Bamboo stem ash powder Effect on Tribo-mechanical properties of Aluminum matrix composite

Dejene Haile Ayane

A Thesis Submitted to Department of Materials Science and Engineering

School of Mechanical, Chemical and Materials Engineering

Presented in Partial Fulfilment of the Requirement for the Degree of Master's in Materials Science and Engineering

Office of Graduate Studies

Adama Science and Technology University

June 2023

Adama, Ethiopia

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Declaration

I hereby declare that this Master thesis entitled “BAMBOO STEM ASH POWDER EFFECT ON TRIBO-MECHANICAL PROPERTY OF ALUMINUM MATRIX COMPOSITE” 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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Name of student Signature Date

Recommendation of Advisors/Supervisors

We, the advisorsof this thesis, hereby certify that we have read the revised version of the thesis entitled **“Bamboo Stem Ash Powder Effect on Tribo-Mechanical Property of Aluminum Matrix Composite”** prepared under our guidance by Dejene Haile submitted in partial fulfillment of the requirement for the degree of Masters of Science in Materials Science and Engineering.

Therefore, we recommended the submission of the revised version of the thesis to the department following the applicable procedures.

Dr. Getinet A.

Major Advisor Signature Date

Dr. Devendra K.

Co-Advisor Signature Date

Approval page for thesis proposal

We, advisors of the thesis entitled **"Bamboo Stem Ash Powder Effect on Tribo-Mechanical Property of Aluminum Matrix Composite"** and developed by **Dejene Haile**, hereby certify that the recommendation and suggestion made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. Getinet A.		
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Co-Advisor/Supervisor	Signature	Date

Approval of Board of Reviewers

We, the undersigned, members of the board of examiners of the thesis by **Dejene Haile**have read and evaluated the thesis entitled **"Bamboo Stem Ash Powder Effect on Tribo-Mechanical Property of Aluminum Matrix Composite"** and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Materials Science and Engineering.

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Glory to the Almighty God, the Father the Son, and the Holy Spirit, who is there before everything, with everything, after everything. Mother of the Word my gift from God has to have my praise. And the other saints who helped me with my every steps.

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ABBREVIATIONS

AMC	Aluminum matrix composite
BLA	Bamboo leaf ash
BSAP	Bamboo stem ash powder
CCM	Carbon-carbon matrix composite
CMC	Ceramic matrix composite
CNT	Carbon Nanotube
CPRAMMC	ceramic particle reinforced aluminum metal matrix composites
CS	Compressive strength
DTA	Differential thermal analysis
DTG	Differential thermogravimetric
EDS	Electro-dispersion spectroscopy
EIS	Electrochemical impedance spectroscopy
HAMC	Hybrid Aluminum matrix composite
MMC	Metal matrix composite
OM	Optical microscope
PM	Powder metallurgy
PMC	Polymer matrix composite
PRMMC	Particle-reinforced metal matrix composite
PSR	Particle size ratio
TGA	Thermo-gravimetric analysis
TMDC	transition metal dichalogenides
TS	Tensile strength
WT%	Weight percentage
XRD	X-ray diffraction

