

Investigation of Mechanical Properties of Al-B₄C-Ti64-MoS₂ Composite Developed Through Powder Metallurgy Technique and Optimization of Process Parameter



Mulisa Jiregna Temesgen

A Thesis Submitted to Department of Mechanical Engineering
College of Mechanical, Chemical and Material Engineering

Presented in Partial Fulfillment of the Requirement for the Degree of Master's
in Manufacturing Engineering

Office of Graduate Studies
Adama Science and Technology University

January, 2025
Adama, Ethiopia

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DECLARATION

I hereby declare that this master thesis entitled “**Investigation of Mechanical Properties of Al-B₄C-Ti64-MoS₂ Composite Developed Through Powder Metallurgy Technique and Optimization of Process Parameter**” is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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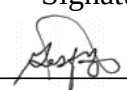
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ACKNOWLEDGEMENT

I praise God, the Almighty, for providing me this opportunity. Next to that, I would like to express my deep sense of respect and gratitude to Dr. Moera Gutu Jiru, my supervisor, for his invaluable and fruitful constructive suggestions and guidance that have enabled me to overcome all the problems and difficulties while carrying out this study. He stayed along with me and motivated me constantly and stimulated me to the fullest extent. I feel fortunate for his support and involvement, and this is virtually impossible to express in words. I also express my gratitude to Dr. Devendra Kumar Sinha for his valuable comments and advice during this study. Thanks for providing me with the required material for this study at no charge. Moreover, I thank from the bottom of my heart Mr. Sintayehu Zeleke, head of the Department of Mechanical Engineering at ASTU, for his warm welcome and providing all necessary support. His support has played a major role in the success of this research. I would like to express my deepest gratitude to the ASTU Material Science and Engineering department and their laboratory assistance for their invaluable support throughout this research. Their expertise, guidance, and resources have been instrumental in the successful completion of this study.

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ACRONYMS AND ABBREVIATIONS

AHMMC	Aluminum Hybrid Metal Matrix Composite
ANOVA	Analysis Of Variance
CP	Compacting Pressure
FWHM	Full width at half maximum
GA	Genetic Algorithm
GRA	Grey Relation Analysis
HV	Vickers Hardness
ICDD	International Centre for Diffraction Data
MMCs	Metal Matrix Composites
OM	Optical Microscope
PDF	Powder Diffraction File
PM	Powder Metallurgy
RF	Reinforcement
SEM	Scanning Electron Microscopy
ST	Sintering Temperature
UTM	Universal Testing Machine
XRD	X-Ray Diffraction
Wt. %	Weight percentage

ABSTRACT

The demand for lightweight materials with superior mechanical and tribological properties has been increasing in the automotive, aerospace, and marine industries. Aluminum is the most popular lightweight material, but lower strength when compared to other structural materials like titanium and steel. This thesis study focused on the fabrication of the aluminum hybrid metal matrix composite (AHMMC) reinforced with boron carbide (2, 4, 6 wt.%), titanium grade 5 (1, 3, 5 wt.%), and molybdenum disulfide (4 wt.%) using the powder metallurgy method and testing its mechanical properties. Characterization of microstructure of the sample were done using Optical Microscope (OM), Scanning Electron Microscope (SEM), and X-ray diffraction (XRD). The density and porosity of the sample were determined through Archimedes' principle. Other properties such as hardness, compressive strength, and wear resistance were analyzed as per ASTM standard. The corrosion resistance of the sample was investigated using an electrochemical analyzer. The weight percentage of reinforcements and the process parameters of powder metallurgy were optimized using Taguchi-based grey relational analysis and genetic algorithm. From the optimally fabricated sample, significant improvement of physical, mechanical, and tribological properties was obtained. The OM and SEM results showed that the reinforcement was uniformly distributed. The XRD test confirmed the presence of different phases in the composite. The addition of B₄C, Ti64, and MoS₂ reinforcements to the Al matrix has improved its physical, mechanical, and tribological properties. Hence, newly developed aluminum metal matrix composite (Al/B₄C/Ti64/MoS₂) was expected to be used in the automotive, aerospace, and marine industries.

Key words: Aluminum hybrid metal matrix composite, GA, GRA, mechanical properties, powder metallurgy.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Composite materials are made from two or more material constituents whose physical or chemical properties are different. Composites have different characteristics from their individual constituents, and the individual constituents remain separate and distinct. They have recently become widely employed worldwide because of their excellent properties and ease of manufacture. And also, they have a leading role in the fast growth of technology and in manufacturing sectors to fulfill the demands for outstanding mechanical, thermal, wear, and physical qualities at a cheap cost. Based on their matrix constituents, the three most common kinds of composites are metal matrix composites, organic matrix composites (which include two classes of composites, namely polymer matrix composites and carbon matrix composites, commonly referred to as carbon-carbon composites), and ceramic matrix composites. Another classification of composite materials is based on reinforcement materials such as fiber-reinforced composites (further divided into discontinuous or continuous fibers), laminar composites, and particulate composites. In composite materials, reinforcements are bind together by the matrix to form a stronger structure (Reddy Nagavally, 2017; Markovičová & Zatkalíková, 2019; A. K. Sharma, Bhandari, Aherwar, & Rimašauskiene, 2020; Agarwal et al., 2020; Lakshmikanthan et al., 2022).

The metals that are reinforced with fibers or particles for the purpose of enhancing physical and mechanical properties are called metal matrix composites (MMCs) (Selvam et al., 2021). Types of metal matrix composites that comprise two or more reinforcements are called hybrid metal matrix composites (HMMCs). The hybrid composites are developed to be lightweight, resistant to wear, and able to combine the benefits of reinforcements according to application requirements. Hybrid composites improve the characteristics of a previously existing conventional composite. It has high efficiency and performance to be widely used for engineering applications (Dhanabal, 2015; M. K. Singh et al., 2020). The demand for stronger lightweight composite with high efficiency and performance is increasing in a wide variety of industries, for which light metal matrix composites are an asset (A. K. Sharma et al., 2020). The lighter metals that are used as matrix in MMCs are aluminum, magnesium, and titanium (Mavhungu et al., 2017).

1.1.1 Aluminum Hybrid Metal Matrix Composites

In today's industrial application, aluminum-based composites are a great substitute for ferrous alloys because of their many advantages, including their light weight, low density, high strength, and resistance to corrosion (Maruthi Varun & Raman Goud, 2019). Aluminum and its alloys are highly suitable for producing composites with a wide variety of reinforcement materials. It offers great promise to produce composites with the required properties for certain applications (A. K. Sharma et al., 2020). Aluminum matrix composites provide superior properties that cannot be achieved by any currently in use monolithic material. The properties of aluminum matrix composites highly depend on the nature of reinforcement and types of processing techniques (Garg et al., 2019).

The fabrication techniques that are used to produce the aluminum metal matrix composites are divided into three broad categories: solid-state processing, gaseous-state processing, and liquid-state processing (Lakshmikanthan et al., 2022; B. Singh et al., 2023). One type of solid-state processing is powder metallurgy, which is the most advanced process for the production, processing, and shaping of various kinds of materials. It started with ceramics processing, the methodology comprising the production of a powder. Since it was transformed into a compact solid production, it has gotten great attention. The different technologies used for powder production are gas atomization, chemical reduction, milling, and mechanical alloying. The methods used for powder consolidation are pressing, sintering, hot isostatic pressing, and spark plasma sintering (Novák, 2020). The quality of components produced by the powder metallurgy (PM) technique is largely dependent on the control of process parameters (Edosa et al., 2022).

The main problems of the MMC fabrication process that affect the composite properties are wettability, low densification, particle agglomeration, and undesired chemical reactions between matrix and reinforcements (D. K. Sharma et al., 2019). When compared to other manufacturing techniques, powder metallurgy is one of the most promising and versatile methods to fabricate particle-reinforced aluminum metal matrix composites. This process ensures the fabricated MMC's homogenous microstructure, good wettability between the matrix and reinforcement, and the absence of any undesired phases (Vani & Chak, 2018).

1.1.2 Aluminum Matrix Reinforcing Particles

The addition of reinforcing materials to the light metallic matrix significantly improves the specific strength, stiffness, damping behavior, wear behavior, creep, and fatigue properties (K. M. Pandey & Dey, 2015). These improved properties make them a candidate material to replace steel and iron in most applications (Soorya Prakash et al., 2016). Reinforcing material shape and physical conditions plays a leading role in obtaining the desired properties of MMCs (L. Singh et al., 2020). The reinforcements that are used in metal matrix composites can be categorized into three types: particulate, short fiber or whisker, and continuous fiber or sheet (Vijaya Ramnath et al., 2020). Particle reinforcements are the micro- or nano-sized constituents of metallic materials, ceramic particles, intermetallic particles, and carbon-based particles (Nash & Zhao, 2020).

The reinforcements that can be combined with aluminum in the fabrication of aluminum hybrid metal matrix composites have basic properties like high wear resistance and high strength (ceramics), self-lubricating (graphite, MoS₂, CNT, and graphene), high thermal conductivity (carbon, diamond, and cubic boron nitride), and low cost (fly ash, rice husk ash, and coconut shell ash) (Maruthi Varun & Raman Goud, 2019; Chandel et al., 2021). Because of their excellent mechanical and physical qualities, particulate-reinforced aluminum matrix composites are promising materials for various industry applications (Prasat & Mahesh, 2020). The isotropic properties and relatively low cost of ceramic-reinforced aluminum matrix composites have made them a popular choice for engineering applications. Ceramic particulate that are used as reinforcement materials include carbides (SiC, TiC, B₄C, ZrC), nitrides (AlN, BN, ZrN, TiN), borides (ZrB₂, TiB₂), and oxides (Al₂O₃, TiO₂, ZrO₂) (D. K. Das et al., 2014; Mohanavel et al., 2020; Li et al., 2022).

1.1.3 Application of Aluminum Hybrid Composites

Aluminum metal matrix composites are widely used in the automotive, defense, marine, electronics, and aerospace industries because they have excellent strength to weight ratios, excellent stiffness to weight ratios, and better resistance to wear and corrosion (Chelladurai et al., 2021). The use of aluminum hybrid composites (AHM) in the automotive sector is not only to enhance performance but also to reduce weight and improve fuel efficiency, ultimately leading to lower emissions and better energy efficiency. The components that are produced from AHM in this sector are engine components (pistons and cylinder liners), braking systems, drive train components (cardan shafts and crankshafts), structural parts

(gears, valves, and belt pulleys), and body and chassis components (housings for pumps and turbines and supporting parts) (Stojanović & Ivanović, 2015; Chandel et al., 2021).

Aluminum hybrid composites or AHMMCs have enormous potential in the aeronautical sector to replace aluminum alloy and monolithic composites. Different aviation parts that are made from aluminum hybrid composites are fuselage components, wing structures (wing spars, ribs, and skin panels), control surfaces (ailerons, elevators, and rudders), landing gear components (brackets and struts), interior components (seat frames and paneling), engine components (casings and mounts), satellite structures (satellites and space), and drone frames (Yolcular Karaoglu et al., 2021; Parveez et al., 2022; Oyewo et al., 2024).

1.2 Statement of the Problem

The automotive, aerospace, and marine industries are continually working to improve the performance and efficiency of automobiles, aircraft, and watercraft components. This demand can be achieved by reducing the weight of components, which directly impacts fuel efficiency and overall performance. Among lightweight metals, aluminum is the most suitable material to reduce the weight of engineering components. It has low density, good castability and machinability, a high strength-to-weight ratio, good corrosion resistance, and fatigue strength. But it has limited strength, stiffness, hardness, and wear resistance when compared to other structural metals like steel and titanium. Although aluminum's weight is advantageous in the aerospace industry, when some specific parts require higher strength-to-weight ratios and better fatigue resistance, it is often replaced with titanium. The automotive body panels and structural components are increasingly using aluminum to reduce weight and improve fuel efficiency, but they face challenges in crash safety performance compared to steel. When the marine aluminum parts are in contact with dissimilar metals in saltwater environments, they suffer galvanic corrosion. This study aims to address the weak mechanical properties and wear resistance of aluminum by reinforcing it with B_4C , Ti64, and MoS_2 using powder metallurgy techniques. In previous researches (Senthil Kumar et al., 2021; Haile et al., 2024), pure aluminum was reinforced with Mg, MoS_2 , Al_2O_3 , B_4C and bamboo powder particulates using powder metallurgy, and their properties were investigated without optimizing the powder metallurgy process parameters. However, in this study, the optimal set of powder metallurgy process parameters was determined using optimization to achieve improved physical and mechanical properties. This research is expected to contribute to the development of advanced lightweight materials with

enhanced mechanical and tribological properties, meeting the demands of high-performance industries.

1.3 Research Questions

1. What are the main process parameters of the powder metallurgy technique?
2. What is the effect of reinforcements on the physical, mechanical, and tribological properties of the Al-B₄C-Ti64-MoS₂ composite? What techniques are used to determine the properties of the samples?
3. What is the optimal combination of reinforcements weight percentages and powder metallurgy process parameters?

1.4 Objectives of the Study

1.4.1 General Objective

The general objective of this study is to experimentally investigate the metal matrix composite of aluminum (Al) reinforced with boron carbide (B₄C), titanium grade 5 (Ti64), and molybdenum disulfide (MoS₂), which is developed by the powder metallurgy technique.

1.4.2 Specific Objectives

The specific objectives are as follows:

1. To characterize particle distribution, size, and morphology of reinforcing phases within the Al metal matrix using OM and SEM, and phase analysis using XRD.
2. To study density and porosity as per ASTM B962-23.
3. To investigate the wear properties of fabricated samples according to ASTM G99-23 and also to investigate the corrosion behavior.
4. To test the compression strength and hardness of Al-B₄C-Ti64-MoS₂ composite in accordance with ASTM B925-15 and ASTM B933-20 standards, respectively.
5. To optimize the process parameters of powder metallurgy technique (such as compacting pressure and sintering temperature) and also the weight percentage of reinforcements for the best mechanical and tribological properties of the composite.

1.5 Scope of the Study

The primary focus of this research was developing aluminum hybrid metal matrix composite by combining it with boron carbide, molybdenum disulfide, and titanium aluminum

vanadium. The powder metallurgy technique was used for sample fabrication, and the fabricated samples were characterized by OM, XRD, and SEM. Porosity and density were analyzed by Archimedes principles. Hardness and compression strength were tested by Vickers hardness tester and UTM, respectively. Wear resistance was tested by a pin-on-disc wear tester and corrosion resistance was analyzed by an electrochemical analyzer. Also, the powder metallurgy process parameters of the developed composites were optimized by using Taguchi-based Grey relational analysis and genetic algorithm.

1.6 Significance of the Study

This research has immense importance due to several key factors:

1. *Mechanical and tribological properties improvement:* AHMMC developed in this study offers improved mechanical and tribological properties that can meet specific performance requirements. The Al metal matrix combined with reinforcing materials (B₄C, Ti64, and MoS₂) exhibits enhanced hardness, compressive strength, corrosion resistance, and wear resistance compared to monolithic Al metal.
2. *Understanding the capability of developed composite:* Investigating the ability of this HMMC and its unique properties is crucial for enabling the development of high-performance materials for various applications.
3. *The capability developed composite to be implemented:* The demand for lightweight materials with superior mechanical properties is ever-increasing, especially in the aerospace, marine, and automotive industries, to decrease fuel consumption and obtain structural integrity. So, this composite has the capability to be implemented in these industries. By using Al-B₄C-Ti64-MoS₂, engineers can design and fabricate components that are lighter, stronger, and more durable, resulting in improved fuel efficiency, reduced emissions, and enhanced performance.
4. *Determining the suitable condition for fabrication:* Additionally, this study explored the challenges and opportunities associated with the powder metallurgy method processing and manufacturing of Al-B₄C-Ti64-MoS₂. The successful integration of B₄C, Ti64, and MoS₂ reinforcing materials into the Al matrix requires careful consideration of factors such as particle dispersion, interfacial bonding, and processing techniques. By addressing these challenges and identifying effective processing level, this research can contribute to the development of reliable and cost-effective manufacturing processes for Al-B₄C-Ti64-MoS₂.

1.7 Research Motivation

The desirability of light and high-corrosion-resistant materials with superior physical, mechanical, and tribological properties in the automotive, marine, and aviation sectors has increased dramatically in recent years in order to ensure safety, reliability, and cost-effectiveness and also to reduce fuel consumption and global warming. Aluminum is a light material that is versatile for a wide range of applications, with unique properties such as high corrosion resistance, high strength-to-weight ratios, and excellent heat dissipation properties. Although aluminum is widely used due to its good properties, some weaknesses, especially compared to steel and titanium, limit its application. This research is based on its weaknesses and is aimed at addressing these weaknesses.

1.8 Limitations of the Study

This study has some limitations:

1. The sample size for this study was small ($n = 9$), which may limit the generalizability of the effects of the powder metallurgy process parameter and reinforcement weight percentage. Also, small sample can lead to an ambiguous result.
2. The samples were sintered under uncontrolled conditions, which can cause thermal fluctuation (non-uniform heating and cooling rates). Thermal fluctuation during sintering operations can result in porosity. Also, uncontrolled sintering conditions can cause the formation of unnecessary phases, which can affect the mechanical and tribological properties of the composite.
3. The compaction process was performed at minimum pressure. This can cause poor interparticle contact, which is essential for effective sintering. Inadequate compaction pressure may result in low density and high porosity.
4. This study was only focused on powder metallurgy technique for sample fabrication. This may limit the ability to test the effectiveness of various processing methods on the developed composite. Because the result obtained from this finding may not be applicable to other processing methods, which could yield different microstructural and mechanical properties. Furthermore, it is not possible to compare the effects of powder metallurgy with other processing techniques on the properties of AHMMC.

1.9 Organization of the Thesis

This thesis report consists of five chapters, and each of the chapters focuses on the experimental investigation of the Al-B₄C-MoS₂-Ti64 hybrid composite developed through the powder metallurgy method. Under chapter one background of the study, problem statement, objectives of the study, research scope, significance of the study, research motivation, and research limitations are discussed. In chapter two the research papers that are presented by other scholars on aluminum metal matrix composites reinforced with particulates are reviewed. Also, metal matrix composite fabrication methods, especially powder metallurgy techniques are reviewed. At the end, the literature gap is identified. The information about the materials and experimental methods used was discussed in chapter three. The testing and characterization process of the produced specimen is briefly presented in this chapter. Furthermore, the experimental result analysis method is discussed. In chapter four the results obtained from different tests were discussed and interpreted briefly. Chapter five contains the conclusion of the study, recommendations, and future work.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter provides a review of the published literature on pure aluminum and aluminum alloy metal matrix composites reinforced with particulates. It contains a review of the effect of particle reinforcements on the mechanical and tribological properties of aluminum metal matrix composites. The various manufacturing methods used to produce aluminum-based composites are discussed. The powder metallurgy process parameters optimization method for aluminum metal matrix composites is reviewed. Moreover, metal powder production methods are discussed.

2.2 Background of Metal matrix composites

Metal Matrix Composite (MMC) was first developed in the 1960s to improve the mechanical properties of metals for use in high-performance applications such as aerospace. The early development of MMCs was motivated by the need for materials that combined the best properties of metals (such as ductility and toughness) with ceramics (such as strength and wear resistance) (Sarmah & Gupta, 2024). Metal matrix composites have recently become more widely used and manufactured in a variety of engineering applications. Because MMCs have better mechanical and thermal properties than conventional materials. A variety of metals, particularly low-density metals or alloys, are commonly used as the matrix material for composites fabrication. Currently, the most commonly used metals used as a matrix in metal matrix composites are Aluminum, Copper, Iron, Magnesium, Nickel, and Titanium (A.K. Sharma, Bhandari, Aherwar, & Rimašauskiene, 2020; Suresh Kumar et al., 2021).

Metal matrix composites (MMCs) are the materials that can provide combined properties. These attribute combinations include high specific strength, good thermal properties, strong damping capacity, high wear resistance, high specific stiffness, and high corrosion resistance. The use of MMCs has expanded beyond the aerospace and automotive industries to include recreation, defense, marine, and sports (Kogi Ibrahim et al., 2023). The MMCs have advantages over monolithic metals and polymer matrix composites. Compared to monolithic metals and PMCs, they can provide a high-temperature performance range and give superior strength, stiffness, thermal conductivity, abrasion resistance, creep resistance, or dimensional stability (Bajakke et al., 2019).

Particulate reinforcements in Metal Matrix Composites (MMCs) provide several benefits over laminate and fiber reinforcements. Particulate-reinforced MMCs show isotropic behavior, which means that their mechanical properties are consistent in all directions. This contrasts with fiber-reinforced composites, which frequently exhibit anisotropic properties, resulting in directional dependence in strength and stiffness. Particulate-reinforced composite fabrication processes are generally simpler and less expensive than laminate and fiber-reinforced composites. Powder metallurgy and stir casting are two techniques that can be used to incorporate particles into the matrix more efficiently. Particulate reinforcements, particularly ceramics, enhance the wear resistance of the composite significantly. This makes them suitable for applications where abrasion resistance is critical, such as in automotive and aerospace components (Casati & Vedani, 2014; Bajakke et al., 2019; Ravichandaran et al., 2024).

2.3 Ceramic Particulates Reinforcement

Ceramic materials are commonly used as reinforcements in Metal Matrix Composites (MMCs) due to their superior mechanical properties, which include high hardness, wear resistance, and thermal stability (Sarmah & Gupta, 2024). Ceramic particles' microstructural properties have a significant impact on metal matrix composites (MMCs), as they influence the mechanical performance and overall behavior of the composites. The quality of interfacial bonding between the ceramic particles and the metal matrix is critical for effective load transfer. Strong interfacial adhesion enhances mechanical properties by allowing stress to be transmitted from the matrix to the reinforcement effectively. Poor bonding can lead to delamination or debonding under load, reducing the composite's strength (Dinaharan, 2016; Nagaraju et al., 2023). Some common ceramic particulates utilized in MMCs are Silicon Carbide (SiC), Alumina (Al_2O_3), Boron Carbide (B_4C), Zirconia (ZrO_2), and Titanium Carbide (TiC) (Kalel & Patil, 2018).

M. Kumar & Mishra. (2014) developed hybrid composites from Al6063 metal matrix using the stir casting method. Alumina (Al_2O_3) was added at a constant weight percentage (10 wt.%), and molybdenum disulfide (MoS_2) was added by varying its weight percentage (3, 5, 7, and 9 wt.%). According to this study, density of the developed composite increased with MoS_2 , but ultimate tensile strength decreased. Gireesh et al. (2018) reinforced Al6061 with SiC, Al_2O_3 , and fly ash by a stir-casting process to investigate the improvement in mechanical properties. Silicon carbide and alumina were added with different weight fractions (5, 7.5, and 10 wt. % simultaneously), and fly ash was added with a constant weight

fraction (5% wt. %). When SiC and Al₂O₃ content increased from 5 to 10 wt. % tensile strength and yield strength increased, but hardness decreased. This study found that high hardness, high yield strength, and high wear resistance of hybrid composite was achieved with 20% of total reinforcement but no considerable change in impact strength.

Mahesh et al. (2019) used powder metallurgy to reinforce a pure aluminum matrix with TiO₂, TiC, and TiN at weight percentages of 5, 10, and 15%, respectively. A horizontal ball mill was used to combine aluminum and reinforcement powder. The mixed powder was pressed in a cylindrical die using a compacting pressure of 300 MPa and sintered at 450°C in a tube furnace in the presence of nitrogen atmosphere for four hours. This study found that the wear rate examined using a pin-on-disc test machine decreases in all three AMMCs as the reinforcement weight percentage increases. Maruthi Varun & Raman Goud. (2019) investigated aluminum 7075-based composite developed using the stir casting method. Silicon carbide (SiC) was added with varying weight percentages (3%, 6%, and 9%) and molybdenum disulfide (MoS₂) with a constant weight percentage (1%). In this study it was reported that the hardness and tensile strength of the produced composite were increased with SiC weight percentage. Ahamad et al. (2020) developed a hybrid composite of Al matrix reinforced with an equal proportion of Al₂O₃ and TiO₂ (2.5, 5.0, 7.5, and 10 wt.%) using stir casting. This study revealed that the further addition of Al₂O₃ and TiO₂ reinforcements to the Al metal matrix decreased the hardness of the composite due to the amalgamation of reinforcements. Al/ 5% Al₂O₃/5% TiO₂ hybrids have improved mechanical properties.

