al6351-Graphite-WC Hybrid Metal Matrix Composites. ECS Journal of Solid State Science and Technology, 12(10), p.107001. SCIE

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Phase, Microstructure, and Tensile Strength of Al6351-Graphite-WC Hybrid Metal Matrix Composites

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This study investigates the microstructure and mechanical characteristics of Al6351-based hybrid metal matrix composites reinforced with Graphite (Gr) and Tungsten carbide (WC) (0.5–0.5, 1.0–1.0, 1.5–1.5, and 2.0–2.0 wt%). The liquid metallurgy (stir casting) route was used to prepare the hybrid composites, the microstructure and material performance were characterized by using SEM, X-ray diffraction, impact, hardness, and tensile testing. According to the findings, incorporating graphite and tungsten carbide into the composite led to enhancements in both microstructure and mechanical properties. The sample reinforced with 1 wt% Gr and 1 wt% TiC carbide demonstrated the highest tensile strength, and hardness. The highest recorded value of Engg. UTS and Rockwell hardness were 199.2 N mm^{-2} and 76 HRC, respectively. On the other hand, the composite that contained 0.5 wt% graphite and 0.5 wt% tungsten carbide exhibited the best toughness as 28 joules, among all the samples that were produced. The lowest density was observed with 2 wt% Gr and 2 wt% TiC reinforcement as 2.62 g cc^{-1}. A uniform dispersion of reinforcement particles was observed. The findings of this study suggest potential applications of hybrid MMCs reinforced with graphite and tungsten carbide in the aerospace and automotive industries.
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Metal Matrix Composites (MMCs) have attracted considerable interest in the past few years due to their remarkable mechanical properties and adaptability for application in diverse fields.[1] MMCs are characterized by the incorporation of one or more reinforcement materials into a metallic matrix to enhance their properties. The combination of two or more reinforcements with the base metal matrix is known as a hybrid metal matrix. These two reinforcements in hybrid MMCs can lead to further improvements in mechanical properties, making them highly suitable for applications in the aerospace and automotive industries.

Incorporating various types of reinforcement materials serves distinct purposes. Graphite, for instance, significantly enhances tribological properties, while its combination with tungsten carbide yields promising outcomes attributed to their distinctive mechanical and thermal characteristics.[2–4] Adding graphite along with Al_2O_3 shows improved mechanical properties.[4] SiC and Graphite are frequently employed as reinforcements in metal matrix composites. SiC enhances the mechanical properties of the MMCs, while Graphite helps to preserve the matrix's toughness.[5,6]

Titanium carbide and other titanium-based ceramics are effective additives to aluminum matrix composites for automotive applications.[7] The addition of TiB_2 particles resulted in improved mechanical and wear characteristics, with increasing TiB_2 content leading to increased hardness and tensile strength, but a decrease in elongation.[8]

Several studies show that aluminum metal matrix reinforced with ZrB_2 exhibits decreased wear rate and enhanced wear endurance with an expansion in ZrB_2 weight percentage. The study also shows that ZrB_2 reinforcement increases hardness.[9–11]

Incorporating low-cost green reinforcements such as fly ash particles, agro waste, and ground nutshell ash into stir-cast aluminum alloy 6351 results in favorable hardness and wear characteristics.[12–15] Synthesized ceramics based on agricultural waste are not only cost-effective but also utilize a renewable and sustainable resource that can be replenished through ongoing agricultural processes.

Several studies show that SiC used as reinforcement particles significantly improve the microhardness and ultimate tensile strength (UTS) of the composite, with higher SiC content resulting in a shift from ductile to brittle fracture mode.[16] The brittleness induced can be reduced by using heat treatment process.[17] Like SiC, B_4C particles also provide wear resistance and improved surface hardness compared to base alloy.[18] Al-B_4C nanocomposites show that increasing the B_4C content led to a decrease in compressibility rate and sinterability.[19,20] In addition to serving as a strengthening agent, the B_4C particulate-reinforced Al6061 composite is employed for neutron shielding purposes, owing to its high strength and low density. The neutron transmission ratio displays a declining trend with rising B_4C content and plate thickness. Moreover, the tensile strength of the composite exhibits an initial increase, followed by a decrease, as the B_4C content is increased. The failure mode observed interfacial debonding and cleavage fracture of particles.[21,22] Reinforcing SiC and B_4C simultaneously shows improved strength and hardness, enhanced wear resistance, better thermal stability improved electrical conductivity, higher radiation shielding efficiency as compared to adding them individually.[23–26]

The introduction of nitride particles, such as Si_3N_4, through the stir casting method, demonstrates that as the weight percentage of Si_3N_4 particles in the aluminum matrix increases, the density, porosity, and hardness of the composites also increases, while the ductility decreases.[27–30]

Several studies analyzed dry sliding wear behavior of Al 6351 alloy and Al6351-based composites with Al_4SiC_4 reinforcement. Al_4SiC_4 reinforced composites exhibited a higher wear rate due to reinforcement particle removal through micro-cutting abrasion. However, adherent oxide development reduced wear loss with substantial strain hardening in all specimens.[31,32]

Aluminum matrix reinforced with alumina-carbon in equal proportion shows good strength due to interfacial bonding.[33] Adding aluminum oxide and titanium oxide as a reinforcement produces a composite with high strength and low density which is suitable for aviation applications.[34]

Carbon nanotubes (CNTs) exhibit numerous desirable characteristics, including a high strength-to-weight ratio, exceptional strength, reduced mass density, efficient heat conduction, substantial surface area, and enhanced electronic properties. These unique attributes enable their utilization in diverse applications, particularly in the development of novel composites. Incorporating CNTs into nanocomposites can substantially improve their mechanical and electrical properties, despite the obstacles encountered.[35] Chemical vapor deposition is a viable method for producing high-quality CNTs on a large scale and at a low cost, making CNTs a strong competitor for many new applications.[36]

Despite the significant advancements in the field of MMCs, there remain several areas of research that require attention in order to

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3. Ali, S., Murtaza, Q. and Gupta, P., 2023. Evaluation of phase, microstructural and mechanical characteristics in stir casted AA6351-Gr-TiC hybrid metal matrix composites. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, p.09544062231217623. SCIE

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Evaluation of phase, microstructural and mechanical characteristics in stir casted AA6351-Gr-TiC hybrid metal matrix composites

Shahazad Ali[1], Qasim Murtaza[1] and Pallav Gupta[2]

Abstract

The demand for advanced materials with enhanced mechanical properties for various engineering applications has spurred research into hybrid metal matrix composites. This study aims to explore the influence of incorporating Gr-TiC reinforcement particles into the AA6351 metal matrix. The fabrication process involved adding different weight percentages of Gr-TiC (0.5-0.5, 1.0-1.0, 1.5-1.5, and 2.0-2.0 wt%) to the AA6351 metal matrix using the liquid metallurgy technique. Comprehensive analyses were conducted on the fabricated samples to assess their phase, microstructure, EDS, density, hardness, tensile strength and fractured morphology. X-ray diffraction analysis showed that the interfacial bonding between the matrix and reinforcement particles caused a preparatory stage of development. Moreover, scanning electron microscopy confirmed that the reinforcement particles were uniformly distributed throughout the aluminum matrix. Due to the presence of graphite and porosity in the fabricated samples, the density of the aluminum metal matrix decreased. The samples with a reinforcement proportion of 2.0 wt% graphite and 2.0 wt% TiC exhibited the lowest density of 2.61 gram/cc. The maximum levels of hardness, engineering ultimate tensile strength, and true ultimate tensile strength were observed at a weight percentage of 1.0 wt% for both Gr and TiC, with values of 85 HRC, 206.7 N/mm^2, and 260.43 N/mm^2 respectively.

Keywords

AA6351, hybrid metal matrix composites, graphite, titanium carbide, liquid metallurgy, mechanical properties

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Introduction

In Engineering, the level of complexity of the problem is increasing day by day which is creating new challenges for the engineer to develop novel materials to satisfy the need of time. The strength-to-weight ratio is an important consideration when selecting a material for any machine element because increasing weight may result in an increase in running costs. Pure materials are generally not used for machine part fabrication due to their low strength, poor wear resistance, and poor corrosion resistance. Using pure materials can be expensive endeavor. These challenges are overcome by the researcher by fabricating a novel hybrid metal matrix composite (HMMC). A hybrid metal matrix composite is made up by adding two or more ceramic reinforcements in a single matrix to produce a material with superior properties and functionalities. Aluminum Hybrid metal matrix composites provide improved strength, toughness, wear resistance, and thermal properties compared to pure aluminum or its alloy.[1] Several techniques are used for fabricating Aluminum HMMCs, some of them are explained below.[2]

Liquid Metallurgy (Stir casting) is a method for producing aluminum-based HMMCs. The preheated reinforcing particles are added to the molten metal matrix and homogeneously dispersed using a stirring mechanism. The mixture is then poured into a mold and solidified to form the HMMC.[3]

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Based on Mechanical characterization and Microstructural characterization of Hybrid metal matrix composite (AA6351/Gr/B4C/TiC/WC), Following research paper were presented in international conference.

1. Ali, S., Murtaza, Q. and Gupta, P., 2023. Exploring the Wear Behaviour of Al6351-Gr Composite Reinforced with B4C, TiC, and WC Particles. Smart And Innovative Development In Science, Engineering & Technology(SIDSET-2023), : Bhilai Institute Of Technology, Durg and AICTE IDEA Lab, AIP conference. Date: 16-18 Aug 2023 (International Conference)

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at Bhilai Institute of Technology Durg, CG.

Best wishes for all future endeavors.

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2. Ali, S., Murtaza, Q. and Gupta, P., 2023. Mechanical Characterization of Al6351 Reinforced with TiC, B4C, and WC Proportional Effects and Microstructural Analysis. Smart And Innovative Development In Science, Engineering & Technology(SIDSET-2023), : Bhilai Institute Of Technology, Durg and AICTE IDEA Lab, AIP conference. Date: 16-18 Aug 2023 (International Conference)


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Best wishes for all future endeavors.

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Summary

Curriculum Vitae

1.	Department	**Mechanical Engineering**		
2.	Title (Mr./ Mrs. Miss/Dr./ Prof.)	**Mr.**		
3.	Name	**Shahazad Ali**		
4.	UG Degree	**B.Tech Mechanical Engineering**		
5.	UG University	**AKTU Lucknow**		
6.	UG Pass % & Division	**70.03**		
7.	PG Degree	**M.Tech(Machine Design)**		
8.	PG University	**Jamia Millia Islamia New Delhi**		
9.	PG Pass % & Division	**8.33 CGPA**		
10.	Highest Degree (UG/PG/Ph.D)	**PG**		
11.	Other Qualification	**Autodesk certification**		
12.	Aadhar Card No.	**56679923427**	16. PAN Card	**AQPOA8372M**
13.	Experience (Research) (IN YEARS)			
14.	Publication (Conference) (IN NOS)	International-05	National -	Total-04
15.	Publication (Journal)	International – 4	National-	Total-
16.	No. of Patent	**01**		
17	Workshop (IN NOS)	**20**		