Gonfa et al. (2022) fabricated Al 6061-based metal matrix composites by adding SiC (5, 10 wt%) and MoS₂ (2, 4 wt.%) using the stir casting method. The hardness, tensile strength, and wear rate tests were performed on nine samples that were fabricated based on the Taguchi L₉ orthogonal array. It was reported that the addition of SiC improves hardness, tensile strength, and wear rate. The hardness and tensile strength were only increased up to 2 wt.% addition of MoS₂, and improved wear resistance was achieved at 4% MoS₂. Hemadri et al. (2022) carried out an investigation on the Al6262 metal matrix reinforced with different mass percentages of WC (4, 8, 12 wt. %) and MoS₂ (2, 4, 6 wt. %) particulates using the stir casting method. The Charpy Impact test, microhardness test, tensile test, and microstructural characterization were performed on the composites. This research explored that increasing the WC and MoS₂ weight fractions increases the tensile, hardness, and impact strength of the produced composite.

A. K. S. Pandey et al. (2024) investigated the tribological behavior of aluminum reinforced with magnesium (Mg) and silicon carbide (SiC) through powder metallurgy and hot pressing. The two tribological feature tests, such as wear resistance and friction behavior, performed on a pin-on-disc device show an improvement in wear resistance. The effect of process variables is also investigated by choosing three levels of input parameters, namely compression pressure (300, 350, and 400 MPa) and SiC and Mg composition (3%, 6%, and 9%). This study found that combining SiC and Mg weight percentages reduced wear rate and friction coefficient. The sample with 9% Mg and SiC had the highest hardness after being fabricated at 350 MPa compacting pressure. Ayodele et al. (2023) found that Al-TiB₂ composites exhibited improved tensile strength, hardness, and wear resistance compared to the fabricated Al matrix. The composite was developed by varying TiB₂ (2 to 8 wt.%) using a Turbula mixer and fast-assisted sintering technology.

John et al. (2017) demonstrated the impact of ZrC on the tribological and mechanical properties of Al-12Si. This researcher developed the samples by adding different weight percentages of ZrC (5, 10, 15 wt.%) and a constant weight percentage of Si (12 wt.%) to Al through the powder metallurgy method. The high-energy ball mill with a ball-to-powder weight ratio of 20:1 was used to pulverize and mix the individual powders at a constant speed of 300 rpm in a wet medium in the presence of toluene (to avoid oxidation and agglomeration). The green compact sintering process was performed in a muffle furnace under an argon gas atmosphere (to avoid oxidation) at 550 °C for 1hr. The developed samples were characterized by Scanning electron microscope (SEM) and X-ray diffraction (XRD) techniques. Wear resistance and hardness of the composite were tested by the Pin-on-disc wear testing machine and the Vickers hardness testing machine respectively. This study showed that wear resistance, coefficient of friction, and hardness increased with the ZrC content increases.

2.3.1 Boron Carbide Particle as Reinforcement in AHMMCs

Boron carbide serves as an excellent reinforcement material in aluminum matrix composites due to its high hardness, low density, and thermal stability. The incorporation of boron carbide significantly enhances the mechanical properties of MMCs, making them suitable for various demanding applications across multiple industries (Kummari & Paramesh, 2019). Compared to other ceramic reinforcements, boron carbide has a relatively low density, which helps maintain the lightweight characteristics of aluminum-based composites while improving mechanical properties. Boron carbide-reinforced MMCs demonstrate

superior wear resistance compared to unreinforced aluminum alloys. This characteristic is crucial for applications in automotive and aerospace industries where components are subjected to high wear conditions (Ravindra et al., 2023; Arun C Dixit et al., 2024).

Brillon et al. (2022) incorporated boron carbide (B_4C) at different volume fractions ranging from 2–12% into aluminum (Al) matrix by powder metallurgy using the hot-pressing process. This finding showed that the hardness, strain hardening threshold, ultimate tensile strength increased with increases of B_4C volume fraction and the thermal conductivity (TC) and the coefficient of thermal expansion (CTE) decreased. Fazil et al. (2020) investigated the mechanical properties and wear resistance of AA2124 composites reinforced with 9 wt.% of B_4C using the stir casting method. SEM and EDS were used to examine the microstructural and elemental composition of the developed composite, respectively. This study reported that the hardness, ultimate tensile strength, yield strength, and wear resistance of the composite were improved compared to as-cast AA2124.

Çelik & Seçilmiş. (2017) studied the effect of B_4C on wear behavior of Al matrix composite. The powder metallurgy method was used to develop the samples with different weight percentages of B_4C (4, 8, 12, 16 wt.%). The powders were mixed for 20 min using a Planetary Ball Mill of 300 rpm in the presence of steel balls of 5 mm. The mixed powders were compacted at 350 MPa and sintered at 580°C for 90 min in an atmospheric environment. The wear resistance tests were conducted at different loads (5, 10, 15 N), different sliding distances (250, 500, 750, 1000 m), and a constant speed of 0.46 m/s. The microstructural changes in the worn and unworn surfaces were analyzed using an optical microscope, SEM, and EDS. The hardness test was carried out on a Shimadzu HMV microhardness tester applying a load of 1 N for 15 s. The reported experimental studies revealed that hardness and wear resistance increase with increasing B_4C .

Liu et al. (2019) synthesized an Al7075 aluminum alloy hybrid composite reinforced with B_4C and MoS_2 using the stir casting process. The MoS_2 was added at a constant weight percentage (3%) and B_4C at various weight percentages (4%, 8%, and 12%). An optical microscope was used to observe the microstructures of etched specimens. SEM was used to observe the microstructure and the dispersion of the B_4C and MoS_2 particles in the aluminum matrix composites. The presence of B_4C and MoS_2 reinforcement particles in aluminum hybrid composites was investigated by XRD. The wear resistance test was performed at room temperature using the standard pin-on-disc. The Micro-Vickers hardness test was carried out on polished composite samples at 5 different locations to increase the

measurement accuracy. The compression tests were performed as per ASTM E8 Standard at room temperature. This study demonstrated that a higher weight percentage of B_4C and MoS_2 increases the hardness, ultimate strength, and yield tensile strength of the hybrid.

Nagaraju et al. (2023) synthesized ceramic particle-reinforced (B_4C and Gr) aluminum metal matrix composites through stir casting by varying the weight percentage of reinforcement particles with a ratio of 3:2 to analyze their effect on tribological properties. This study found that two samples with 12 wt.% B_4C —8 wt.% Gr and 15 wt.% B_4C —10 wt.% Gr showed a 16.45% increase in wear resistance due to the incorporation of a higher quantity of Gr solid lubricants alongside B_4C . Ravindra et al. (2023) experimentally determined the effect of nano B_4C on the mechanical and wear properties of an Al7049-based composite created using a stir casting technique. The samples were created with increasing weight percentages of nano B_4C from 3 to 9 wt. %. The wear tests conducted under ASTM G99 standards by varying loads and speeds show superior wear resistance as compared to Al7049 alloy. The hardness, ultimate strength, yield strength, and compression strength of composites were found to increase with the weight percentage of nano B_4C .

Bharathi & Kumar (2023) fabricated aluminum metal matrix composites reinforced with different weight percentages of silicon carbide (2, 3, 4, 5, and 6 wt.%) and a constant weight percentage of boron carbide (2 wt.%) using the powder metallurgy technique. The powders were mixed by mechanical stirring at 2000 rpm and compacted with a hydraulic jack under high pressure (735 MPa). The green compact was degassed at 400°C for 3 hours to eliminate moisture, hydrogen, and oxygen. The green compact was sintered in a high-temperature furnace at 550°C for 3 hours. This study showed the hardness and compressive strength of the composite were increased with the increase of SiC weight percentage. The addition of SiC and B_4C reinforcements to aluminum can significantly improve the composite's hardness, compressive strength, and wear resistance. Haile et al. (2024) synthesized aluminum hybrid composite by reinforcing it with bamboo stem ash powder (BSAP) (2.5, 5, 7.5, and 10 wt.%), alumina (2.5 wt.%), boron carbide (5 wt. %), and molybdenum disulfide (2 wt. %) through powder metallurgy. This study evaluates the effects of bamboo stem ash powder on physical and mechanical properties of aluminum.

2.4 Metal Particulates Reinforcements in AHMMCs

Metal particulates are increasingly utilized as reinforcements in metal matrix composites (MMCs) due to their ability to enhance mechanical properties and performance

characteristics. Various metallic materials are used as reinforcements in MMCs, including pearlitic steels, stainless steel, copper, nickel, titanium, and even metallic glasses. These materials are chosen for their inherent ductility, toughness, and good wettability with metal matrices, which facilitates strong interfacial bonding (Alaneme et al., 2019). Unlike ceramic reinforcements that can lead to brittleness, metallic reinforcements enhance both ductility and toughness. This is particularly advantageous in applications where impact resistance is critical. The ability of metals to deform plastically allows for better energy absorption under load (Chawla & Shen, 2015).

Haripriya et al. (2021) fabricated MMCs from pure Aluminum (melting point of 660.4 °C) metal matrix reinforced with Titanium (melting point of 1660°C) as reinforcement material by stir casting method. Titanium particulate was added to aluminum in the ratio of 3% and 6%. The highest improved tensile strength, compressive strength, and yield strength were obtained from the Al + 6% Ti composite. Ikumapayi & Akinlabi, (2019) prepared AA7075-T651 aluminum metal composite (AMC) reinforced with α - β grade titanium alloy powder (Ti-6Al-2Sn-2Zr2Mo-2Cr-0.25Si) through friction stir processing (FSP). The potentiodynamic polarization technique was employed to investigate the corrosion behavior of the developed sample. The experiment involved immersing the sample in a 3.5% NaCl solution at 25°C. The corrosion rate was reduced from 5.0718 mmpy to 0.087675 mmpy when α - β grade titanium alloy was used as reinforcement. The ultimate tensile strength of the developed composite was 624 MPa, which is close to the unreinforced AA7075-T65 value, which is 620.903 MPa.

Titanium alloy Ti6Al4V is widely used as a matrix material in metal matrix composites (MMCs) due to its excellent mechanical properties, including high strength, low density, and good corrosion resistance. Ti6Al4V is known for its exceptional strength-to-weight ratio, making it ideal for applications in aerospace, automotive, and biomedical fields where lightweight yet strong materials are crucial (Shaikh et al., 2022). Gowthami & Vemula. (2024) reinforced Al801 with zirconia-toughened alumina (ZTA), graphene platelets (GPs), and Ti6Al4V particulates using ultrasonic-assisted stir casting. The mechanical properties test, wear resistance test, and microstructural characterization were carried out on two different composites (Al8011/5ZTA/1GP and Al8011/5ZTA/1GP/2.5Ti6Al4V). This study found that Ti6Al4V enhanced the hardness and tensile strength of composite compared to composite fabricated without Ti6Al4V.

2.4.1 Self-Lubricated Particles as Reinforcement in AHMMCs

Rebba & Ramanaiah, (2015) conducted an experiment on the composite developed from the AA2024 aluminum alloy metal matrix and B₄C and MoS₂ reinforcements. This study aimed to improve the properties of the AA2024 composite, based on previous studies that concluded 4 wt.% of B₄C and 4 wt.% of MoS₂ achieves good mechanical properties. Three different samples were developed by varying the weight percentage of boron carbide (1, 2, and 3 wt. %) and molybdenum disulfide (1, 2, and 3 wt. %). Sadoun et al. (2020) investigated the effect of GN particles on the structural, microhardness, and wear properties of Al-Al₂O₃-GN hybrid composites that were developed by powder metallurgy. The alumina (Al₂O₃) and graphene nano-sheets (GNs) were coated with a thin layer (~5 nm) of silver using electroless deposition to improve their wettability. The samples were fabricated by varying GNs (0.25, 0.5, 1 wt.%), and Al₂O₃ content was kept constant (5 wt.%). The powders were mixed ultrasonically for 30 min and dried in a vacuum oven at 60°C. The samples were consolidated by hot pressing at 700 MPa under an argon atmosphere and kept in the die for 15 min under applied pressure. According to this study, relative density decreased with increasing GN contents, but hardness and wear resistance increased. Senthil Kumar et al. (2021) used the powder metallurgy technique to produce a pure aluminum (Al) metal matrix composite reinforced with magnesium (4 wt.%) and molybdenum disulfide (2, 4, and 6 wt.%). The study found that increasing the weight percentage of molybdenum disulfide improved density, microhardness, compression strength, toughness, corrosion resistance, and wear resistance.

Vuddagiri & Ravisankar. (2022) added alumina (Al₂O₃) and molybdenum disulfide (MoS₂) to the Al-Si-Mg alloy by stir casting method to investigate their tribological impact. The wear resistance and friction coefficient improved Al-Si-Mg by adding Al₂O₃ and MoS₂. Han et al. (2022) evaluated the mechanical and tribological properties of Al composites reinforced with TiB₂ and two solid lubricants, graphite and nano MoS₂. Stir casting technique was used to create the composites, with TiB₂ and graphite at a constant weight percentage of 10% and nano MoS₂ at 10, 15, and 20%. This study found that wear loss and coefficient of friction reduced with increased addition of nano MoS₂ weight percentage. Dhyani et al. (2023) fabricated an aluminum matrix composite reinforced with solid lubricant molybdenum disulfide (MoS₂) of different weight fractions (1.5, 3.5, 5.5, 7.5, and 9.5 wt. %) using stir-casting. This study demonstrated that incorporating 5.5 wt.% MoS₂ enhanced strength and wear properties of aluminum. Nirala et al. (2023) demonstrated that

incorporating CNT (2 vol%) and SiC/B₄C (8, 12 vol. %) in aluminum matrices using the squeeze stir casting method significantly improved mechanical and tribological properties. The composite reinforced with B₄C shows greater mechanical and tribological properties than the composite reinforced with SiC.

Ajithkumar & Xavier, (2023) synthesized a hybrid metal matrix composite of Al7075 by adding SiC, B₄C, graphene, and multi-walled carbon nanotubes (MWCNT) reinforcements using the squeeze casting method combined with mechanical stirring and ultrasonication. The samples fabricated were 10% SiC-0.1% B₄C, Al7075-10% SiC-0.1% graphene, and Al7075-10% SiC-0.1% Multi-Walled Carbon Nanotubes (MWCNT). The study revealed that the composite containing B₄C has high flank wear (0.9835 mm), and the composite containing graphene has low flank wear (0.2314mm). The composite containing CNT showed medium wear (0.4408mm). During the turning operation, crater wear in the graphene-based composite was high (1.4373 mm), medium in the CNT-based composite (1.0823 mm), and low (0.3707 mm) in the B₄C-based composite.

Reddy et al. (2024) developed an aluminum 7475 metal matrix composite reinforced with graphite (3, 6, 9, and 12 wt.%) and coconut shell ash (10 wt.%) through stir-casting. It was discovered that the developed composite has improved hardness and tensile strength. Tensile strength was increased up to 9% weight percentage addition of Gr reinforcement and then decreased at 12% weight percentage of Gr reinforcement due to clustering. Similarly, hardness was improved up to 9% weight percentage of Gr addition and then decreased at 12% weight percentage of Gr. Olmez et al. (2024) investigated the composite fabricated using stir casting from Al6061 aluminum alloy as a matrix and graphite as a reinforcement. Three different samples were developed by adding different weight percentages of graphite (4%, 6%, and 15%). As this study stated, the percentage of elongation decreased with an increased weight percentage of graphite. The composite's hardness decreased as the weight percentage of graphite increased. The highest hardness was achieved with a 4% graphite weight percentage. Graphite decreased the hardness of the composite because it is a soft material.

2.5 Fabrication of Metal Matrix Composite

It is necessary to choose the most appropriate manufacturing process for producing the aluminum hybrid metal matrices because different manufacturing techniques have distinct benefits in certain applications. The basic classifications of manufacturing methods for

metal-matrix composites are liquid-phase processes and solid-phase processes (Dash et al., 2018; Anand & Senthil Kumaran, 2020).

2.5.1 Liquid-Phase Processes

MMC production techniques known as "liquid-state processes" create composites by incorporating the reinforcing material into a molten metal matrix and then solidifying it. These processes are characterized by intimate interfacial bonding. This permits the formation of dense matrices and near-net-shaped components, even in complex geometries, at a remarkably quick rate of production. The one limitation of liquid-state processes is that high-temperature processing can result in the formation of a brittle interfacial layer between the involved phases, which has a negative impact on the composite properties. Uniform distribution of dispersed material without particles floating, sedimenting, or clustering/agglomerating in the molten alloy can be difficult (A. Kumar et al., 2020); (Mussatto et al., 2021). Some types of these processes are discussed below.

Stir Casting: It is the method in which a reinforcement is mechanically stirred into a molten metal to achieve uniform distribution. After solidification, the casting is removed from the mold and subjected to various post-processing steps, such as heat treatment, machining, and surface finishing, to obtain the final desired properties and dimensions (Sankhla and Patel, 2022; Gotagunaki et al., 2023). The stir casting process has several disadvantages, including non-uniform reinforcement distribution, poor wettability, potential chemical reactions between the reinforcement and metal matrix, and reinforcement damage during the mechanical stirring process (S. Khan & Almadhoni, 2015; V. M. Kumar & Venkatesh, 2019).

In-situ processes: In-situ processing involves chemical reactions between the matrix and reinforcement. This reaction creates reinforcer phases in the form of precipitates. The reactive type process consists of two elements, which react exothermically to form the reinforcing phase. In the non-reactive type process, the monotectic and eutectic phases form the reinforcement and matrix during fabrication (Essien & Vaudreuil, 2022). The main advantage of this process is the ability to form a reinforcing phase in the matrix during the cooling and solidification processes. It also allows for uniform distribution, resulting in a strong bond between the matrix and the reinforcing phase. It has a controlled microstructure, reduced porosity, and high temperature performance (B. Das et al., 2016; Önal & Gavgali,

2017). The main disadvantage of the in-situ process is the limited selection of reinforcements that are thermodynamically stable within a particular matrix (Essien & Vaudreuil, 2022).

Infiltration: The composite production by infiltration method is carried out by impregnating a porous precursor material (such as ceramic particles, fibers, or woven) into molten metal to fill the pores. It can be defined as the method of sending fluid into the porous solid material by vacuum or gas. The driving force of the infiltration process can be capillary force or external pressure. The different types of infiltration methods are gas pressure infiltration, squeeze casting infiltration, and pressure die infiltration (Sree Manu et al., 2016).

2.5.2 Solid Phase Process

A solid-state process is a method for creating metal matrix composites that uses high temperatures and pressures to create atomic diffusion between the metal matrix and the reinforcement. This process diminishes dispersed phase matrix wetting and reduces segregation effects and brittle reaction product formation. Additionally, high residual stresses during solidification are avoided, especially when compared to liquid-state processes. The materials that have a huge melting point difference are more easily fabricated through a solid-state process (Mussatto et al., 2021). Among the different types of solid-phase processes, some of them are discussed below.

Friction Stir Processing (FSP): It is an environmentally friendly surface composite fabrication and surface modification process that uses the same principle of friction stir welding (FSW). This technique is gaining popularity as a promising way to create surface metal matrix composites (Parray et al., 2020).

Laser Cladding: Laser cladding is a modern manufacturing technique for altering the surface of metallic materials in today's industries. This method includes the deposition of a new layer on a substrate by laser fusion of blown powders or pre-placed powder coatings. It is used to increase the surface qualities, such as wear resistance, hardness, oxidation resistance, corrosion resistance, biocompatibility, and heat resistance, by depositing a thick layer of modern materials on their surface (A. K. Das, 2021).

Powder Metallurgy Process: This technique is the most common solid-state process that is suitable for the fabrication of micro- and nano-ceramic-reinforced MMCs. PM routes are extensively used for investigations of new composites and for the production of MMCs (Mussatto et al., 2021).

2.6 Powder Metallurgy Technique

The term powder metallurgy (PM) covers a wide range of methods that are used to fabricate components from metal powder (Jayasathyakawin et al., 2020). The process of powder metallurgy involves appropriately mixing metal or alloy powders, compacting in a high-pressure die, and then sintering at a high temperature to ensure optimal particle bonding (Anand & Senthil Kumaran, 2020). This technique is highly efficient, less expensive, high material utilization, less energy consumption, and no or very little machining required (Satish & Satish, 2018).

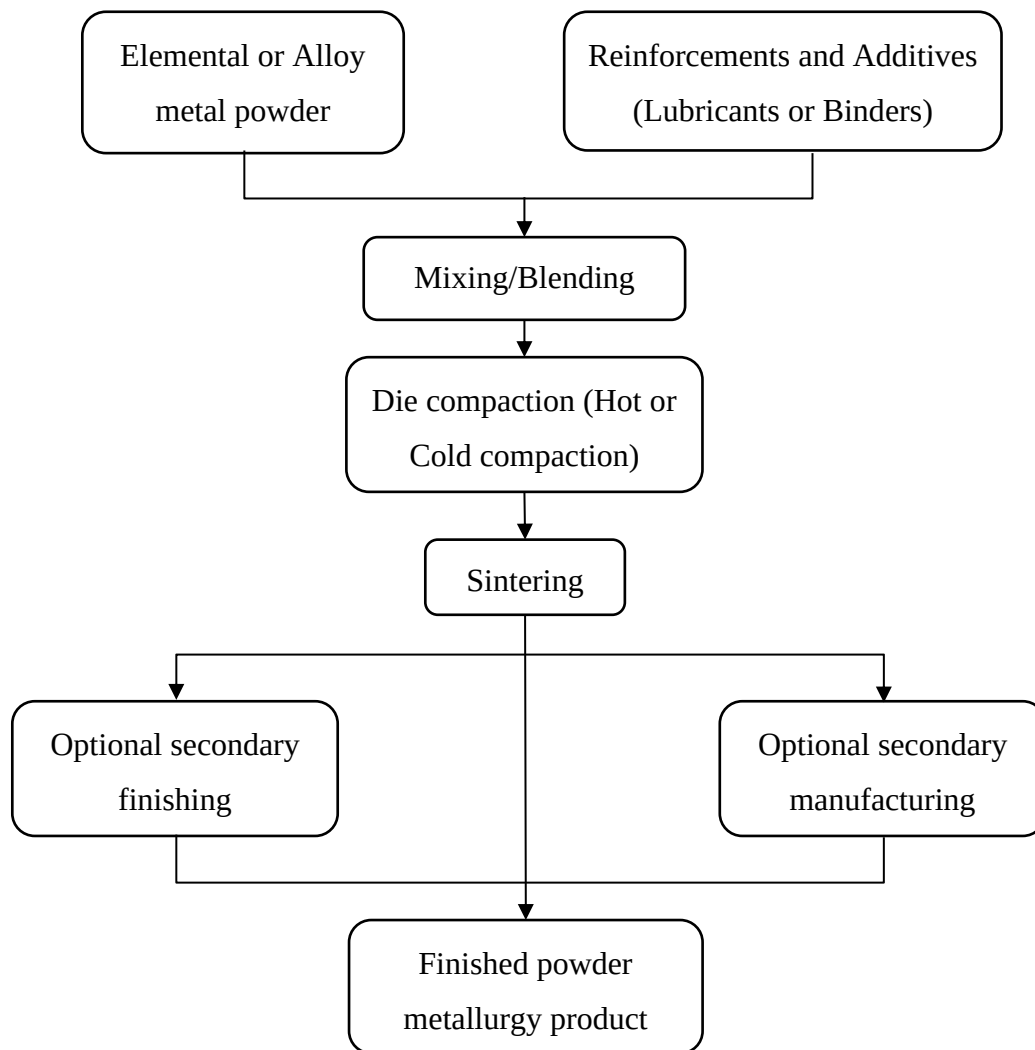


Figure 2.1 Flow chart for powder metallurgy composite production (Lajis et al., 2014)

The powder metallurgy technique begins with the production of powder. After that, the powder is combined or blended with lubricants or binders. The mixed powder is then compacted in a die, followed by sintering. Finally, an optional secondary manufacturing and finishing process is applied to create special properties or improve the precision of the

powder metallurgy product (Lajis et al., 2014). This is depicted in Figure 2.2. The challenges that can arise when fabricating MMC using powder metallurgy include achieving uniform powder distribution, overcoming poor interfacial bonding, addressing particle agglomeration, controlling porosity, and ensuring proper reinforcement dispersion. Differences in their properties may present a number of challenges, including mismatched densification behavior, thermal expansion mismatches, and chemical compatibility. Some techniques that are used to overcome these problems are proper mixing techniques, control of compaction parameters (adjusting the compaction pressure, temperature, and dwell time), and the introduction of a suitable interlayer or interfacial material (Saboori et al., 2018); (Ali & Hafez, 2023).

2.6.1 Metal Powder Production Methods

Powder properties such as particle size, shape, distribution, and composition affect the flowability, packing density, and sinter-ability of the powder. The three principal methods by which metallic powders are commercially produced are atomization, chemical reduction, and electrolytic deposition. Also, mechanical methods are sometimes used to reduce powder sizes, but these methods are much more commonly associated with ceramic powder production. In the atomization method, powder is produced from solidified spray droplets of molten metal. Chemical reduction method is a chemical reaction by which metallic compounds are reduced to elemental metal powders. A common process involves liberation of metals from their oxides by use of reducing agents such as hydrogen or carbon monoxide at an elevated temperature (below the melting point) in a controlled furnace. The reducing agent is made to combine with the oxygen in the compound to free the metallic element. In electrolytic deposition method an electrolytic cell is constructed in which the source of desired metal is the anode. The anode is slowly dissolved under an applied voltage transported through the electrolyte and deposited on the cathode. The deposit is removed, washed and dried to yield a metallic powder of very high purity (Asgarian et al., 2014; Sun et al., 2017; Amado et al., 2019; Garboczi & Hrabec, 2020).

In the powder metallurgy technique, the choice of appropriate processing conditions and the achievement of the required properties greatly depend on the shape of the particle. Particle shape especially influences powder sinter-ability, packing density, compressibility, mechanical property, reactivity, and flowability. Based on their dimensions, particle shapes are categorized into three groups: one-dimensional (those which have a large aspect ratio, such as acicular and rod-like), two-dimensional (those which have length and width much

prevailing on thickness, such as dendritic and flaky), and three-dimensional (such as spherical, angular/irregular, porous, and rounded) (Jakub et al., 2016; Nouri & Sola, 2018).

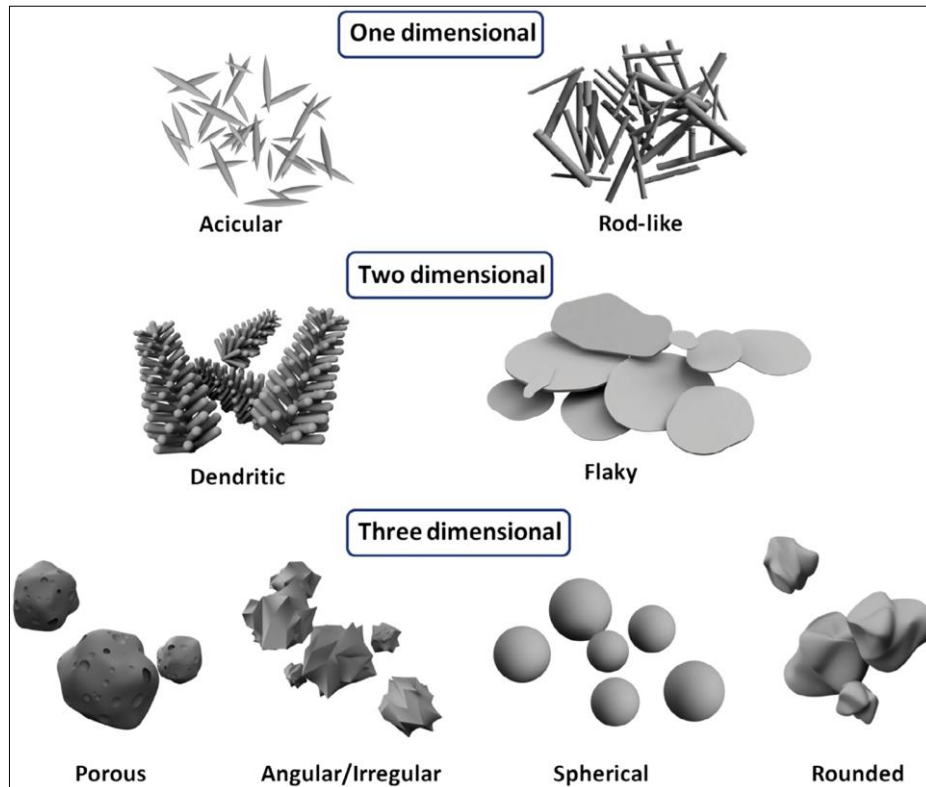


Figure 2.2 Shapes of powders based on their dimension (Nouri and Sola, 2018)

2.6.2 Powder Mixing Process

In the powder metallurgy technique, mixing powders is imperative to achieving the desired material properties. The primary objective of mixing is to achieve a uniform distribution of the reinforcement particles within the matrix metal powder. Mixing factors such as mixing time, mixing intensity, and the use of binders or lubricants can affect the uniform powder distribution and the resulting microstructure of the final product. The mixing quality has a significant impact on the final properties of the material, with factors like particle size, mixing time, and uniform dispersion having key roles. The mixing/milling time should be long enough to obtain a more uniform mixture by reducing the agglomeration or clustering of particles, but overmixing can decrease particle size, alter particle shape, and work harden particles. Moreover, controlling the atmosphere during mixing helps to avoid contamination, such as the formation of oxides on particle surfaces (N. Kumar et al., 2019; Edosa et al., 2022).

Salur et al. (2021) reinforced Al7075 with yttria (Y_2O_3) (0.5 wt.%) nanoparticle in order to examine the effects of milling time on Y_2O_3 dispersion and interfacial bonding. The powders were mixed by a planetary mill machine at 400 rpm with different milling times (0.25, 1, 1.5, 2, and 10 h). The tungsten carbide ball of 10 mm diameter with a 10:1 ball-to-powder mass ratio was used. This study showed that increasing milling time improves hardness and ultimate tensile strength. Shaikh et al. (2019) evaluated the behavior of aluminum matrix composites reinforced with rice husk ash (5, 10, and 15 wt.%) and silicon carbide (10 wt.%) using powder metallurgy. The powders were mixed for 30 minutes in a planetary ball mill with a constant speed of 120 rpm. The ball-to-powder ratio was 10:1, and liquid ethanol was used to prevent oxidation. The green compacts were carried out uniaxially on the hydraulic pallet machine at 400 MPa. To avoid sticking of the specimen during the ejection, zinc stearate was used as die wall lubrication. The compacted specimens were sintered for 45 min in a temperature range of 450 ± 25 °C in an induction furnace under an argon gas atmosphere. According to this study, the mechanical and tribological properties of the developed composite only increased up to 10 wt. % rice husk ash.

Kanthavel et al. (2016) explored the effect of molybdenum disulfide (MoS_2) on the tribological properties of the Al- Al_2O_3 - MoS_2 metal matrix hybrid composite. In this study, three different specimens were fabricated, Al/5 Al_2O_3 , Al/5 Al_2O_3 /5 MoS_2 , and Al/5 Al_2O_3 /10/ MoS_2 , using the powder metallurgy process. The powders were mixed in a planetary tumbler mixer using stainless steel balls of 10 mm diameter. The ball-to-powder weight ratio was 10:1, and the mixer was operated at 50 rpm in the presence of toluene medium to avoid the oxidation and penetration of powders on the wall of the vial. This study showed that adding 5% molybdenum disulfide would improve the tribological properties of an aluminum hybrid composite.

2.6.3 Powder Compacting Process

The powder compacting process in the powder metallurgy technique is important to achieve high product density and uniformity of that density throughout the compact. This process involves compressing powder into a shape known as a green compact. Higher compacting pressure is used to increase green density, which is essential for achieving high product density and uniformity throughout the compact. Parameters such as compaction pressure, compaction speed, and dwell time influence the density, dimensional accuracy, and mechanical properties of the green compact. Factors such as tool design, and shape

complexity also play a role. The density distribution obtained with different compacting pressures can vary, impacting the final properties of the material (N. Kumar et al., 2020).

2.6.4 Sintering Process

The sintering process is a heat treatment applied to green compact at a high temperature below the melting point of the major constituent of the powder metallurgy material in a controlled atmosphere. It is used to increase the bond between particles and enhance the strength of the powder metal compact, leading to the desired properties in the final product (Edosa et al., 2022). Sintering parameters like temperature, heating rate, holding time, and atmosphere influence densification, grain growth, and the final mechanical properties of the sintered part. Post-sintering processes such as heat treatment, machining, surface finishing, and coating can further modify the properties and surface characteristics of the sintered part (Behera et al., 2019).

2.7 Multi-response Optimization Method

The Multi-Response Optimization Method is a technique used to optimize multiple results simultaneously. In engineering, multi-response optimization is essential to obtaining the best overall system performance by considering and balancing various factors simultaneously. This method enables engineers to find solutions that enhance all responses without compromising any particular response. The responses in multi-response optimization may not compete with each other, and the goal is to optimize all responses simultaneously to improve overall product or system performance (Beshah et al., 2015); (Winarni & Indratno, 2018).

The main methods used for multi-response optimization are the Taguchi Method, Grey Relational Analysis (GRA), and Data Envelopment Analysis (DEA) (Y. Kumar & Singh, 2014); (Mardani et al., 2017). GRA is a method that can be used in conjunction with the Taguchi method, allowing it to take advantage of the benefits of both methods to solve multi-response optimization problems. It aims to measure the similarity or closeness between different response profiles and identify the input variable settings that maximize the overall closeness or similarity to the desired response. This method is a more suitable technique, and it is easy to predict the effects of different parameters within the levels studied. In the GRA method, the parameters obtained from the Taguchi method are converted to a single performance characteristic called the grey relational grade for the optimization of multiple performance characteristics. Grey relational analysis is particularly useful when dealing with

complex systems, limited data, or uncertain environments. It allows for a comprehensive assessment of multiple responses and facilitates decision-making by identifying the input variable settings that lead to the best overall performance or closeness to the desired targets (Girish et al., 2019; Hussain et al., 2020).

In multiple-response optimization, a variety of metaheuristic algorithms are used, including the Genetic Algorithm (GA), which is a probabilistic search algorithm that provides near-optimal solutions rather than exact solutions. GA is based on the principles of natural selection and genetics. Then each individual is evaluated using a fitness function that compares its performance to the optimization objective. After that, individuals are selected from a randomly generated population to serve as parents for the next generation. And these chosen parents undergo crossover to produce offspring. Furthermore, mutation causes random changes in some genes in offspring in order to preserve genetic diversity within the population and prevent premature convergence. Finally, the produced offspring replaces some or all of the old population, and the algorithm repeats this until a stopping condition is met. Because Genetic Algorithm (GA) values are stochastic and heuristic, they are not guaranteed to be the absolute optimal solution (Bhoskar et al., 2015; Katoch et al., 2021; Rajwar et al., 2023).

2.8 Literature Summery

Generally, summarizing the surveyed literature, researchers identified and investigated the effects of particulate reinforcements on aluminum metal matrix composites to improve their mechanical, physical, and tribological properties. Those reinforcements were typically added in the form of particles and dispersed within the aluminum matrix. As it was presented in various literatures, particulate reinforcements such as boron carbide, silicon carbide, aluminum oxide, graphene nanoplatelets, graphene nano-sheets, zirconium dioxide, titanium grade 5, molybdenum disulfide, titanium dioxide, carbon nanotubes, tungsten carbide, zirconia-toughened alumina, graphene platelets, titanium boride, yttria, and zirconium carbide can significantly increase the strength, hardness, corrosion resistance, and wear resistance of aluminum based composites. Among the various commercially available techniques for producing aluminum and aluminum alloy metal matrix composites, powder metallurgy is the most efficient, least expensive, has high material utilization, consumes less energy, and requires no or little machining. Powder metallurgy technique involves four main processes: powder production, powder mixing, compacting, and sintering. Metallic powders were commercially produced using three methods: atomization, chemical reduction, and

electrolytic deposition. The Taguchi Method, Grey Relational Analysis, and Data Envelopment Analysis are three different multi-response optimization methods. The most popular metaheuristic algorithms are the Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA), and Ant Colony Optimization (ACO).

2.9 Research Gap

Despite the fact that many research has been carried out on different aluminum and aluminum alloy metal matrices reinforced with particulates, the investigation of mechanical, physical, and tribological properties of pure aluminum reinforced with B_4C , MoS_2 , and Ti64 is still an unexplored area (Senthil Kumar et al., 2021; Brillon et al., 2022; Haile et al., 2024). The importance of this research over previous studies is developing advanced lightweight materials with improved mechanical and tribological properties in order to meet the demands of high-performance industries. A lot of work has been carried out to improve the mechanical, physical, and tribological properties of pure aluminum and aluminum alloys by reinforcing them with different particulates. In a few studies (Maruthi Varun & Raman Goud, 2019; S. Liu et al., 2019; Gonfa et al., 2022; Hemadri et al., 2022; Bharathi & kumar, 2023; Haile et al., 2024) boron carbide, titanium grade 5, and molybdenum disulfide were used as reinforcement materials individually or combined with other materials in the reinforcing of pure aluminum. But there is lack of comprehensive studies on the synergistic effects of combining B_4C , MoS_2 , and Ti6Al4V as reinforcements in pure aluminum matrices, particularly regarding their impact on mechanical and tribological properties. Additionally, there is insufficient exploration of the optimal processing parameters in powder metallurgy for achieving desired microstructural characteristics and performance outcomes. In the studies of Çelik & Seçilmiş. (2017) and Brillon et al. (2022) only boron carbide was used as reinforcement, and the high hardness of boron carbide can result in poor packing of green compact. So, to improve the properties of green compact, a solid lubricant, such as molybdenum disulfide, is required to be added. Furthermore, because boron carbide can reduce aluminum toughness, more high-compressive-strength materials, such as titanium grade 5, are required to be added. So, the exploration of aluminum hybrid metal matrix composites is still a burning issue to improve their performance for engineering applications. This study addresses the gaps of reinforcing pure aluminum with B_4C , Ti64, and MoS_2 reinforcements using the powder metallurgy technique and optimizing process parameters, which were previously unresolved.

CHAPTER THREE

MATERIAL AND METHODOLOGY

3.1 Introduction

This chapter presents the materials and methodology employed in the development, testing, and characterization of the Al-B₄C-Ti64-MoS₂ hybrid composite. The selection of materials used for the fabrication of composites, the fabrication approach and specimen preparation methods, experimental procedures, and testing set-ups are outlined.

3.2 Materials

This study synthesized the metal-matrix hybrid composite using pure Al as the matrix material and B₄C, Ti64, and MoS₂ as reinforcing materials. The average particle sizes of the purchased Al, B₄C, and MoS₂ are 74μm of 99.5% purity, 45μm of 99.7% purity, and 44μm of 98% purity, respectively. The Ti64 powder particle size was 74μm. The average particle size of the powders used in this study was identified by using ImageJ software. Their SEM images are shown in Figure 3.1. The shapes of aluminum particles were spherical and spheroidal.

Table 3.1 Chemical composition of pure Al powder, as per the supplied company's (SATYAM ENTERPRISES, brand name: SELAB) specification

Constituents	As	Pb	Fe	Al
Wt. %	0.0005	0.03	0.5	Reminder

Table 3.2 Properties of aluminum and reinforcements (Zhu et al., 2017;Bharathi & kumar, 2023; Haile et al., 2024;Najafizadeh et al., 2024)

Properties	Metal Matrix	Reinforcements		
	Al	B ₄ C	Ti64	MoS ₂
Density (g/cm ³)	2.70	2.52	4.43	5.06
Compression strength (MPa)	70 – 80	3000 - 5000	900 – 2000	200 – 400
Melting point(°C)	660	2350	1878 –1933	1185 – 2375
Color	silvery-white	black	metallic gray	lead-gray

The boron carbide particles were in the shape of dendritic, the molybdenum disulfide particles shape was also dendritic, and the titanium grade 5 particles were in the shape of angular. The chemical composition of aluminum is shown in Table 3.1. The properties of the aluminum metal matrix and reinforcements are shown in Table 3.2.

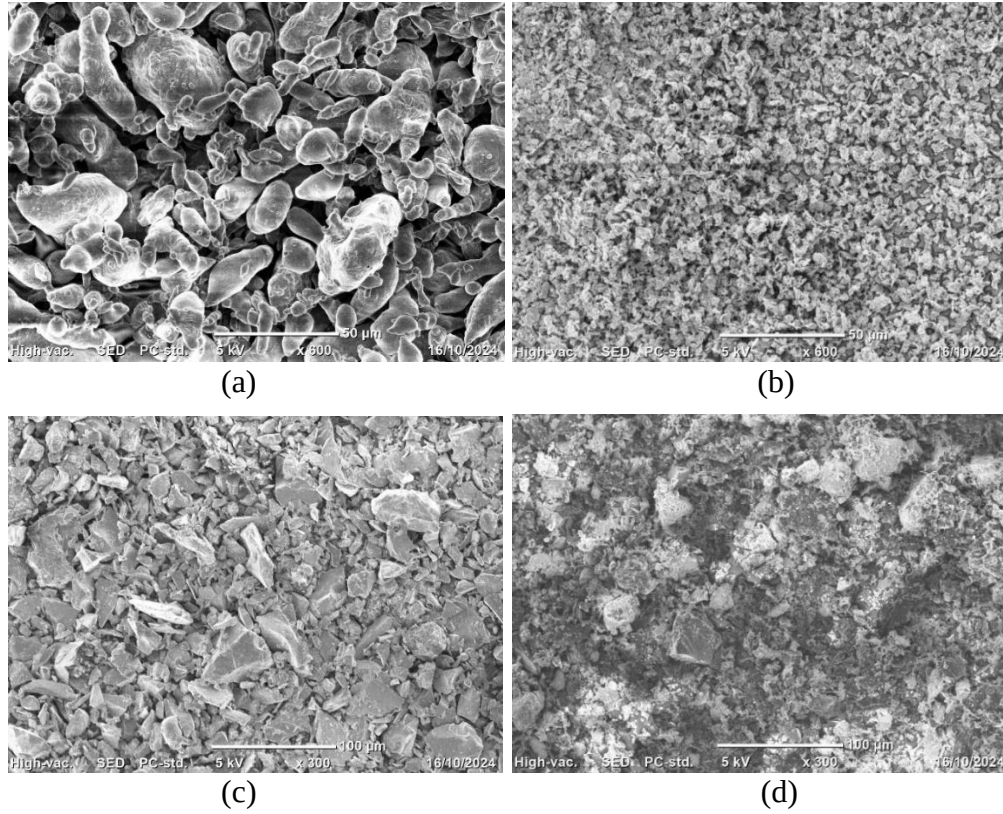


Figure 3.1 SEM micrograph of (a) aluminum (Al), (b) boron carbide (B₄C), (c) titanium grade 5 (Ti64), and (d) molybdenum disulfide (MoS₂)

Titanium alloy Ti-6Al-4V, also sometimes called TC4, Ti64, or titanium grade 5, are alternative candidates for the fabrication of MMCs. It is composed of 6% aluminum and 4% vanadium, which stabilize the alpha and beta phases, respectively. Ti64 is an alpha-beta titanium alloy that has high specific strength, stiffness, good machinability, and excellent corrosion resistance, making it a popular choice for a wide range of applications such as aerospace structures, biomedical implants and prostheses, and other applications where low density and high strength are required. But its wear resistance is inadequate (Soorya Prakash et al., 2018; Samy et al., 2021; Marin & Lanzutti, 2024). Titanium alloys (Ti-6Al-4V) has a high melting point, a high Young's modulus, and high plasticity (Pushp et al., 2022).

Molybdenum disulfide (MoS₂) is an inorganic compound of the transition metal dichalcogenides (TMDs) series, that has one atom of Molybdenum and two atoms of Sulfur. It has exceptional lubricating properties because layers of MoS₂ can slide past each other

easily due to weak interlayer forces, reducing friction and wear. MoS₂ is chemically and thermally stable, and has a high hardness and low density, making it a suitable reinforcement. It uses as a reinforcement in metal matrix composites to increase the mechanical properties, and improves the wear resistance (Samy et al., 2021).

3.3 Methodology

The samples were produced by means of a powder metallurgy fabrication process in order to obtain better material properties. Material characterization was conducted through OM, SEM and XRD to analyze microstructure, particle size, phase and particle distribution of reinforcements over the matrix. Also, mechanical properties testing was carried out through a Vickers hardness test, and a universal testing machine. The wear resistance of the samples was studied by the pin-on-disk test. The corrosion resistance of the samples was tested by electrochemical technique. The process parameters were analyzed and optimized under Taguchi-based grey relation analysis, ANOVA, and genetic algorithm. The general experimental procedure of this study is illustrated in Figure 3.2.

3.3.1 Specimen Fabrication Procedure

Specimen preparation was carried out for different compositions of Al (85 – 93 wt. %), B₄C (2–6 wt. %), Ti64 (1 – 5 wt. %) and MoS₂ (4 wt. %) which were weighed using a weighing balance (Brand name: HR-250AZ) shown in Figure 3.3, which has 0.1 mg accuracy (Haripriya et al., 2021; Brillon et al., 2022; Bharathi & kumar, 2023). The total gram of each sample was four grams (4g). The total gram of the matrix and the reinforcement within each sample were calculated based on the selected weight percentage of the matrix and the reinforcement. The selected weight percentage of matrix and reinforcements within each specimen is illustrated in Table 3.3. The weight percent composition of reinforcements used in this research work was assumed based on a literature review. Nine different specimens were fabricated by varying their matrix and reinforcement composition to investigate reinforcement effects. In addition to that, the effects of powder metallurgy process parameters such as compacting pressure and sintering temperature were investigated by varying their value from one sample to another, as shown in Table 3.5.

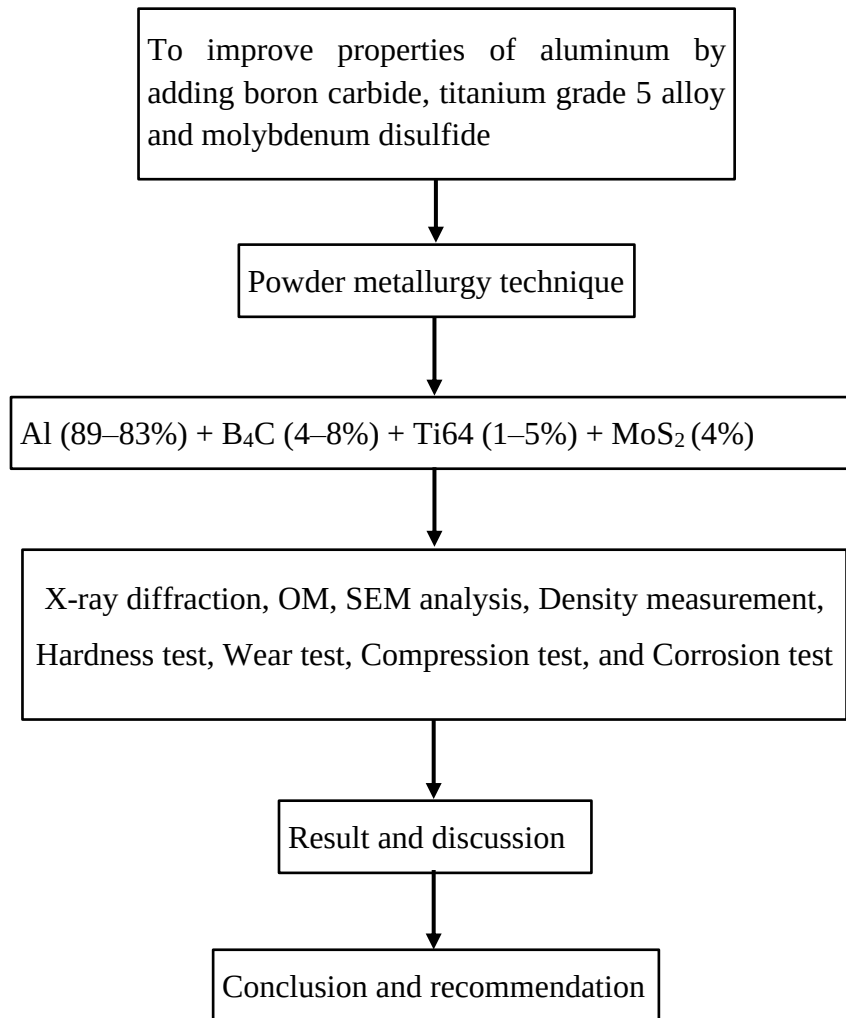


Figure 3.2 General methodology of the research

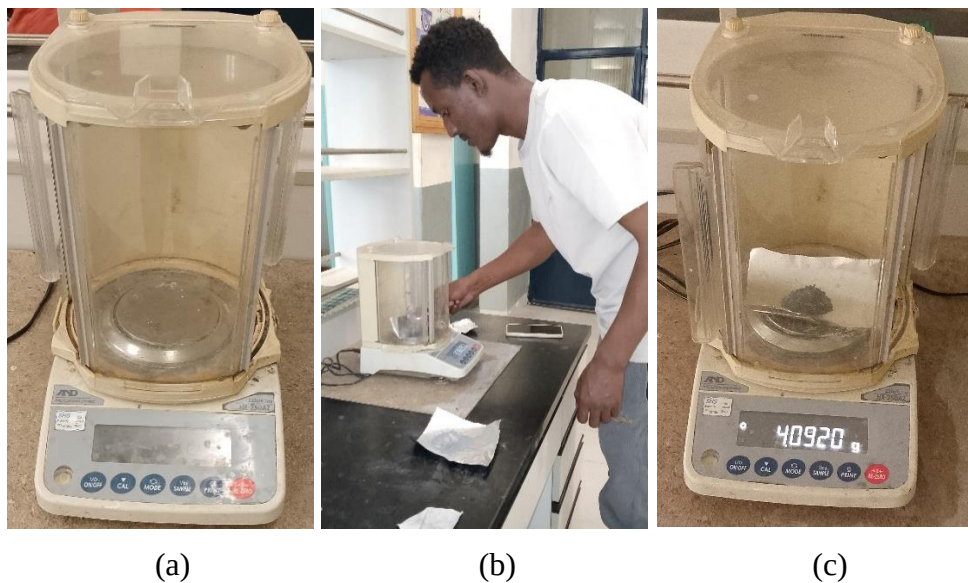


Figure 3.3 (a) Weighing equipment (b) Measuring powders (c) Total gram of sample

Table 3.3 Compositions of matrix and reinforcing materials

Specimen	Matrix	Reinforcements		
	Al (w. %)	B ₄ C (w. %)	Ti64 (w. %)	MoS ₂ (w. %)
S ₁	93	2	1	4
S ₂	91	2	3	4
S ₃	89	2	5	4
S ₄	91	4	1	4
S ₅	89	4	3	4
S ₆	87	4	5	4
S ₇	89	6	1	4
S ₈	87	6	3	4
S ₉	85	6	5	4

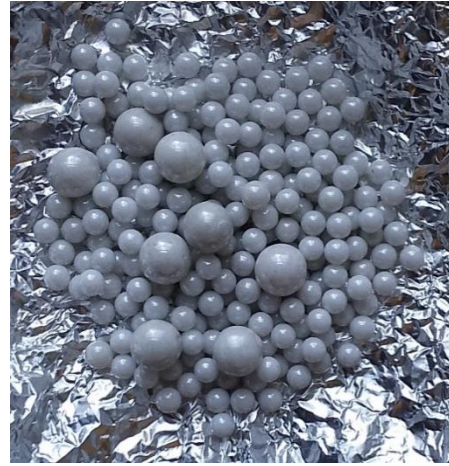
3.3.2 Specimen Fabrication Process

During the manufacturing of the specimens using PM, there were several processing steps. Those steps are (i) powder mixing; (ii) powder compacting; and (iii) sintering of green compacts. Before proceeding to the powder mixing process, the grams of matrix and reinforcements powder for each sample were weighed. After that, the powders were mixed at constant mixing time (1hr.) (John et al., 2017) using a High Energy Mixer/Mill machine shown in Figure 3.4(a). The rotation speed of the milling machine was 400 rpm, and the balls used were zirconium balls shown in Figure 3.4(b). The powder-to-ball weight ratio was 1:10.

The mixed powders were then compacted into cylindrical billets of 16 mm diameter using a hydraulic press machine (Brand name: Lab Press) shown in Figure 3.5. The die and punch material used in the compacting of powder was stainless steel. The die dimension is 16 mm internal diameter and 40 mm height. The compaction process was obtained by uniaxial pressing at room temperature with a 5-minute holding time. The pressure applied to the specimens was carried out based on the design of the experiment shown in Table 3.5. As it is shown in this table, three different pressures (50, 60, and 70 MPa) (Garg et al., 2016; Haile et al., 2024) were used to fabricate the samples.



(a)



(b)

Figure 3.4 (a) High energy mixer/ mill machine (b) Zirconium balls



(a)



(b)

Figure 3.5 (a) Hydraulic press machine (b) Sintering Furnace

The compacted specimens of Al and Al-B₄C-Ti64-MoS₂ composites were then sintered for one hour (Shaikh et al., 2019) in a furnace (brand name: High Temperature Box Furnace, as shown in Figure 3.5(b)). This process was performed to eliminate porosity and create bonds between powder particles. The green compact and sintered samples are shown in Figure 3.6.

The sintering process used in this study to produce the samples has three phases (heating, sintering, and cooling), as shown in Figure 3.7. During the heating phase, the sintering process began at room temperature (20°C), and the samples were heated at a constant rate of 15°C/min. This phase is to reduce thermal shock and ensure uniform heating throughout the composite. During the sintering phase, the samples were heated at the sintering

temperature (550, 600, and 650 °C) for one hour (Garg et al., 2016; J. Liu et al., 2019; Haile et al., 2024). During the cooling phase, the samples were cooled at a rate of 15 °C/min (J. Liu et al., 2019). This phase is used to avoid the formation of stresses or defects in the composite due to thermal gradients.

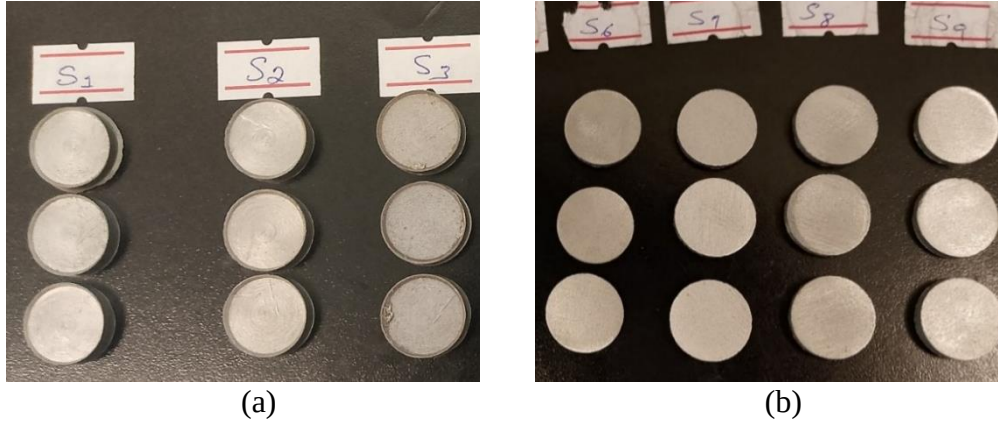


Figure 3.6 (a) Green compact (b) Sintered samples

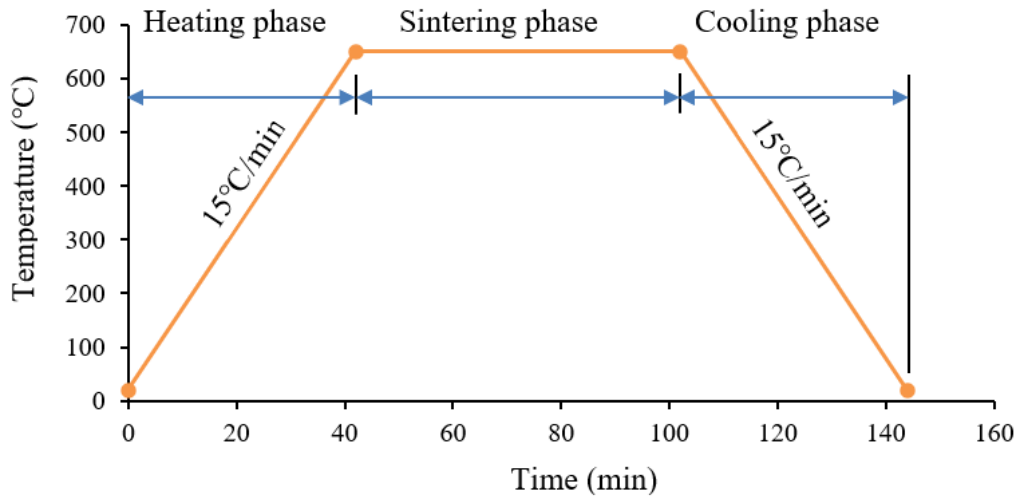


Figure 3.7 Sintering cycle used to produce Al-B₄C-Ti64-MoS₂ composite

3.3.3 Specimen Preparation for Characterization

To perform sample characterization, the sample must first be prepared in such a way that it is suitable for the analysis. In this finding, specimens were prepared for various tests in accordance with ASTM E3 standards. Grinding operations were performed to achieve the required surface finish for characterization, using various grades of silicon carbide paper (120, 220, and 240 grade) and aluminum oxide paper. The specimens were then polished to create a flat, scratch-free, mirror-like surface.

3.3.4 Microstructural Characterization

Microstructural characterization was carried out by OM, SEM, and XRD. Phase analyses of the optimized specimen were conducted by an X-ray diffractometer (XRD) (brand name: MAXIMA, model: XRD-7000 X-RAY DIFFRACTOMETER). It was operated with 40 kV tube voltage, 40 mA tube current, 2 θ measurement range (10–90°), and 3°/min scanning speed. Phase identification and quantitative phase analysis were performed using Origin Pro software. Relative intensity was calculated using equation 3.1 to verify phase composition. OM (brand name: HUVIZT) and SEM (brand name: JEOL) devices were used to analyze the microstructure of AHMMC, such as the distribution, size, and morphology of reinforcing phases within the metal matrix. The particle shape of the matrix and reinforcements was determined by SEM.

$$I_R = \frac{I}{I_r} \quad (3.1)$$

Where:

I_R = relative intensity

I = intensity of peak

I_r = reference intensity



(a)



(b)

Figure 3.8 Characterizing equipment (a) SEM, (b) OM

3.3.5 Physical Property Test

Density Determining Method

Density is a physical property of a material that describes its mass per unit volume. It is an important property of materials, particularly in engineering applications where weight and strength are critical factors. The composition and structure of the MMCs, as well as the manufacturing method used to produce them, can affect density. In this research, the density of the specimens was measured using the Archimedes method to identify the effects of powder metallurgy process parameters and reinforcements. The procedure of this method involves: first measuring the mass of the composite specimen in air (W_{Air}), then immersing the specimen in a liquid medium, typically water, and measuring the mass of the sample while submerged (W_{Fluid}). Finally, the density of the composite specimen was calculated using equation 3.2. As per ASTM B962-23, the surface roughness of the specimens was removed using 120-grit sanding, and surface pores were sealed by oil impregnation.

The relation for calculating the density of the specimen by Archimedes method is as follows:

$$\rho_{sample} = \frac{W_{Air} \times \rho_{Fluid}}{W_{Air} - W_{Fluid}} \quad (3.2)$$

Where: $\rho_{specimen}$ = density of the specimen

W_{Air} = weight of the specimen in atmospheric air

W_{Fluid} = weight of the specimen in a fluid

ρ_{Fluid} = density of the water (0.9982 g/mL at 20 °C)

Porosity Determining Method

Porosity in composite materials refers to the presence of voids or pores within the material's structure. It represents the fraction of the total volume of the composite that is occupied by these void spaces. The porosity is represented by the symbol ϕ , and its value ranges between 0 and 1 when it is expressed as a fraction or between 0% and 100% when it is expressed as a percentage. In MMCs, the presence of pores or voids can significantly affect the material's properties, including its strength, stiffness, and hardness. The two commonly used techniques to determine porosity in metal matrix composites (MMCs) are: Archimedes' Method and Image Analysis. But this study employed Archimedes' method, which is based on the principle of buoyancy and is widely used for porosity determination in MMCs. This method provides a direct measurement of the overall porosity in the composite.

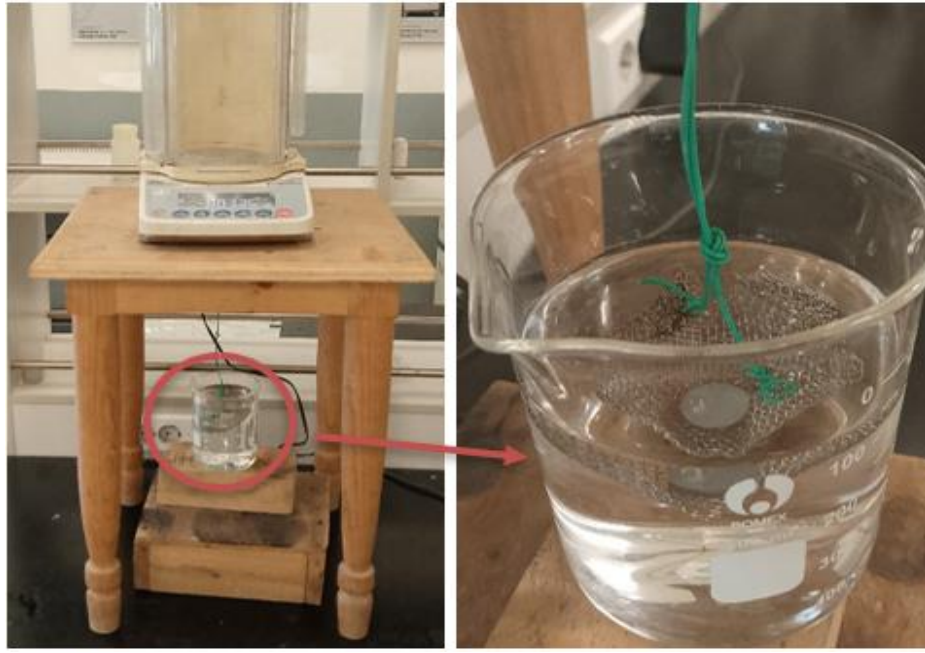


Figure 3.9 Archimedes methods of density measurement in distilled water

The steps involved in the Archimedes' method are as follows:

- a. Calculate the volume of the specimen using the density of the liquid, typically water.

$$\text{Buoyant force} = W_{Air} - W_{Fluid} \quad (3.3)$$

$$\text{Volume of specimen} = \text{Buoyant force} / \text{Density of liquid } (\rho_{Fluid})$$

$$V_{Specimen} = \frac{W_{Air} - W_{Fluid}}{\rho_{Fluid}} \quad (3.4)$$

- b. Calculate the apparent density of the composite using the weight in air and the volume.

$$\text{Apparent density}(\rho_A) = \frac{W_{Air}}{V_{Specimen}} \quad (3.5)$$

- c. Calculate the theoretical density of the composite, which can be determined based on the composition of the matrix and reinforcement materials.

$$\rho_t = (W_m \times \rho_m) + (W_r \times \rho_r) \quad (3.6)$$

Where: ρ_t = theoretical density

W_m = weight fraction of the matrix material

W_r = weight fraction of the reinforcement material

ρ_m = density of the matrix material

ρ_r = density of the reinforcement material

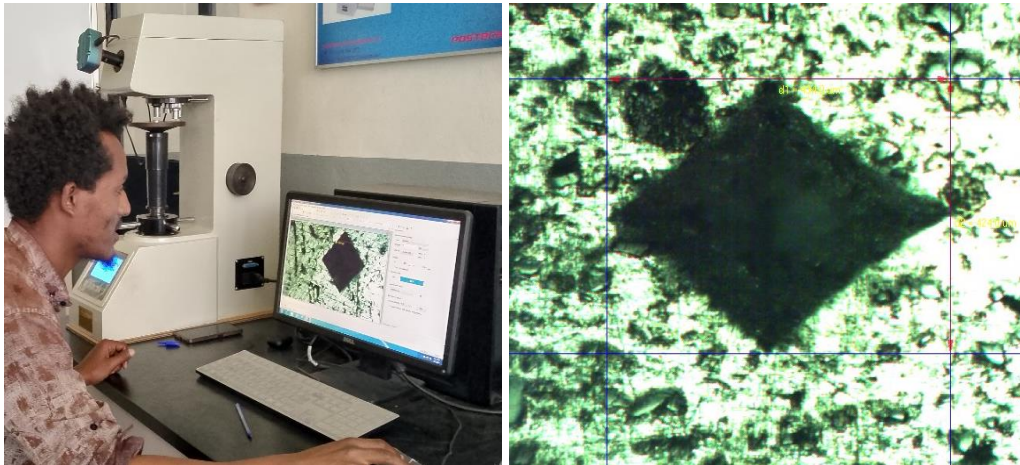
d. Finally, calculate the porosity using the formula:

$$\text{Porosity } (\phi) = \frac{\text{Theoretical density} - \text{Apparent density}}{\text{Theoretical density}} \times 100$$
$$\phi = \frac{\rho_t - \rho_A}{\rho_t} \times 100 \quad (3.7)$$

3.3.6 Mechanical Property Test

Hardness Test

Hardness is the ability of a material to resist deformation, indentation, or scratching. It is a very important characteristic in engineering applications as it indicates a material's ability to withstand wear, friction, and erosion by external factors. The various hardness testing methods available are the Rockwell Hardness Test, Brinell Hardness Test, Vickers Hardness Test, Knoop Hardness Test, and Shore Hardness Test. Among them, in this study, the Vickers hardness test method was used. This method is based on the indentation of a specimen's surface using a diamond indenter in the shape of a square-based 136° pyramid. The test involves applying a specific load to the specimen's surface using a Vickers hardness testing machine (brand name: HVS-50).



(a) Performing test

(b) Test result

Figure 3.10 Vickers hardness test machine while performing test and result

The load was maintained for a predetermined dwell time to ensure proper indentation. The diamond indenter was pressed into the specimen's surface, creating a square-shaped indentation. The load used for hardness test was 10 kgf with 5 seconds a holding time. The indentation size was measured using a microscope or an automated measurement system.

The two diagonals of the indentation were measured, and their average length was used to calculate the Vickers hardness number (HV) using equation 3.7. This test was conducted as per ASTM-B933-16 for all specimens.

The Vickers hardness number is calculated using the formula:

$$HV = \frac{\text{Constant} \times \text{Test force}}{\text{Surface area of indentation}}$$

$$HV = \frac{0.102 \times 2F \left(\sin \frac{136^\circ}{2} \right)}{d^2} \quad (3.8)$$

Where: HV = Vickers hardness number

F = applied load in kilograms-force (kgf)

d = average length of the diagonals of the indentation in millimeters (mm)

Compression Test

Compressive strength of a material is the ability of the material to withstand compressive loading without failure. Compression testing is used to evaluate the compressive strength and mechanical properties. In this study, a compression test was performed using a Universal Testing Machine (UTM) (model: UTN/E-100) as per the ASTM B925–15 standards. This test was conducted by applying the compressive load gradually to the specimen until it failed. The UTM used has a data acquisition system, so test results were analyzed automatically and reported on the screen of the computer-aided UTM.



Figure 3.11 The Universal Testing Machine (UTM) for compression test

3.3.7 Corrosion Test

Corrosion is the gradual deterioration of materials (usually metals) through chemical or electrochemical reaction with their environment. The corrosion testing determines the resistance of materials to corrosion under certain environmental conditions, including temperature, humidity, and salt water. In this study, the corrosion resistance of the specimen was tested by electrochemical technique (using a potentiodynamic polarization device; brand name: SP-300). It was performed by immersing the optimum specimen in a 3.5% NaCl bath for 30 minutes (El-Aziz et al., 2015a). Potentiodynamic polarization involves sweeping the potential of the specimen between anodic and cathodic regions while measuring the resulting current. The data from this test was defined by a curve known as the Tafel curve, which was derived from the Tafel equation.

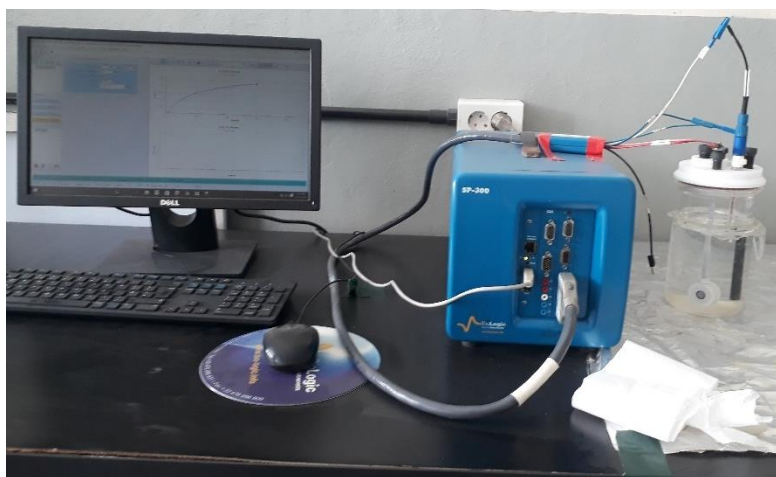


Figure 3.12 Potentiodynamic polarization device used for corrosion test

The Tafel curve describes the relationship between current density and overpotential in electrochemical reactions. It provides information about the corrosion potential (E_{corr}) and corrosion current (I_{corr}), which can be used to assess the corrosion behavior and resistance of the material. Corrosion potential refers to the electrode potential at which anodic and cathodic currents are equal and no net current flows. This potential is an important parameter to determine the corrosion behavior of material. Because the greater the corrosion potential, the lower the likelihood of corrosion. The corrosion current is the current density at the corrosion potential, and it is an important parameter that quantifies the rate of electrochemical reactions occurring on the surface of a corroding material. The lower corrosion current density indicates a slower corrosion rate. The corrosion rate of the optimum composite was computed using the following Stern-Geary equation (Munasir et al., 2019).

$$\text{Corrosion rate (mmpy)} = 0.00327 \times I_{corr} \times \frac{E_w}{d} \quad (3.9)$$

Where: I_{corr} = corrosion current

E_w = equivalent weight (g)

d = density (g/cm³)

3.3.8 Wear Test

Wear is the phenomenon of deformation in the material due to relative motion (like rubbing or impacting) between a surface and contacting substances. When conducting a wear test, several process parameters, such as the applied load, sliding speed, test duration, and presence of lubrication, need to be considered to ensure accurate and meaningful results. In this study, a pin-on-disc (brand name: TR-20-MICRO) wear test technique was conducted as per ASTM G99-23 Standard.



(a) Whole machine setup



(b) Top part of the machine

Figure 3.13 Micro pin on disc tribometer (DUCOM TR-20 Micro model) machine

The wear property of the samples was determined under the test parameter of 30N (S. Liu et al., 2019) applied loads on the 30mm diameter wear truck with a 10 min (Mahan et al., 2023) test duration. And, it was also operated with a sliding speed of 250 rpm (Maryam et al., 2023) at room temperature. Different tribological parameters of samples, such as weight loss, wear rate, coefficient of friction, and volumetric wear rate, were calculated by the equations (3.10), (3.11), (3.12), (3.13), and (3.14) (Patel et al., 2020; Mahan et al., 2023).

$$\Delta W = W_1 - W_2 \quad (3.10)$$

$$W_r = \frac{\Delta W}{S_d}, \Rightarrow S_d = \pi D N T \quad (3.11)$$

$$\mu = \frac{F_f}{P} \quad (3.12)$$

$$V_{loss} = \frac{\Delta W}{\rho_{sample}} \quad (3.13)$$

$$W_v = \frac{V_{loss}}{S_d} \quad (3.14)$$

- Where:
- ΔW = weight loss of the specimen (g)
 - W_1 = initial weight of the specimen (before wear) (g)
 - W_2 = final weight of the specimen (after wear) (g)
 - W_r = wear rate (g/m)
 - W_v = volumetric wear rate (mm³/m)
 - S_d = sliding distance (m)
 - μ = coefficient of friction
 - F_f = force of friction (N)
 - P = applied load (N)
 - V_{loss} = volume loss of the sample (mm³)
 - ρ_{sample} = density of the sample (g/mm³)
 - D = diameter of wear truck (mm)
 - N = sliding speed (rpm)
 - T = test duration (s)

3.3.9 Designs of Experiment for Composite Fabrication

The experiment was carried out on the effects of two input parameters of powder metallurgy technique (such as compaction pressure and sintering temperature) and the weight percentage of reinforcements (B₄C and Ti64). The levels of these parameters (Garg et al., 2016; J. Liu et al., 2019; Haripriya et al., 2021; Brillon et al., 2022; Bharathi & kumar, 2023); Haile et al., 2024) are stated in Table 3.4. The total weight of each sample was four gram

(4g), and the composition of matrix and reinforcements within the sample is illustrated in Table 3.3.

Table 3.4 Powder metallurgy process parameters and their level

Factors	Levels		
	1	2	3
B ₄ C (wt. %)	2	4	6
Ti64 (wt. %)	1	3	5
Compaction pressure (MPa)	50	60	70
Sintering temperature (°C)	550	600	650

Since this study aims to improve the properties of the aluminum, the fabrication of samples was performed by varying the weight percentages of B₄C and Ti64. The minimum and maximum level of boron carbide and titanium grade five was selected based on previous studies.

Table 3.5 Design of experiment based on L₉ orthogonal array

Sample	Reinforcements (RF)		Compacting pressure (CP)	Sintering Temperature (ST)
	B ₄ C (A)	Ti64 (B)		
S ₁	2	1	50	550
S ₂	2	3	60	600
S ₃	2	5	70	650
S ₄	4	1	60	650
S ₅	4	3	70	550
S ₆	4	5	50	600
S ₇	6	1	70	600
S ₈	6	3	50	650
S ₉	6	5	60	550

But MoS₂ was fixed throughout the samples, because according to many literatures, it was reported to be effective only up to 4% (Gonfa et al., 2022). When MoS₂ exceeds the optimal

range (around 4%), wear rates increase and mechanical properties decrease significantly. The excessive weight percentage of MoS₂ within the matrix causes MoS₂ not to adhere well to the matrix, leading to ineffective lubrication during operation (Rani et al., 2017). The Al matrix weight percentage was varied based on the amount of reinforcement within the sample, which means the remaining mass after the mass of reinforcement is calculated, as illustrated in Appendix B.

Designing the experiment for composite fabrication parameters and weight ratio of reinforcements according to the principle of design of experiment (DOE) is imperative to accomplishing the aim of this study. The L₉ orthogonal array design, which is Taguchi-based, was used to randomly design the parameters and their levels using Minitab 21 statistical software. This design is used to obtain the responses of the experiments. Also, it is used to randomly construct combinations of parameters and determine the number of samples. The samples for this research work were manufactured according to the design of the experiment shown in Table 3.5, through PM techniques.

3.3.10 Data Analysis and Optimization Method

In this study data analysis and optimization are crucial to identify the point at which compacting pressure, sintering temperature, and reinforcements weight ratio is effective. The process parameters (such as compacting pressure and sintering temperature) and reinforcement weight ratio were analyzed and optimized using grey relational analysis (GRA), ANOVA, regression modeling, and genetic algorithm (GA) techniques based on the experimental results obtained from physical tests and mechanical tests. The steps to be followed in the genetic algorithm are shown in Figure 3.14.

Grey relational analysis and regression modeling were employed to change the multi-responses (different experimental results) obtained from the experiments carried out according to the Taguchi method design of experiments (Table 3.5) into a multi-objective model. The steps used to implement grey relational analysis are shown below.

Step 1: Change the replicated response data into the S/N (η) ratio (X_i) using the following formulas:

$$\eta = -10 \log \left[\frac{1}{n} \sum_{i=1}^n \frac{1}{X_i^2} \right] \quad (3.15)$$

$$\eta = -10 \log \left[\frac{1}{n} \sum_{i=1}^n X_{ij}^2 \right] \quad (3.16)$$

Where:

η = signal to noise ratio

X_i = the experimental value per trial

n = number of replications

i = number of trials

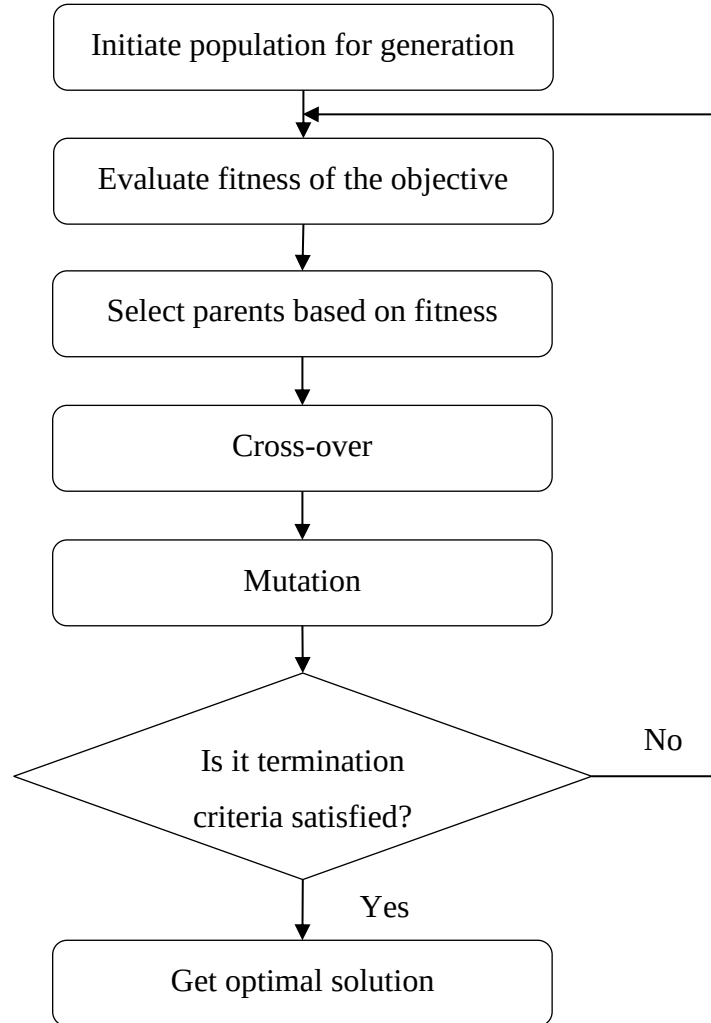


Figure 3.14 Flow chart of Genetic Algorithm (GA) (Albadr et al., 2020)

The hardness experimental results were changed to the S/N ratio by equation 3.15, because it is desired in higher value. The observed density and porosity result data were transformed S/N ratio equation 3.16, because they are desired lower value. The S/N ratio helps quantify how effectively the experimental conditions lead to desirable outcomes while minimizing undesirable variability or noise.

Step 2: Normalize the data in order to eliminate the influence of different measurement units and to ensure that all the data sets are transformed into comparable ranges. After this process, the data values obtained range between 0 and 1.

$$Y_{ij} = \frac{X_{ij} - \min(X_{ij})}{\max(X_{ij}) - \min(X_{ij})} \quad (3.17)$$

$$Y_{ij} = \frac{\max(X_{ij}) - X_{ij}}{\max(X_{ij}) - \min(X_{ij})} \quad (3.18)$$

Where: Y_{ij} = normalized value for i th trial for j th response

X_{ij} = S/N ratio value for i th trial for j th response

i = trial number ($i = 1, 2, \dots, n$)

j = response number ($j = 1, 2, \dots, m$)

Equation 3.17 is used to normalize the S/N ratio of hardness, while equation 3.18 normalizes the S/N ratios of density and porosity.

Step 3: Compute the coefficient of grey relational for the normalized values.

$$\delta_{ij} = \frac{\Delta_{\min} + \gamma \Delta_{\max}}{\Delta_{ij} + \gamma \Delta_{\max}} \quad (3.19)$$

Where: δ_{ij} = grey relational coefficient for the i th trial and j th

Δ = response

$\Delta_{\max}$ = absolute difference between $Y_{\max}$ and Y_{ij}

$\Delta_{\min}$ = maximum value of Δ

$Y_{\max}$ = minimum value of Δ

γ = maximum value of normalized S/N ratio

distinguishing coefficient which is defined in the range

$$0 \leq \gamma \leq 1$$

Step 4: Calculate the grey relational grade (β_i).

$$\beta_i = \frac{1}{m} \sum \delta_{ij} \quad (3.20)$$

where m = number of responses

Step 5: Use regression modeling and a genetic algorithm to obtain the optimum level based on the maximum average β_{ij} value.

A regression model is used to create a mathematical model based on input parameters (CP, ST, and RF) and the grey relational grades associated with the experimental response result. The precision and adequacy of regression modeling was determined ANOVA. The developed multi-objective model was optimized by a genetic algorithm (GA) in order to determine the best set of weight percentages of reinforcements and powder metallurgy process parameters.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

The objective of this study was to develop a novel hybrid composite material by incorporating boron carbide (B_4C), titanium grade 5 (Ti64), and molybdenum disulfide into the Al metal matrix. The composite was fabricated using a powder metallurgy technique by varying the reinforcement concentration (B_4C and Ti64) and powder metallurgy process parameters (compacting pressure and sintering temperature). To obtain the composite with the best properties among the fabricated samples, its composition and process parameters were optimized. The composite microstructure and the phase it contains were analyzed. In addition, physical, mechanical, and tribological properties were investigated.

4.2 Experimental Results and Discussion

In this section, all experimental results were discussed in detail with graphs and tables.

4.2.1 Density of Al- B_4C -Ti64-MoS₂ composite

The density of the developed composite samples was determined using the Archimedes method as per ASTM B962-23. The weights of nine samples, which have three trials, were measured, and their densities were computed using equation 3.2, as tabulated in 4.1.

Table 4.1 Experimental density of Al- B_4C -Ti64-MoS₂ composite

Sample	Density (g/cm ³)			Average Density	St. Dev
	1	2	3		
S ₁	2.536	2.555	2.562	2.551	0.014
S ₂	2.635	2.603	2.595	2.611	0.021
S ₃	2.700	2.717	2.645	2.687	0.038
S ₄	2.663	2.631	2.684	2.659	0.027
S ₅	2.554	2.580	2.564	2.566	0.013
S ₆	2.519	2.547	2.537	2.534	0.014
S ₇	2.583	2.603	2.606	2.597	0.013
S ₈	2.496	2.522	2.492	2.504	0.016
S ₉	2.514	2.490	2.471	2.491	0.021

Figure 4.1 illustrates the interrelationship of process parameters (CP and ST) and the weight percentages of reinforcements with the average actual density. According to the rule of mixture theory (equation 3.6), adding Ti64 and MoS₂ to the aluminum matrix increases the theoretical density of the aluminum hybrid metal matrix composite because their densities are higher than aluminum's. But the actual density depends upon the sintering condition, compacting pressure, and the properties of reinforcements.

As shown in Figure 4.1, increasing the weight percentage of boron carbide (B₄C) and titanium grade 5 (Ti64) particles reduced the density of the developed aluminum hybrid composite. As stated in the literature (Nayak et al., 2022; A. Kumar et al., 2020), this could be due to their hard and non-deforming properties, which limit deformation during compaction. Furthermore, Vani & Chak, (2018) discovered that as the reinforcement weight percentage increases, the inter-particle spacing increases, resulting in less effective packing and increased voids, lowering the composite's density.

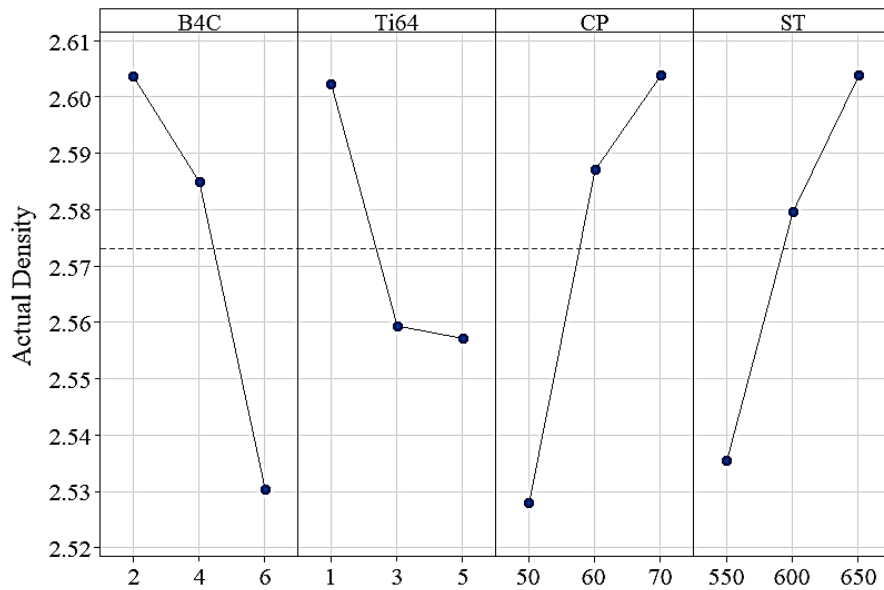


Figure 4.1 The effect of process parameters and reinforcements on density

On the other hand, it was observed from the graph that the actual density increased with increasing sintering temperature and compaction pressure. The increasing sintering temperature increases atomic diffusion within the composite, which results in particle rearrangement and enhancement of interfacial bonding. So higher sintering temperatures enable the composite to be more densified. Moreover, increasing compaction pressures improve particle packing and reduce inter-particle space (voids). According to Yuan et al.

(2021) findings, when powders are well packed and porosity content is reduced, the mechanical properties of the green compact improve.

Table 4.2 Response table for signal to noise ratios of density

Level	B ₄ C	Ti64	CP	ST
1	-8.311	-8.306	-8.055	-8.081
2	-8.247	-8.162	-8.253	-8.230
3	-8.062	-8.152	-8.312	-8.309
Delta	0.249	0.154	0.256	0.228
Rank	2	4	1	3

The S/N ratio response table reveals the extent to which process parameters and reinforcement can affect the density, as shown in Table 4.2. The compaction pressure was the most influential parameter affecting the density of the developed composite. Compaction pressures significantly increase density while decreasing porosity. Next to compaction pressure, boron carbide was the most influential factor, indicating that increasing its volume fraction reduces the overall density of the composite. This is due to boron carbide's naturally low density. Sintering temperature and titanium grade 5 have a lower impact than compaction pressure and boron carbide.

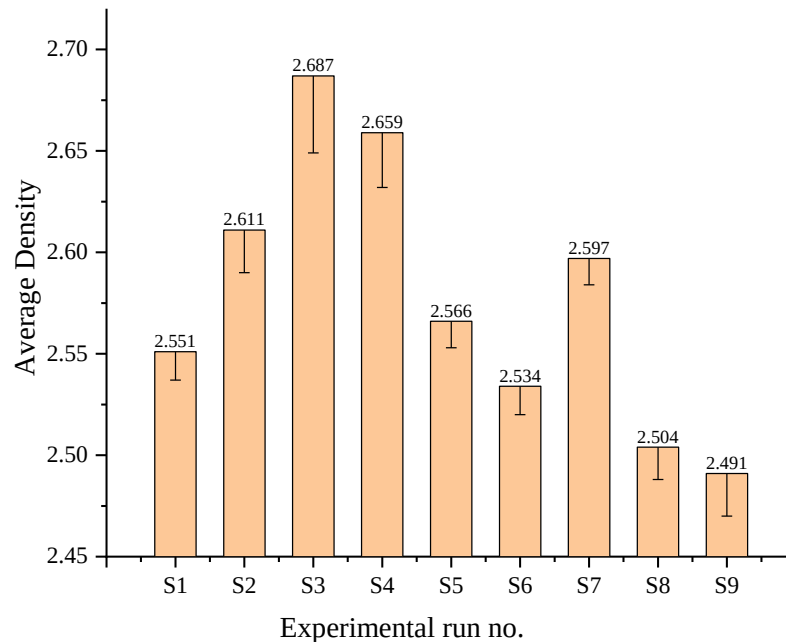


Figure 4.2 Experimental density of Al-B₄C-Ti64-MoS₂ composite

As illustrated in Figure 4.2, the density of the composite increased up to sample three (S₃) in a direct proportion to the Ti64 reinforcement, sintering temperature, and compaction

pressure. However, after three sample (S_3), it decreased as either pressure or temperature decreased sequentially. According to the graph in Figure 4.2, sample four (S_3) had the highest density. It was produced at a higher temperature (650 °C) and high pressure (70 MPa). Compared to S_9 , the density of S_1 was higher. Despite the higher reinforcement content, S_9 was produced at lower compaction pressures and sintering temperatures. So, its porosity was higher, resulting in a lower density. In their study, L. K. Singh et al. (2018) and Sadat Hamzah et al. (2023) reported that increasing reinforcement content, decreasing sintering temperature, and decreasing compaction pressure reduces composite density.

4.2.2 Porosity of Al-B₄C-Ti64-MoS₂ composite

The porosity of fabricated composite samples was analyzed using the Archimedes technique. It was calculated from theoretical density and experimental density using equation 3.7, as illustrated in Table 4.3. Figure 4.3 shows how process parameters and reinforcements affect porosity. The porosity of the Al-B₄C-Ti64-MoS₂ composite increased with the reinforcement weight percentage (volume fraction). Similarly, Arif et al. (2017) demonstrated that a higher volume fraction of reinforcements can increase porosity. Because it increases the likelihood of improper packing and void formation.

Table 4.3 Porosity of the Al-B₄C-Ti64-MoS₂ composite

Sample	Porosity (%)			Average Porosity	St. Dev
	1	2	3		
S_1	9.700	9.001	8.759	9.153	0.489
S_2	7.299	8.448	8.723	8.157	0.756
S_3	6.167	5.561	8.075	6.601	1.312
S_4	5.040	6.193	4.300	5.178	0.954
S_5	10.047	9.114	9.689	9.617	0.471
S_6	12.340	11.381	11.706	11.809	0.488
S_7	7.796	7.077	6.949	7.274	0.456
S_8	11.968	11.047	12.097	11.704	0.573
S_9	12.416	13.260	13.899	13.192	0.744

However, as the sintering temperature and compaction pressure increased, the porosity of the fabricated composites decreased. Yuan et al. (2021) observed a similar behavior, noting that high sintering temperatures increase atom diffusion, allowing particles to move closer together and fill voids. Furthermore, this observation is consistent with the findings of X.

Liu & Chen. (2016), who reported that higher compaction pressure reduces inter-particle spaces by forcing particles closer together.

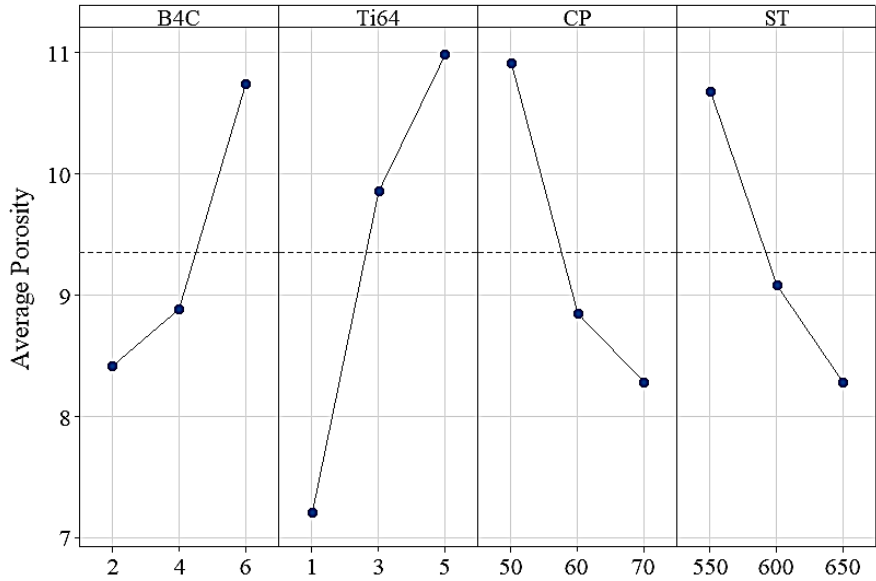


Figure 4.3 Porosity versus reinforcement and process parameters for each sample

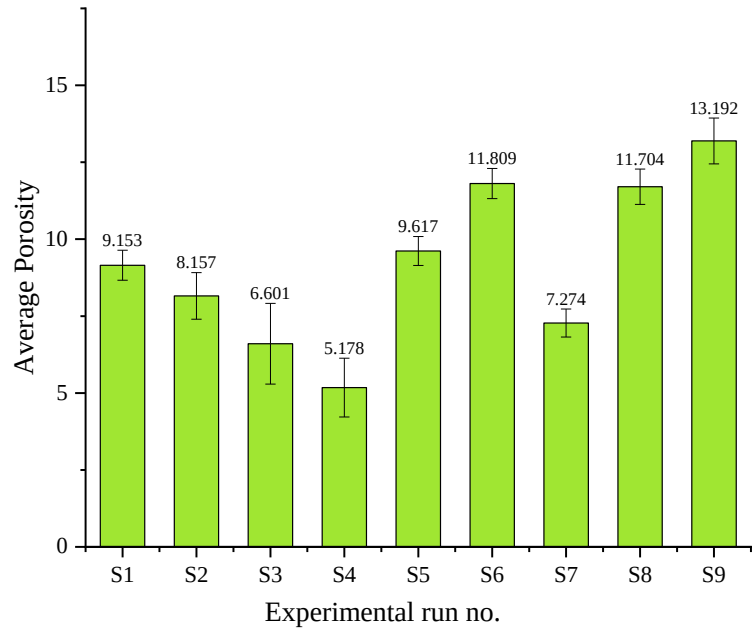


Figure 4.4 Percentage of porosity within Al-B₄C-Ti64-MoS₂ composite

Figure 4.4 shows the percentage of porosity within fabricated composite samples. It reveals that porosity and density have an inverse relationship. As previously stated, the density increased from S₁ to S₃. In this section, it was observed that the porosity of the composite decreases from S₁ to S₄ as the sintering temperature and compaction pressure increase. Sample four had the lowest porosity, produced at 60 MPa compaction pressure and 650 °C

sintering temperature from Al/4% B₄C/1% Ti64/4% MoS₂. In S₅ and S₆, the percentage of porosity increased as sintering temperature and compaction pressure decreased in turn. However, the seventh sample (S₇) has a low porosity percentage next to sample three (S₃) because it was produced at high pressure and moderate temperature. The eighth sample (S₈) had an increased percentage of porosity due to it being compacted by lower pressure, while the percentage of reinforcements was higher. The ninth sample (S₉) had the highest percentage of porosity because it was produced at moderate pressure and low temperature, while there was the highest percentage of reinforcements.

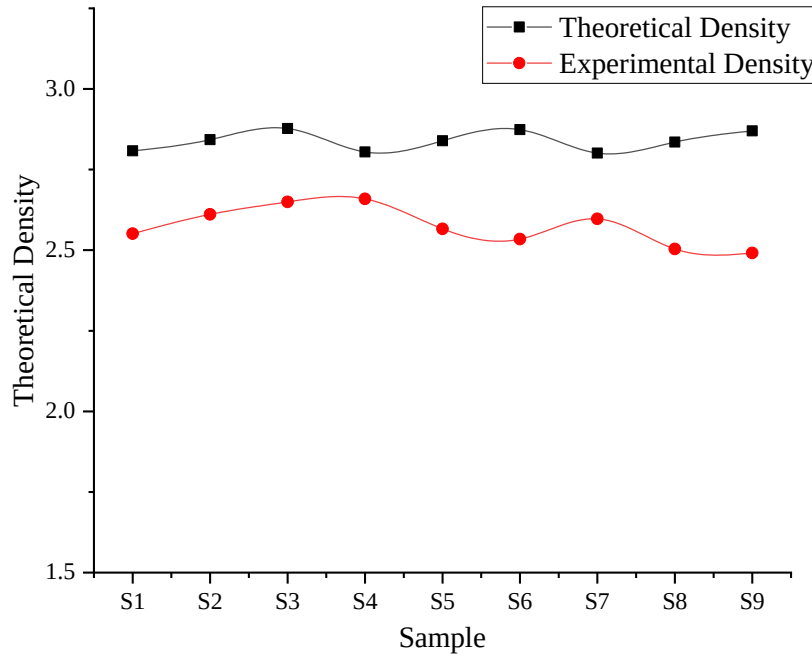


Figure 4.5 Theoretical and experimental density of Al-B₄C-Ti64-MoS₂ composite

Figure 4.5 depicts the effect of decreasing or increasing the difference between theoretical and experimental densities on porosity. When the difference between experimental and theoretical density was large, there was a high percent of porosity within the composite. However, as the difference between them decreased, the percent of porosity also decreased. As a result of the small difference in theoretical and experimental density, sample four had the lowest porosity (5.178 %).

4.2.3 Hardness of Al-B₄C-Ti64-MoS₂ composite

The hardness of the Al-B₄C-Ti64-MoS₂ composite was tested using a Vickers hardness tester. Hardness tests were carried out on the composite specimen's surface in three different locations. The hardness values that were taken from the Vickers hardness test are presented in Table 4.4. The effect of process parameters and reinforcement weight percentage on the

hardness is clarified in Figure 4.6. It was observed that the hardness of the composite increased with increasing sintering temperature and compaction pressure.

Table 4.4 Experimental hardness values of Al-B₄C-Ti64-MoS₂ composite

Sample	Vickers Hardness (HV)			Average	St. Dev
	1	2	3		
S ₁	146.5	148.6	147.3	147.5	1.1
S ₂	193.7	192.5	194.8	193.7	1.2
S ₃	214.8	212.6	213.7	213.7	1.1
S ₄	206.9	205	204.4	205.4	1.3
S ₅	208.5	210.6	208.4	209.2	1.2
S ₆	173.5	175.1	172.9	173.8	1.1
S ₇	217.1	216.6	218.4	217.4	0.9
S ₈	193.5	192.8	195.5	193.9	1.4
S ₉	154.4	157.2	158.1	156.6	1.9

According to Choudhury et al. (2021) report the interfacial bonds of powder particles in the composite increased significantly as the sintering temperature increased due to improved particle diffusion, this directly contributes to higher hardness values. In Meignanamoorthy et al. (2021) study it was reported that increased compaction pressure also improves powder particle packing, resulting in fewer voids and better particle contact, which leads to higher hardness after sintering.

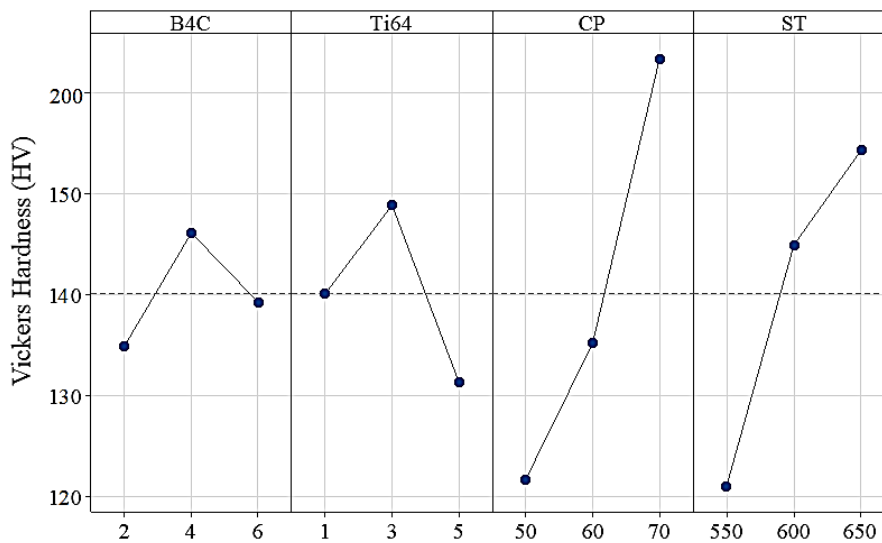


Figure 4.6 The effect of PM process parameters and reinforcement on hardness

However, when the reinforcements were taken into account, it was discovered that the composite's hardness was lowest at the highest reinforcement weight percentage. This was due to the fact that a composite with 5 wt.% Ti64 or 6 wt.% B₄C was sintered only once at high temperature and pressure. This refers to sample one (S₃) and seven (S₇), which have higher hardness. This revealed that when the reinforcement content is higher and the sintering temperature and compacting pressure are low or moderate, the porosity in the composite increases while the hardness decreases.

Figure 4.7 shows that as the weight percentage of Ti64, sintering temperature, and compaction pressure increased concurrently, i.e., from sample one (S₁) to sample three (S₃), the hardness of the composite increased significantly. The hardness of the fourth sample (S₄) is lower than that of the third sample. This suggests that it is most likely caused by a lower compaction pressure or a lower Ti64 weight percentage.

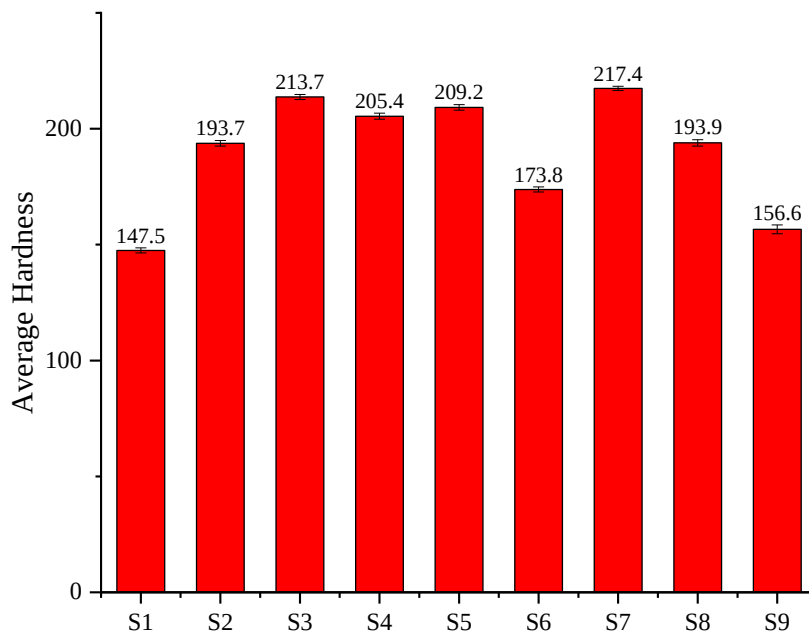


Figure 4.7 Average hardness versus change in process parameter value and reinforcement

The fourth sample was smaller than the third but larger than the second. This indicates that the hardness increased as the weight percentage of B₄C increased. Next to the first (S₁) and ninth (S₉) samples, the sixth sample (S₆) has the lowest hardness. The reinforcements in this sample were larger but compacted under lower pressure, resulting in increased porosity and lower hardness. The sixth (S₆) and eighth (S₈) samples were compacted at the same pressure, but the sintering temperature and B₄C percentage of the eighth sample were higher than that of the sixth. Therefore, increasing the sintering temperature and B₄C content of the eighth sample increased the hardness. The first and ninth samples were sintered at the same

temperature, but the ninth sample had a higher hardness due to the increased reinforcement content and compacting pressure. However, the ninth sample has lower hardness than the other samples. This demonstrates that increasing the content of reinforcements is not the only way to increase hardness, but also by increasing the sintering temperature and compacting pressure.

4.2.4 Compression Strength of Al-B₄C-Ti64-MoS₂ composite

The compression strength test was performed on the sample produced at optimum level using UTM following ASTM Standard B925-15. The graph of applied load versus displacement during this test is shown in Figure 4.8. The obtained maximum compressive strength was 708.127 MPa, and this value demonstrates that the addition of reinforcements (B₄C, Ti64, and MoS₂) improves the ability of the aluminum to withstand compressive loads without failure.

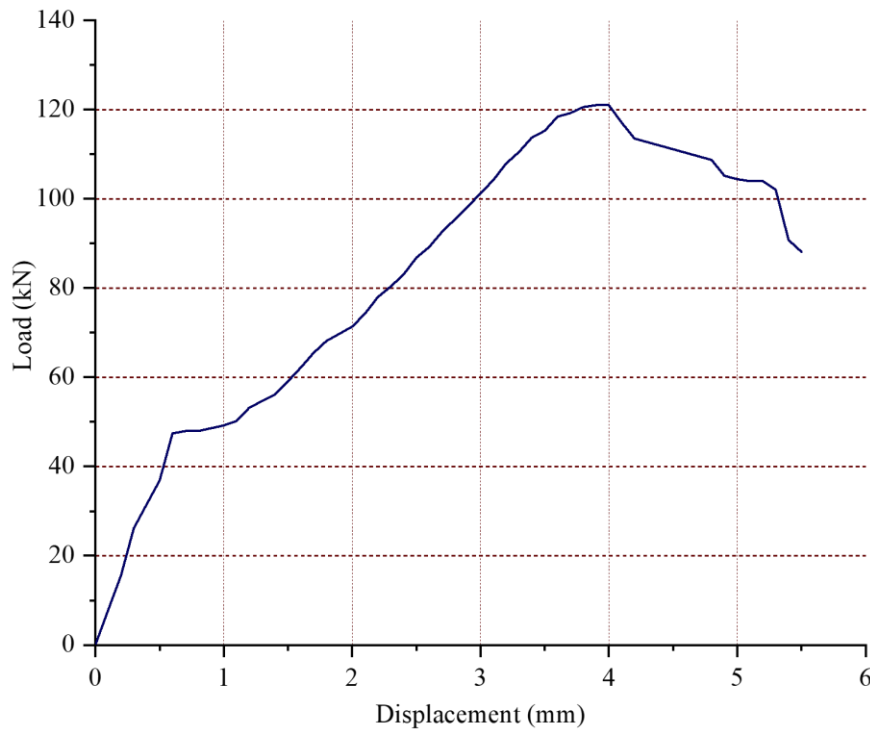


Figure 4.8 Load-displacement graph of Al-B₄C-Ti64-MoS₂ composite

Similarly, Xavier & Suresh. (2016) found that the presence of harder reinforcing particles acts as a barrier to crack propagation within the matrix, increasing durability and resistance to failure. Also, Prakash et al. (2024) reported that adding higher compressive strength reinforcement compared to the matrix material tends to enhance the compressive strength of the composite.

4.2.5 Wear Rate and Coefficient of friction of Al-B₄C-Ti64-MoS₂ composite

The wear resistance of the Al-B₄C-Ti64-MoS₂ composite was examined by the pin-on-disc wear testing method, which has a data acquisition system. It was conducted at room temperature without any lubricating of the sample. In this study, different samples were manufactured by changing the percentage of reinforcements and value of the powder metallurgy process parameter (compacting pressure and sintering temperature), but the wear test was carried out on a monolithic Al metal sample and the sample that was manufactured at the optimum level. Since initially the sample was made at 16 mm diameter and 14 mm length, it was decreased to the required size, 6 mm diameter and 12 mm length, on the lathe machine. The surface of the sample was polished to enhance the quality of the results.

Table 4.5 Experimental wear rate, volumetric wear rate, and coefficient of friction

Sample	Wear rate (g/m)	Volumetric wear rate (mm ³ /m)	Coefficient of friction
Pure Al	8.49×10^{-6}	3.23×10^{-3}	0.4
Al-6%B ₄ C-5%Ti64-4%MoS ₂	5.94×10^{-6}	2.30×10^{-3}	0.31

The wear rate, volumetric wear rate, and coefficient of friction, which were computed based on the experimental result using equations (3.11), (3.12), and (3.14), respectively, are tabulated in Table 4.5. The test results in this table show that the produced Al-6%B₄C-5%Ti64-4%MoS₂ composite experienced a lower wear rate and coefficient of friction than monolithic aluminum. Statistically, the wear rate, volumetric wear rate, and coefficient of friction of the Al/6%B₄C/5%Ti64/4%MoS₂ sample were decreased by 30%, 29%, and 22.5%, respectively, when compared with a monolithic Al sample. This result aligns with findings from a previous study (Aktar Zahid Sohag et al., 2020) that the observed wear rate reduction and coefficient of friction could be attributed to the strong interfacial bonding between the reinforcement and matrix.

Also, it was reported in the S. Liu et al. (2019) study that the addition of B₄C and MoS₂ to the aluminum metal matrix could decrease the wear rate. Furthermore, because titanium alloys have a higher wear resistance than pure aluminum, Ti64 may contribute to an increase in the wear resistance of the aluminum metal matrix. Similarly, J. Singh & Chauhan (2016) found that adding higher wear resistance particles to lower wear resistance materials

improves composite wear resistance. Figure 4.9 depicts the variation of the wear rate of the sample over time after running a 235 m sliding distance at 250 rpm and a 30N applied load. This graph shows that incorporating B₄C, Ti64, and MoS₂ improves the wear rate of aluminum.

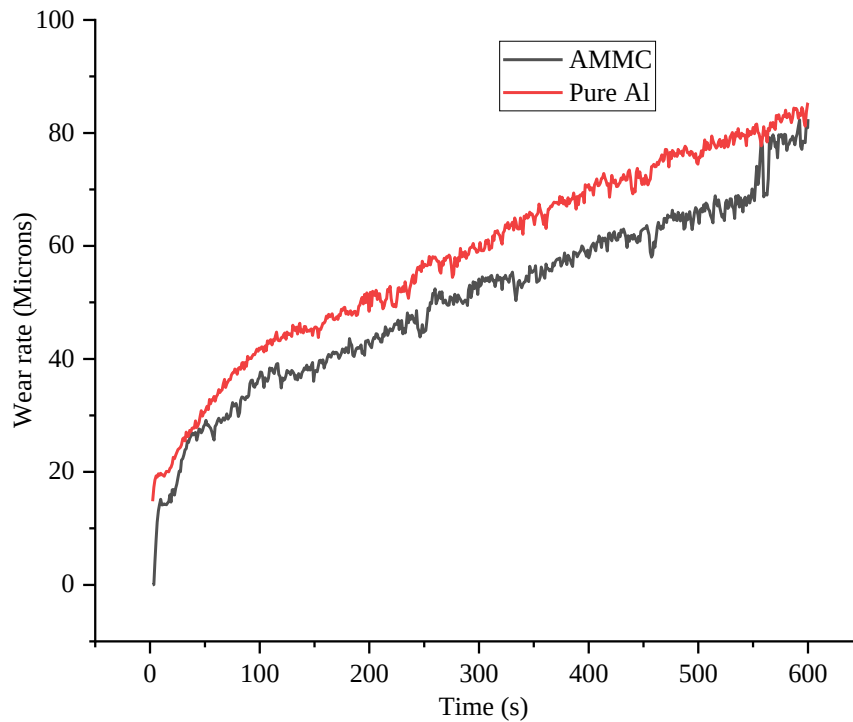


Figure 4.9 Variation of wear rate versus time

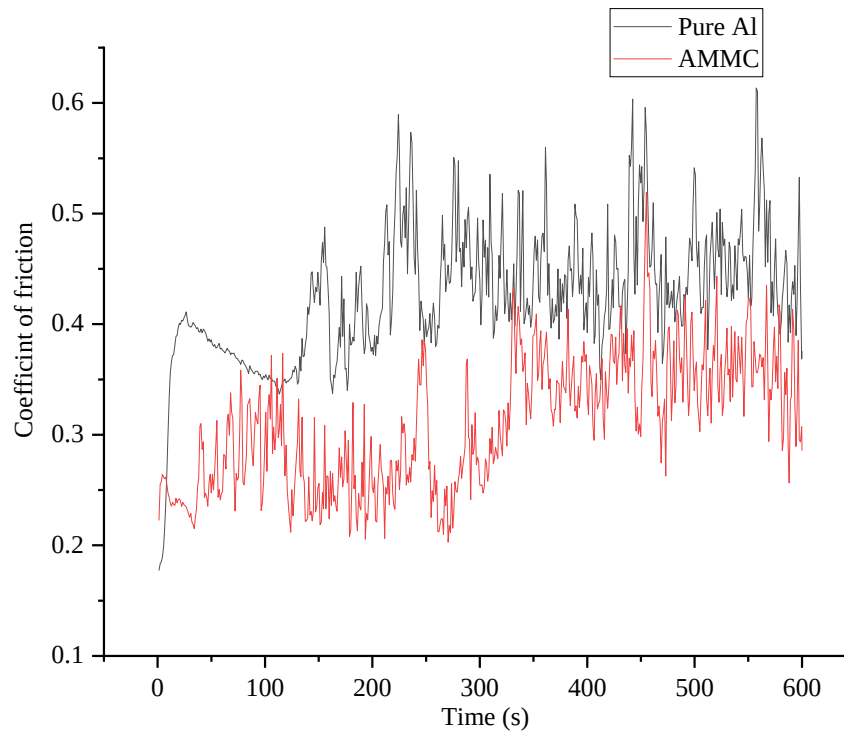


Figure 4.10 Variation of coefficient of friction versus time

Figure 4.10 depicts the change in the coefficient of friction between Al-6%B₄C-5%Ti64-4%MoS₂ and pure Al samples over time. The coefficient of friction graph showed a sinusoidal wave pattern, which could be attributed to the cyclical formation and removal of material from the pin onto the disc surface. It was also reported similarly in Xavier & Suresh (2016) study.

4.2.6 Corrosion Resistance of Al-B₄C-Ti64-MoS₂ Composite

Figure 4.11 depicts the Tafel curves for pure Al and the optimal Al/B₄C/Ti64/MoS₂ hybrid composite. In comparison to the pure Al sample, the optimum sample curve was shifted upward. As reported in Pi et al. (2024) study, this implies that aluminum hybrid composites have higher corrosion resistance than pure aluminum. The corrosion current densities (I_{corr}) and corrosion potentials (E_{corr}) of optimum hybrid composite and pure aluminum, which were analyzed by Origin software, are presented in Table 4.6.

Table 4.6 Experiment result of electrochemical technique tested corrosion

Sample	E_{corr} (V)	I_{corr} ($\mu\text{A}/\text{cm}^2$)	Corrosion rate (mmpy)
Pure (Al)	-0.809	-0.862	0.0033
Composite (AMMC)	-0.768	-1.267	0.0017

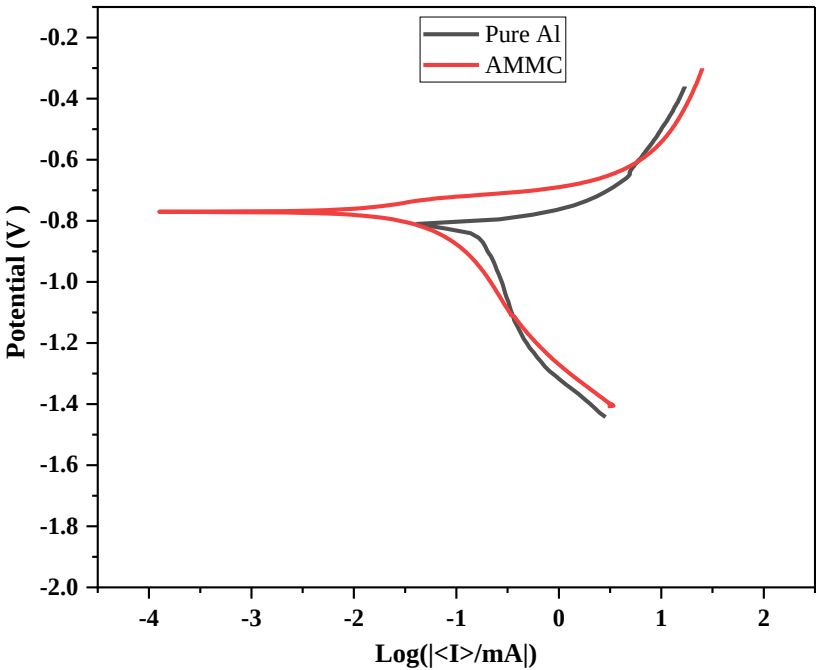


Figure 4.11 Tafel curves of AMMC (Al/B₄C/Ti64/MoS₂) composite and pure Al

Due to the corrosion potential of optimum sample being greater than that of the pure Al sample, it has a lower possibility of corrosion. Also, the corrosion current density of the optimum sample was lower than that of the pure Al sample, and this indicates the corrosion rate of the optimum sample was slower than that of pure Al. Furthermore, the corrosion rate result calculated using equation 3.9 revealed that the optimum sample had a lower corrosion rate than the pure aluminum sample. According to Meignanamoorthy et al. (2021), adding hard particulate acts as a physical protector, reducing the actuation rate and rate of development for pitting corrosion.

4.3 Optimization Process

The optimization of fabrication process parameters and weight percentages of reinforcements to enhance the physical, mechanical, and tribological properties of Al-B₄C-Ti64-MoS₂ hybrid composites produced through powder metallurgy was outlined under this section. The objective of this optimization process was to maximize the density, hardness, and compression strength of the sintered specimens while minimizing porosity. To optimize the fabrication process parameters and reinforcement weight percentages, grey relational analysis (GRA), ANOVA, regression modeling, and genetic algorithm (GA) techniques were employed. GA was chosen for this study because it outperforms other algorithms by maintaining a diverse population of solutions, allowing for simultaneous exploration of multiple regions of the solution space. The Taguchi method, which is effective in analyzing multiple factors simultaneously, was used to establish experimental design. The parameters considered were compacting pressure (50, 60, and 70MPa), sintering temperature (550, 600, and 650°C), boron carbide (2, 4, and 6 wt.%), and titanium grade 5 (1, 3, and 5 wt.%).

4.3.1 Applying Grey Relational Analysis

In this study, density, porosity, hardness, and compressive strength responses were obtained from experiments conducted using an L₉ orthogonal array. These responses were analyzed following the GRA steps outlined in Chapter 3. As the Al-B₄C-Ti64-MoS₂ hybrid composite with high hardness was desired, the higher-the-better criteria (equation 3.15) was applied to convert the hardness response data into the S/N ratio. Because the density and amount of porosity in the composite are required to be small, the lower-the-better criteria (equation 3.16) was used to convert the density and porosity response data into the S/N ratio. The transformed density, hardness, and porosity response data into the S/N ratio are presented in Table 4.7.

Table 4.7 S/N ratio of experimental responses

Samples	S/N Ratio		
	Density (ρ)	Porosity (ϕ)	Hardness (HV)
S ₁	-8.13	-19.24	43.37
S ₂	-8.34	-18.25	45.74
S ₃	-8.59	-16.51	46.60
S ₄	-8.50	-14.38	46.25
S ₅	-8.19	-19.67	46.41
S ₆	-8.08	-21.45	44.80
S ₇	-8.29	-17.25	46.74
S ₈	-7.97	-21.37	45.75
S ₉	-7.93	-22.42	43.89

The next step in Grey Relational Analysis is normalization of S/N values to allow for a fair comparison between different experimental factors. This ensures that the analysis is not skewed by the scale or units of the original measurements. The S/N values of hardness as normalized by using equation 3.17 and density and porosity were normalized by using equation 3.18 as tabulated in Table 4.8.

After the S/N ratio was normalized, the grey relation coefficient (δ_{ij}) was calculated using equation 3.19. In situations where multiple factors need to be evaluated simultaneously, the grey relational coefficient allows for a comprehensive comparison of alternatives based on normalized data. This facilitates the identification of the best option among various choices. At the end, the grey relational grade (β_{ij}) was computed using equation 3.20 to summarize the overall performance of different experimental conditions. The grey relational grade enables the integration of various parameters' performance into a single value, thereby facilitating decision-making across various criteria. The calculated normalized S/N ratio, grey relational coefficient (δ_{ij}), and grey relational grade (β_{ij}) are shown in Table 4.8.

Table 4.8 Normalized S/N ratio, grey relational coefficient and grey relational grade values

Samples	Normalized S/N ratio (Y_{ij})			Grey relational coefficient (δ_{ij})			Grey relational grade (β_{ij})
	P	ϕ	HV	P	ϕ	HV	
S ₁	0.312	0.605	0.000	0.421	0.559	0.333	0.438
S ₂	0.618	0.482	0.702	0.567	0.491	0.627	0.562
S ₃	1.000	0.264	0.956	1.000	0.405	0.919	0.775
S ₄	0.861	0.000	0.854	0.782	0.333	0.775	0.630
S ₅	0.389	0.658	0.901	0.450	0.594	0.835	0.626
S ₆	0.225	0.880	0.424	0.392	0.806	0.465	0.554
S ₇	0.548	0.357	1.000	0.525	0.437	1.000	0.654
S ₈	0.064	0.870	0.706	0.348	0.794	0.630	0.591
S ₉	0.000	1.000	0.154	0.333	1.000	0.371	0.568

4.3.2 ANOVA for Grey Relational Grade

In this study, the ANOVA method was used to determine which controllable parameters (B₄C wt.%, Ti64 wt.%, ST, and CP) have a significant effect on grey relational grade, or it was used to determine the percent contribution of process parameters. This is accomplished by summing all the sum of squares terms (Adj SS) and then taking each individual Adj SS and dividing it by the total Adj SS and multiplying by 100. The percentage contribution of each process parameter (B₄C wt.%, Ti64 wt.%, ST, and CP) to the total sum of squared deviations was used to assess the impact of a controllable parameter change on grey relational grade. The results of ANOVA for the grey relational grade values, which were computed by MINITAB software, are shown in Table 4.9. The results indicate that the percentage contributions of the compaction pressure, sintering temperature, titanium grade 5 wt.%, and boron carbide wt.% are 56.24%, 33.45%, 7.73%, and 0.37%, respectively. Compaction pressure and sintering temperature significantly influenced the grey relational grade, and compaction pressure is the most significant parameter for porosity, density, and hardness of the composite.

Table 4.9 Analysis of Variance (ANOVA) result

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Regression	4	0.064558	0.016140	44.00	0.001	
B ₄ C	1	0.000241	0.000241	0.66	0.463	0.37
Ti64	1	0.005104	0.005104	13.91	0.020	7.73
CP	1	0.037131	0.037131	101.22	0.001	56.24
ST	1	0.022083	0.022083	60.20	0.001	33.45
Error	4	0.001467	0.000367			
Total	8	0.066026				

4.3.3 Regression Analysis and ANOVA

In this study, the regression model (equation 4.1) was developed using MINITAB software based on the GRA data given in Table 4.8. The independent variables in equation 4.1 are weight percentage of B₄C (A), weight percentage of Ti64 (B), compaction pressure (CP), and sintering temperature (ST).

$$\beta_{ij} = -0.656 + 0.00327 A + 0.0146 B + 0.00788 CP + 0.00121 ST \quad (4.1)$$

Analysis of variance (ANOVA) analysis has been carried out to determine the significance of regression modeling. The results of ANOVA for the regression model have been presented in Table 4.9. Based on the statistical analysis results, the model's coefficient of determination, R-sq(adj), was 95.6%, as shown in Table 4.10. This demonstrates that the model was an appropriate fit for the data. The regression model's p-value was also close to zero, indicating that the model performs significantly better than the 0.95 confidence level.

Table 4.10 Summary of regression model

S	R-sq	R-sq(adj)
0.0191596	97.8%	95.6%

These show that the model is properly aligned with the actual test results. The normal probability plot of gray relational grade is shown in Figure 4.12. The points on the plot were approximately normally distributed; this indicates that the regression model was valid.

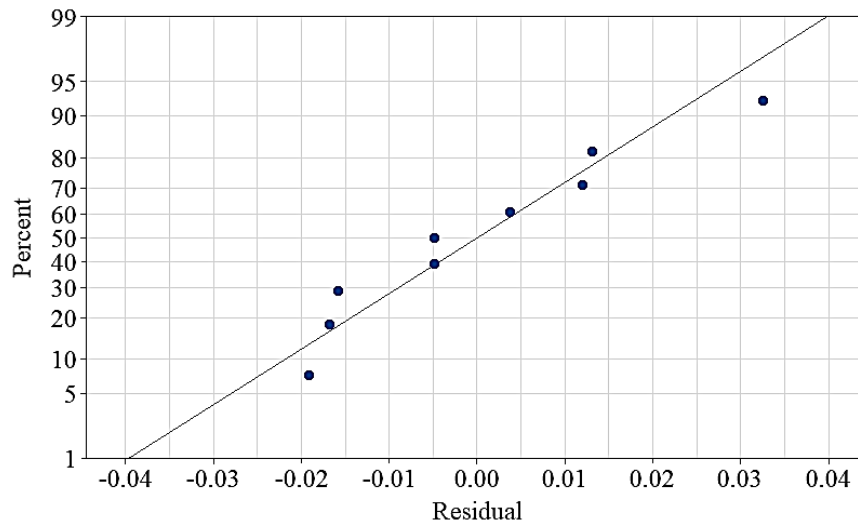


Figure 4.12 Normal probability plot

4.3.4 Multi-Response Optimization

This study employs a genetic algorithm (GA) to identify the optimal set of process parameters and the weight percentage of reinforcement. The MATLAB software was used to obtain the optimum value. In the genetic algorithm program, equation (4.1) was used as an objective function. The optimum value of grey relational grade, which was found by a genetic algorithm on MATLAB software, was 0.70802, and the corresponding process parameters and reinforcement weight percentages were:

$B_4C = 6 \text{ wt. } \%$; $Ti64 = 5 \text{ wt. } \%$; $ST = 650 \text{ } ^\circ\text{C}$; $CP = 70 \text{ MPa}$

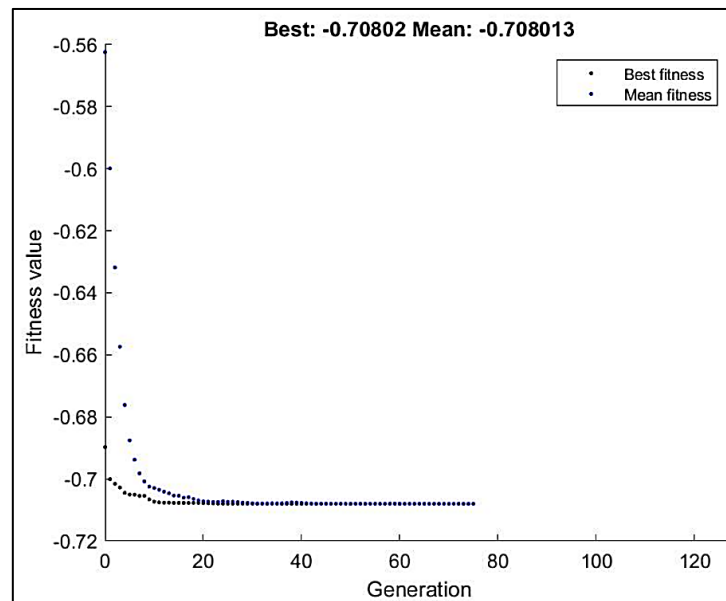


Figure 4.13 Optimization by genetic algorithm

4.3.5 Confirmation Test on Sample Fabricated at Optimum Level

The confirmation test was carried out on the sample that was manufactured under optimal conditions. This test was carried out to see if samples processed at the optimal level performed better than previously processed samples. The optimized process parameter was 650 °C sintering temperature and 70 MPa compacting pressure, and the optimized weight percentages of reinforcements were 6 wt.% of B₄C and 5 wt.% of Ti64. Because the optimization process was based on experimental density, porosity, and hardness results, the optimum level sample was subjected to density, porosity, and hardness confirmation testing. Three samples were tested, and their average value is presented in Table 4.11.

Table 4.11 Experimental result of confirmation test

Trial	Density (ρ)	Porosity (ϕ)	Hardness (HV)
1	2.733	4.761	211.5
2	2.714	5.439	230.0
3	2.742	4.473	225.5
Average	2.730	4.891	222.33

The obtained experimental values indicated an improvement in density, porosity, and hardness. When compared to the previous result, the percentage porosity of the composite was reduced. However, the density of the optimum sample was increased.

4.4 Comparison of this Study's Findings with Published Research Papers

In this section, the physical, mechanical, and tribological properties of the aluminum hybrid metal matrix composite developed in this study were compared to previous aluminum metal matrix composites developed by researchers, as shown in Table 4.12.

Table 4.12 Comparison of optimum composite properties with previous study

Properties	Previous study	Present study
Hardness (HV)	208 (Gonfa et al. (2022)	222.33
Compression strength (MPa)	700 (S. Liu et al., 2019)	708.127
Corrosion rate	0.0199 (El-Aziz et al., 2015)	0.0017
Wear rate	0.0387 (S. Liu et al., 2019)	0.0014
Coefficient of friction	0.49 (S. Liu et al., 2019)	0.31

4.5 Microstructural Analysis

4.5.1 Optical Microscope (OM) Analysis

The sample, produced at an optimal level, underwent an optical microscope test to analyze the distribution of reinforcements within the base metal. OM provides a comprehensive view of the sample's structure. Figure 4.14 shows the OM micrograph of the optimum sample at different magnification levels. These Figures reveal that the reinforcement particles were uniformly distributed throughout the base metal. Therefore, the mixing time taken, speed of mixer, and mixing method employed to mix the reinforcements and base metal were effective. The Ti64 reinforcement particle size was larger than the others, so it was more visible within the composite. The shape, micro-size, and color of boron carbide and molybdenum disulfide were almost similar, making their dispersion in the composite difficult to distinguish. Nonetheless, they were clearly evenly distributed throughout the composite.

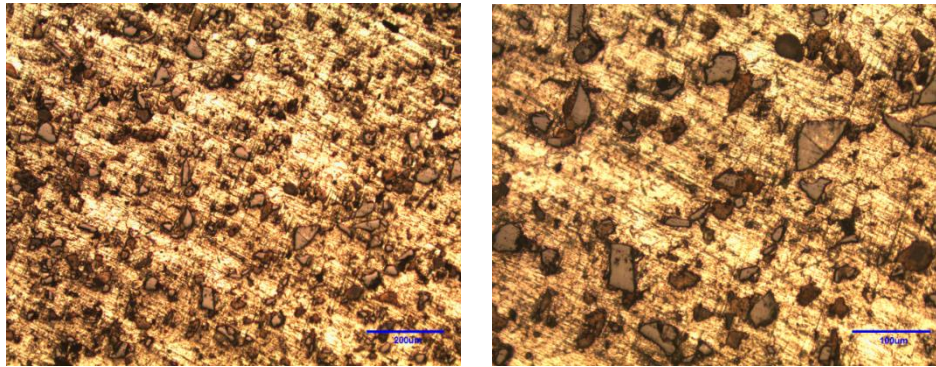


Figure 4.14 Al/6%B₄C/5%Ti64/4%MoS₂ composite micrograph of OM

4.5.2 Scanning Electron Microscopy (SEM) Analysis

Similar to OM analysis, SEM analysis was performed on an optimum sample in order to provide complementary information about the sample's surface morphology. SEM provides detailed surface topography, allowing for the observation of nanometer-sized features that OM cannot. The surface morphology of the optimum sample (Al/6%B₄C/5%Ti64/4% MoS₂ composite), which was scanned by SEM at various magnification levels, is shown in Figure 4.15. As shown in Figure 4.15, the reinforcements (B₄C, Ti64, and MoS₂) were uniformly dispersed in the Al-matrix hybrid composite. Surface micrographs scanned by SEM can also detect the presence of micro-holes and grooves. In Figure 4.15, the sample's micro-holes (porosity) and grooves formed during surface preparation were shown.

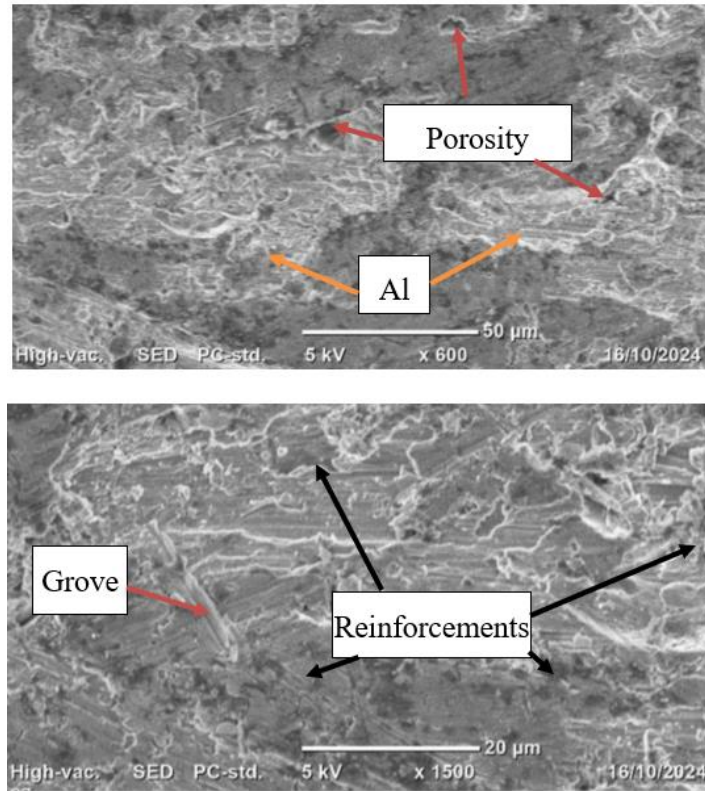


Figure 4.15 Al/6%B₄C/5%Ti64/4%MoS₂ composite micro graph of SEM analysis

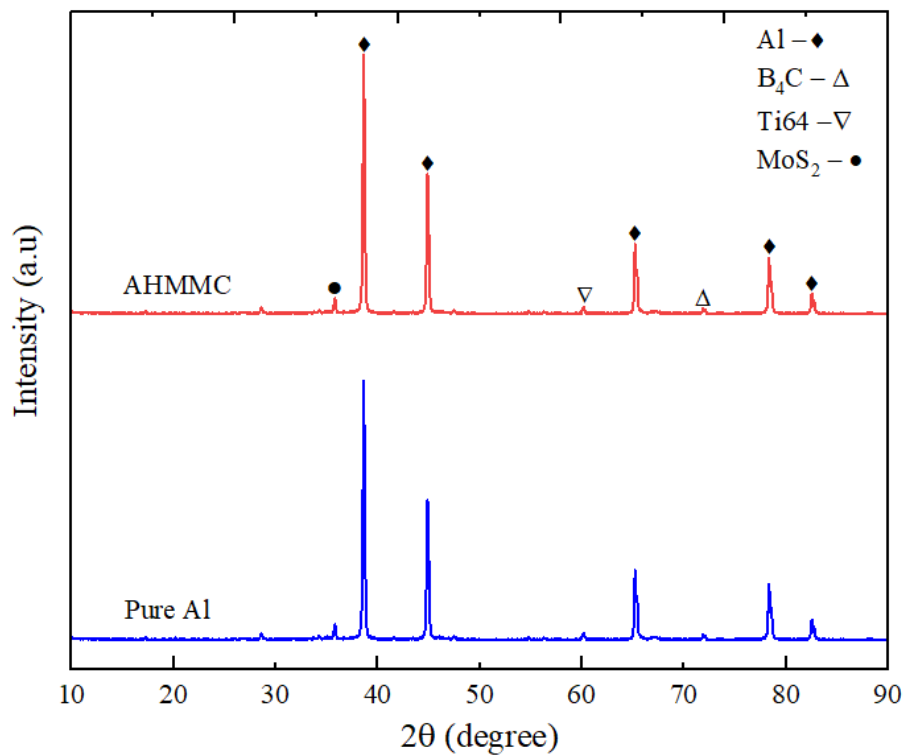
4.5.3 X-Ray Diffraction (XRD) Analysis

The presence of reinforcements (B₄C, Ti64, and MoS₂) in aluminum hybrid composites was investigated using XRD analysis. This analysis was performed on the sample, which was fabricated at the optimum level. The XRD analysis reveals that the aluminum hybrid composite contained the reinforcements B₄C, Ti64, and MoS₂, as shown in Figure 4.16.

Experimental results of the XRD test, which was automatically generated by the data acquisition system of the XRD machine, are shown in Table 4.13. The phases present in the sample were identified by comparing the obtained angle of diffraction (2θ), intensities (I), and interplanar spacing (d) with standard reference patterns from Powder Diffraction File (PDF) databases provided by the International Centre for Diffraction Data (ICDD). The PDF card numbers of aluminum, boron carbide, titanium grade 5, and molybdenum disulfide are 00-004-0787, 00-035-0798, 00-004-0788, and 00-037-1492, respectively.

Table 4.13 Experimental result of XRD

Peak no.	2θ (degree)	d (Å)	$I_R = I/I_r$	FWHM (degree)	Intensity (Counts)
1	35.8068	2.50575	5	0.22590	159
2	38.3151	2.34728	3	0.16000	112
3	38.6414	2.32821	100	0.19700	3335
4	44.8934	2.01742	58	0.20920	1950
5	65.2480	1.42880	31	0.19890	1025
6	65.5026	1.42386	3	0.10400	103
7	78.3681	1.21919	26	0.20810	851
8	82.5481	1.16772	9	0.19710	314

Figure 4.16 XRD analysis of AHMMC (Al/6%B₄C/5%Ti64/4%MoS₂) and Pure Al

The phase composition in the sample was verified by relative intensities calculated using equation 3.1. Peaks 3, 4, and 5 experienced the highest intensities, with 3335, 1950, and 1025, respectively. Their FWHMs were also the highest and closest to one another. In addition to these strongest peaks, peaks 7 and 8 were higher than the others. When the XRD

parameters of these peaks (3, 4, 5, 7, and 8) were compared to standard reference patterns, they revealed the aluminum phase. The corresponding Miller indices of peak 3, 4, 5, 7, and 8 were 111, 200, 220, 311, and 222, respectively. Similarly, comparing the XRD parameters of peaks 1, 2, and 6 to standard reference patterns showed molybdenum disulfide, titanium grade 5, and boron carbide, respectively. The interrelated Miller indices of molybdenum disulfide were 102; for titanium grade 5, it is 002; and for boron carbide, it is 018.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In this study, the hybrid aluminum metal matrix composite was successfully fabricated by incorporating B₄C, Ti64, and MoS₂ particulate reinforcements using the powder metallurgy technique. The weight percentage of reinforcement and the extent of powder metallurgy process parameters were analyzed and optimized by using Taguchi-based GRA and GA. The optimization process was based on experimental results from samples fabricated at different sintering temperatures (550, 600, and 650 °C), compacting pressures (50, 60, and 70 MPa), weight percentages of B₄C (2, 4, and 6), and weight percentages of Ti64 (1, 3, and 5). The powder mixing time and weight percentage of MoS₂ remained constant at 1 hour and 4 wt.%, respectively. The effect of reinforcements (B₄C, Ti64, and MoS₂) and powder metallurgy process parameters on the physical, mechanical, microstructural, and tribological properties of the composite was investigated and concluded as follows:

1. Increasing the weight percentage of titanium grade 5 (Ti64), sintering temperature, and compaction pressure led to a density increase from 2.55 to 2.65 g/cm³. However, as the sintering temperature and compaction pressure vary non-uniformly, so does the density. The density increased primarily due to increased compaction pressure. Also, sintering temperature and compaction pressure had the greatest effect on the percentage of porosity. When the weight percentage of reinforcement increased with decreasing sintering temperature and compaction pressure, the percentage of porosity increased (13.192). The optimum sample had the highest density (2.730 g/cm³) and lowest porosity (4.891 %). Optimal density and low porosity generally result in improved mechanical properties such as hardness and compressive strength. This is critical for applications requiring high load-bearing capacity, making optimal composites ideal for structural components in aerospace, automotive, and industrial applications.
2. The characterization of the optimum sample using OM revealed a homogeneous reinforcement distribution. SEM analyses clearly showed the distribution of reinforcement and the presence of micro voids. The voids that existed in the optimal composites had detrimental effects on both mechanical and tribological properties by introducing stress concentrations, reducing strength, altering failure mechanisms,

and increasing wear rates. XRD analysis revealed the presence of various phases in the optimum composite. The presence of different phases (B_4C , Ti64, and MoS_2) within an aluminum hybrid metal matrix composite material influences its mechanical and tribological properties. Hard reinforcing phases (B_4C and Ti64) increase strength and wear resistance.

3. The Vickers hardness test indicated that the hardness of the Al/ B_4C /Ti64/ MoS_2 composite increased as porosity decreased. The composite produced at the optimum level had the highest hardness, 222.33 HV. The compressive strength of the optimum sample was found to be 708.127 MPa.
4. The optimum sample's wear and corrosion resistance tests showed a wear rate of 5.94×10^{-6} g/m and a corrosion rate of 0.0017 mmpy. When compared to monolithic aluminum, the optimum sample showed a 30% and 48.5% decrease in wear and corrosion rates, respectively.
5. The Taguchi-based grey relational analysis reduced the multi-response to a single response, and genetic algorithm was used to determine the optimal levels. Taguchi-based grey relational analysis is a method that combines the Taguchi and grey relational analysis methods to solve multi-response optimization problems by leveraging the advantages of both. It simplifies the optimization process by converting multiple responses into a single grey relational grade, making it easier to identify optimal process parameters. Genetic algorithms use a probabilistic search approach to find near-optimal conditions, making them useful for complex optimization problems. The optimal PM process parameters and reinforcement weight percentage were 70 MPa of compacting pressure, 650°C of sintering temperature, 6% of boron carbide, and 5% of titanium grade 5.

5.2 Recommendation

Based on the research results and conclusions presented in this study, the following recommendations are suggested.

1. The addition of B_4C , Ti64, and MoS_2 improves the properties of aluminum. To achieve advanced properties, investigate aluminum hybrid matrix composites with a variety of reinforcements, including ceramics, alloys, and solid lubricant materials.
2. It was shown in this study that better dispersion of reinforcements leads to better mechanical, physical, and tribological performance. So, to improve the uniformity of

reinforcement distribution, investigate advanced composite manufacturing techniques.

3. The fabrication process parameters and reinforcement weight percentage for AHMMC should be optimized. Because the composites developed at optimum levels exhibited improved properties.
4. The mechanical and tribological properties of aluminum improved by the addition of B_4C , Ti64, and MoS_2 are especially useful in applications requiring high hardness, wear resistance, and corrosion resistance, such as the marine, automotive, and aerospace sectors.

5.3 Future Work

While this study offers potential improvements in mechanical (hardness and compressive strength), physical (porosity and hardness), and tribological properties (wear resistance and corrosion resistance), some areas require further investigation:

1. Performing an investigation on a large sample size of Al/ B_4C /Ti64/ MoS_2 composites would help to effectively generalize the effects of the powder metallurgy process parameters and reinforcement weight percentage. A large sample size may produce clear and easy-to-analyze results.
2. Sintering samples under controlled conditions can reduce thermal fluctuation and the formation of unnecessary phases. Also, the compaction process performed at low pressure can cause poor interparticle contact. Future studies are expected to sinter and compact the powder under controlled conditions and at high pressure.
3. To understand the effectiveness of PM fabrication technique, it is required to compare the samples manufactured by other processing techniques.
4. The powder metallurgy process parameters that were not considered in this study, such as mixing speed, sintering time, and compacting time, can affect the properties of the sample. By varying the value of these parameters, the composite with better properties will be obtained.
5. Further research is needed to investigate the Al/6% B_4C /5%Ti64/4% MoS_2 properties under various loading conditions, such as fatigue or impact loading, in order to fully evaluate its mechanical performance. Thermal properties tests are also required to evaluate practical applications.

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APPENDIX

Appendix A

A.1 Tools and equipment used in this research

S. N	Tools / Equipment	Function
1	Electronic weighing machine	To measure the weight percentage of matrix and reinforcement and weight loss during the wear test
2	Grinding and polishing	For surface finish
3	High energy ball mill/ mixer	For mixing and reducing the size of the matrix and reinforcements
4	High-temperature box furnace	For sintering the green compact
5	Hydraulic pressing machine	For compacting the mixed powder materials
6	Optical microscope	For reinforcement distribution investigation
7	Pin-on-disc	For wear test
8	Potentiodynamic polarization	For corrosion test
9	Scanning Electron Microscope (SEM)	For reinforcement distribution investigation and existence of porosity
10	Universal testing machine (UTM)	For compression strength test
11	Vickers hardness machine	For hardness test
12	XRD	For phase analyses

A.2 The powders used for composite fabrication



Appendix B

B.1 The required mass of matrix and reinforcements within each sample in grams

Samples	Matrix	Reinforcements		
	Al	B ₄ C	Ti64	MoS ₂
	Gram (g)	Gram (g)	Gram (g)	Gram (g)
S ₁	11.16	0.24	0.12	0.48
S ₂	10.92	0.24	0.36	0.48
S ₃	10.68	0.24	0.6	0.48
S ₄	10.92	0.48	0.12	0.48
S ₅	10.68	0.48	0.36	0.48
S ₆	10.44	0.48	0.6	0.48
S ₇	10.68	0.72	0.12	0.48
S ₈	10.44	0.72	0.36	0.48
S ₉	10.2	0.72	0.6	0.48

B.2 The experimental results of the weight measurement in the air and water

C.1 Sample	W_{air}			W_{fluid}		
	1	2	3	1	2	3
1	1.8605	1.7249	1.6689	1.1281	1.0511	1.0187
2	1.853	1.7943	1.8357	1.1511	1.1061	1.1295
3	1.9263	1.8892	1.8678	1.2141	1.1952	1.1629
4	1.8761	1.8723	1.8789	1.1729	1.1619	1.1801
5	1.7922	1.8188	1.7888	1.0917	1.1152	1.0924
6	1.8271	1.8425	1.8665	1.1031	1.1203	1.1322
7	1.869	1.8734	1.9094	1.1466	1.1549	1.1781
8	1.9165	1.9219	1.869	1.1501	1.1613	1.1205
9	1.8391	1.8548	1.9211	1.1088	1.1111	1.1451

By using the result tabulated above, the density of each sample is calculated using the following equation:

$$\rho_{sample} = \frac{W_{Air} \times \rho_{Fluid}}{W_{Air} - W_{Fluid}}$$

The density of S₁ trial 1 is:

$$\rho_{sample} = \frac{1.8605 \times 0.9982}{1.8605 - 1.1281} = 2.5357 \text{ g/cm}^3$$

Where density of water (ρ_{fluid}) is 0.9982 g/cm³ at 20°C.

Similarly, the density values for each sample are obtained.

Also, percentage of porosity is calculated using:

$$\phi = \frac{\rho_t - \rho_A}{\rho_t} \times 100$$

For S₁ trial 1:

$$\phi = \frac{2.8081 - 1.8605}{2.8081} \times 100 = 9.7003$$

$$\begin{aligned} \text{where } \rho_t &= ((W_m \times \rho_m) + (W_r \times \rho_r))/100 \\ &= (93 \times 2.7) + (2 \times 2.52) + (1 \times 4.43) + (4 \times 5.06))/100 \\ &= 2.8081 \text{ g/cm}^3 \end{aligned}$$

Similarly, the density values for each sample are obtained.

B.3 Experimental result of corrosion resistance test

Sample	Equivalent weight (E_w)	Density
Pure Al	3.2114	2.704
Optimum sample	3.0113	2.669

$$\text{Corrosion rate (mmpy)} = 0.00327 \times I_{corr} \times \frac{E_w}{d}$$

For Pure Al:

$$\text{Corrosion rate (mmpy)} = 0.00327 \times (0.862) \times \frac{3.2114}{2.704} = 0.0033 \text{ mmpy}$$

For Optimum composite:

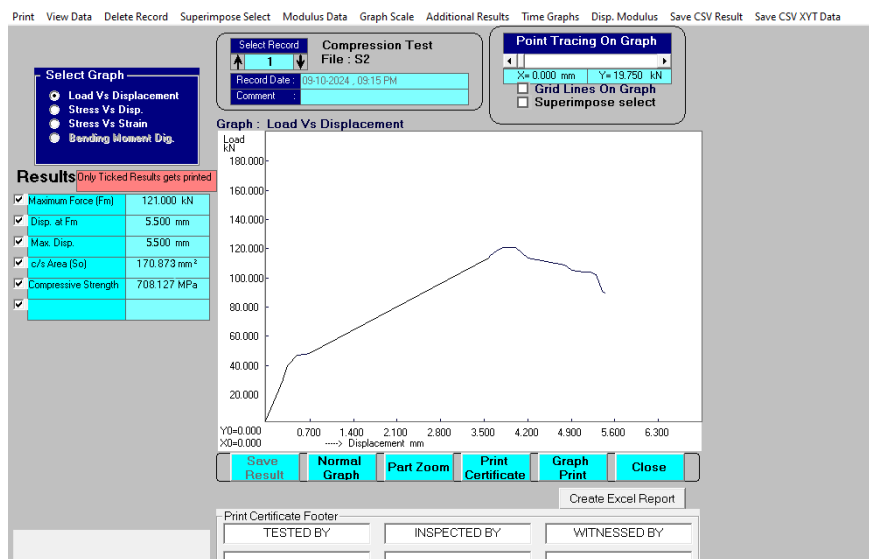
$$\text{Corrosion rate (mmpy)} = 0.00327 \times (0.457) \times \frac{3.0113}{2.669} = 0.0017 \text{ mmpy}$$

B.4 Experimental result of wear test

Sample	Weight before wear test (g)	Weight after wear test (g)	Weight loss (g)	Sliding distance (m)	Frictional force (N)
Pure Al	0.8325	0.8305	0.002	235.62	12.1
Al-6%B ₄ C-5%Ti64-4%MoS ₂	0.8179	0.8165	0.0014	235.62	9.2

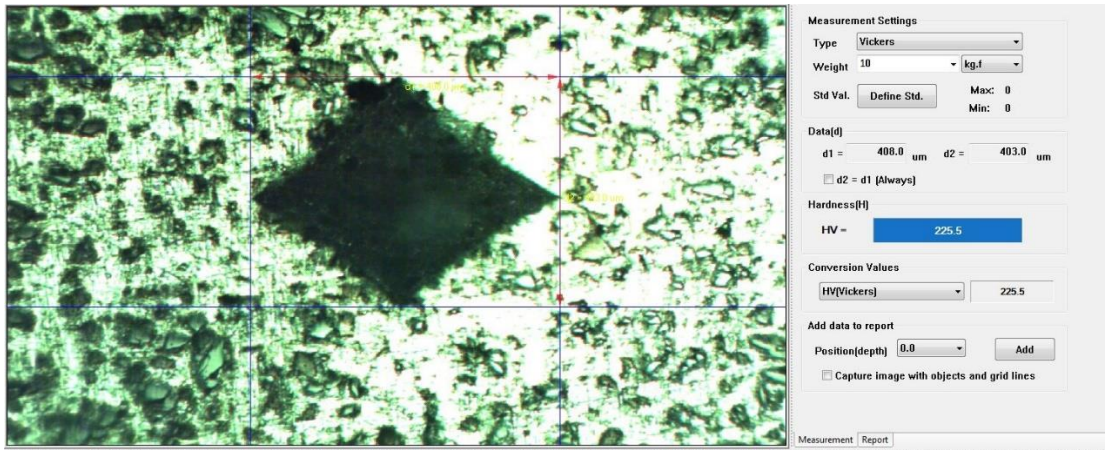
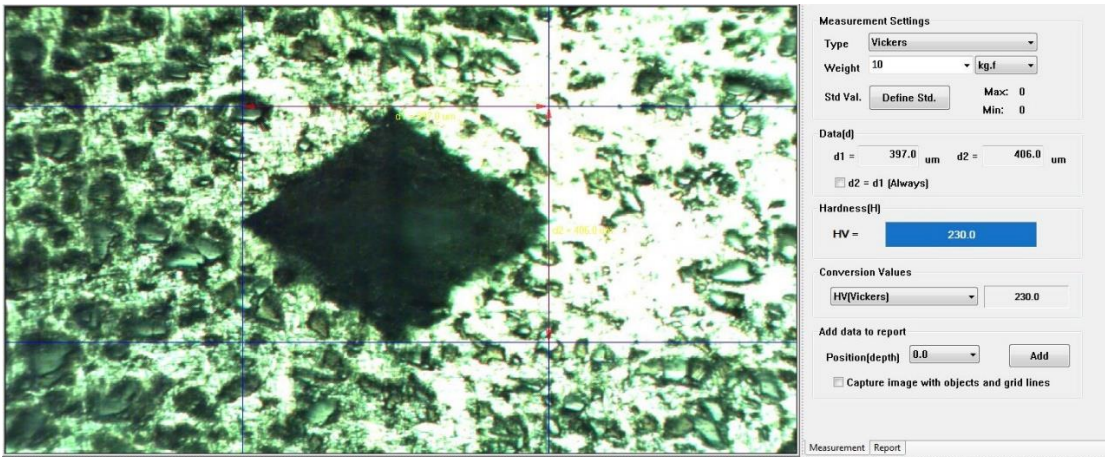
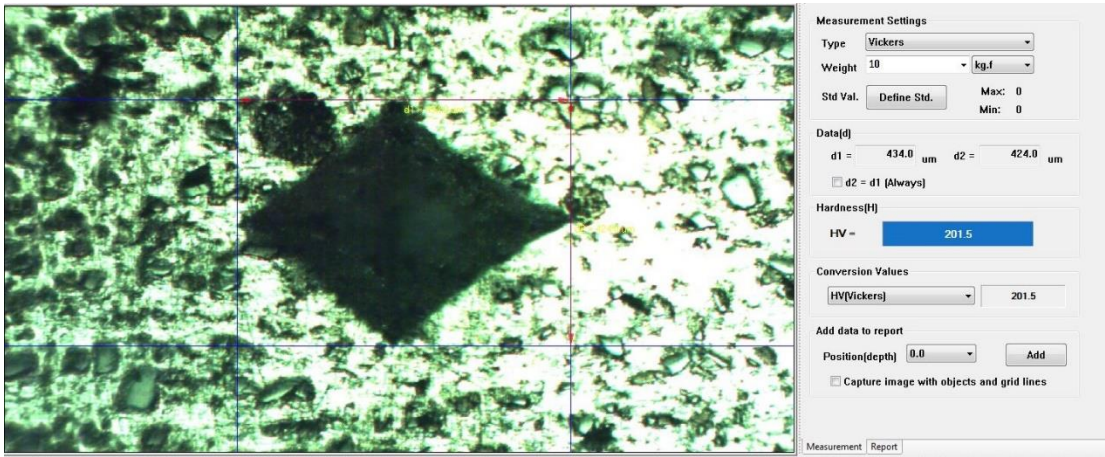
Appendix C

C.1 Experimental result of compression strength of optimum sample

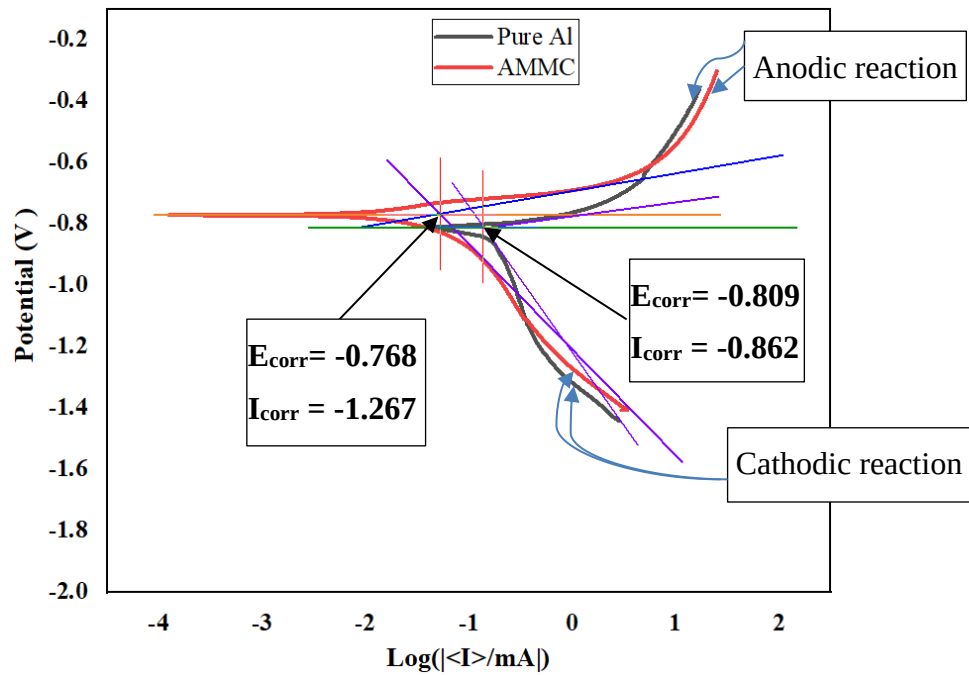


Sample dimension as per ASTM B925–15 was D = 4.75mm and T = 4mm

C.2 Vickers Hardness experimental result of optimum sample

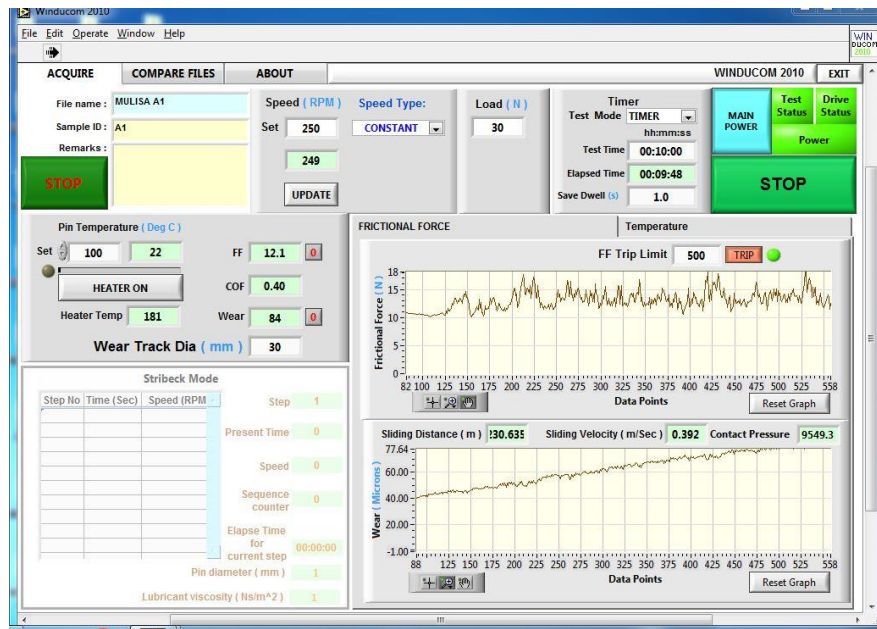


C.3 How to find the potential corrosion (E_{corr}) and corrosion current density from Tafel curve

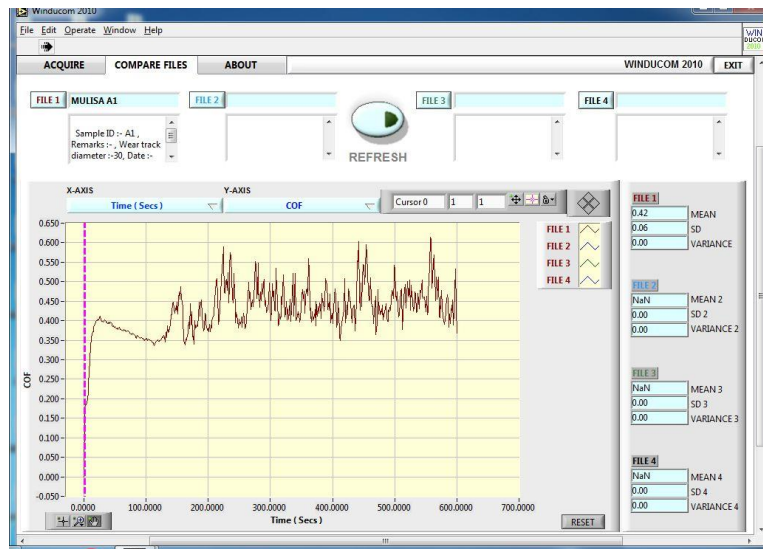


Appendix D

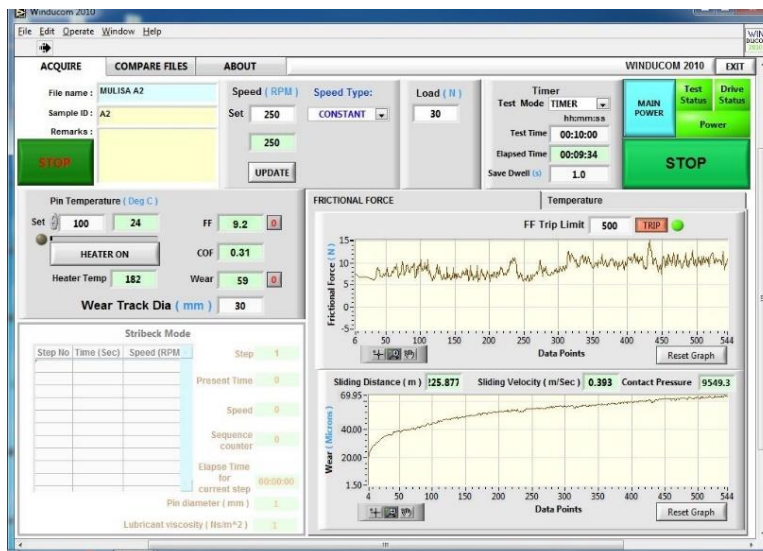
D.1 Different graphs obtained during wear test



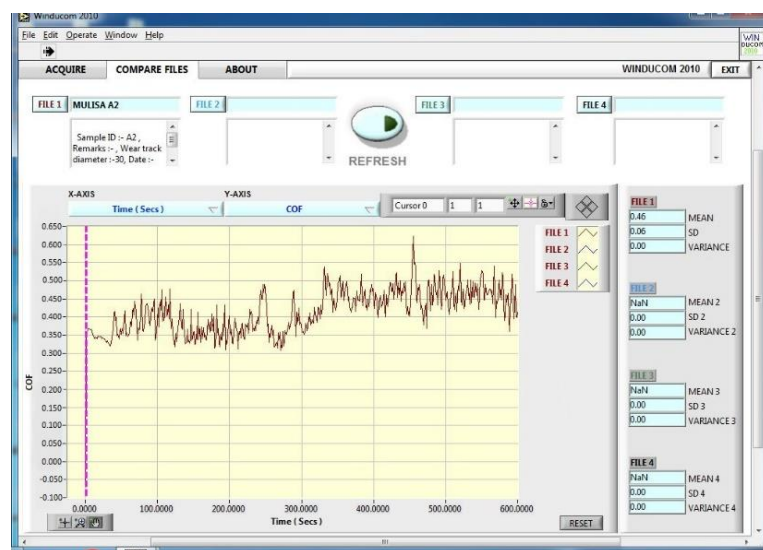
(a) Graph of wear rate and friction force of pure Aluminum



(b) Coefficient of friction of pure Aluminum



(c) Wear rate and friction force graph of Al-6%B₄C-5%Ti64-4%MoS₂



(d) Coefficient of friction of Al-6%B₄C-5%Ti64-4%MoS₂

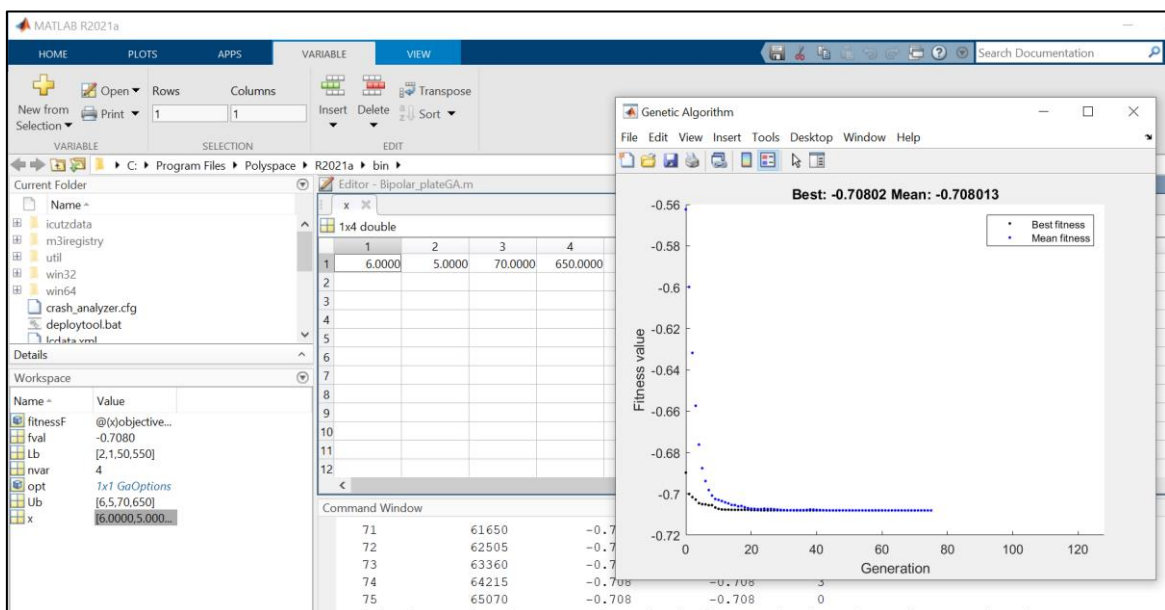
Appendix E

E.1 Genetic algorithm code used on MATLAB software

Genetic algorithm program for Optimization of PM process Parameters and weight percentage of reinforcements

```
clear all
close all
clc
% =====
Lb = [2 1 50 550];% Lower bounds for variables
Ub = [6 5 70 650];% Upper bounds for variables
% =====
nvar = 4;% Number of variables in the obj. function
% =====
% Calling the objective function
fitnessF = @(x)objective(x);
% =====
% Define options, iteration, generation, ....
opt = optimoptions('ga','Display', 'iter',... % Display
iterations
'MaxGeneration', 32*nvar, .... % Define no of Generation
% increasing improve accuracy
'PopulationSize', 900,... % Set Population Size
'FunctionTolerance', 1e-6,... % Set Function Tolerance %
reducing improve accuracy
'PlotFcn','gaplotbestf'); % Visualize the results
% =====
% optimize the function
[x, fval] = ga(fitnessF,nvar,[],[],[],[],Lb,Ub,[],opt);
```

E.2 Optimal values obtained from MATLAB software



Appendix F

F.1 Al/B₄C/Ti64/MoS₂ composite fabrication and sample testing activities

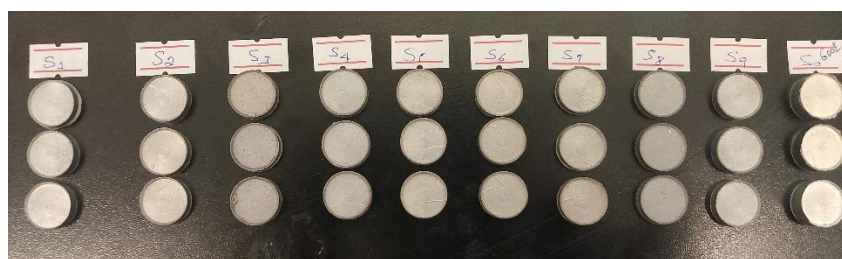


(a) Powder compacting



(b) Compression strength testing

(c) Sample preparation



(d) Samples used for optimization



(e) Samples fabricated at optimum level