ABSTRACT

Natural fiber composites offer a range of advantages, from biodegradability after the component's lifespan little to no output of greenhouse gases and reduced pollution. These properties have made natural fiber reinforced composites popular in military, automotive, aerospace, and residential spaces. Bamboo is one example of a commonly found natural fiber reinforcements. This research looks into its effect on the physical, mechanical, corrosion,and tribological parameters when added to Aluminum matrix composite. In the composites 0, 2.5, 5, 7.5, and 10 weight percent of BSAP were added in addition to the secondary reinforcements (Al_2O_3, B_4C, and MoS_2). X-Ray Diffraction analysis, XRF spectroscopy, FTIR spectroscopy, Thermal (DTA/TGA) analysis and SEM/EDS characterizations for BSAP had been performed. Parameters such as density, porosity, hardness, compressive strength, wear property test, corrosion (both Tafel plot and EIS) results of the composite mixture, as well as Thermal Gravimetric Analysis findings for the composites were all studied. The optimum experimental density found to be 2.44 and the lowest porosity was 0.012% on BP-7.5 sample. The highest values of mechanical and tribological properties also have been seen with 7.5 weight percent BSAP addition. The maximum hardness registered to be 305.7 HV and the maximum compressive strength is 308.32 MPa. The lowest wear rate was 0.0022 micron on 30 N loading. The corrosion inhibition efficiency also recorded to be 99.72%.Optimization of the most influencing parameters; pressure and temperature were conducted on the better composition sample; BP-7.5. The optimum pressing pressure and sintering temperature were 50 MPa and 561^oC respectively. The characterization and tests of the composites confirming that the addition of this natural fiber (BSAP) on Aluminum matrix composites can improve standard materials' behavior when used on correct composition.

Key words: *Bamboo stem ash powder, composites, mechanical property, pure aluminum, tribological property*

CHAPTER ONE

1. Introduction

1.1. Background of the study

Composite materials possess unique qualities that make them ideal for use in extensive variety of applications including structural engineering, automobiles, construction, marine, and airplanes. Their outstanding traits include high strength-to-weight ratios, low density, and high stiffness-to-weight ratio as well as superior fatigue strength-to-weight ratio compared to conventional engineering materials. The advantages of composite materials lead to less fuel consumption and easier production processes with increased payloads, particularly during aviation; hence providing long service times (Arun Kumar Sharma, 2020).

When mud was reinforced with jute and other natural reinforcing materials to create a house in rural regions in ancient times, the history of composite construction was born. The production of composites has advanced significantly over time (Xiaofeng Sun, 2020). Due to their better mechanical qualities as compared to a single metal, metal matrix composites (MMCs) are now often employed in the automotive, military, marine, and aeronautics industries. Since the 1960s, metals have been made stronger and more rigid by adding reinforcements in the form of fibers, particles, or whiskers (Dawit Getu, 2020).

Globally, there is rising interest in sustainable materials for structural applications as a result of a variety of significant problems (such as environmental pollution, energy crisis, resource depletion, etc.) and the resulting limits. However, the choice of structural materials can significantly affect the global climate (i.e., the greenhouse effect). Global worry over the greenhouse effect is growing as the earth's surface temperature increases. It results from the emission of too much carbon dioxide and other chemicals into the atmosphere (Xiaofeng Sun, 2020).

The main goal of creating novel materials for automotive and aerospace applications is to reduce the weight of the vehicle to save fuel. Additionally, current materials need to be researched to enhance the visual appeal of cars (M. Patel, 2018). Alternatives to traditional metallic materials that are lightweight, fatigue resistant, and readily molded to any shape include composite materials. Weight reduction may be done by employing better materials, improved production techniques, and optimizeddesigns (Dawit Getu, 2020).

The most crucial factor in material selection for many industrial applications is specific strength. For instance, it is an important design criterion for spinning machinery parts. Enhanced resistance to wear,high strength, high elastic modulus, and high resistance to creep, and fatigue are characteristics of composites reinforced with ceramic phases, making them potential structural materials for the automotive and aerospace sectors. Traditional monolithic materials aren't always able to combine strength, stiffness, toughness, and density well. Composites are the most promising materials of current research because they have the potential to overcome these drawbacks and satisfy the constantly growing demands of modern technology (M., 2018).

Due to its low density, aluminum is an obvious choice for this kind of application. However, normal commercial aluminum alloys have too low of strength compared to titanium alloys for aluminum to be a superior choice. Applications needing a combination of strength, thermal conductivity, damping qualities, and a low coefficient of thermal expansion with a reduced density are well suited for composite matrix. The use of composite matrix in automotive and other applications is made possible by these characteristics.Low weight, great heat resistance, wear resistance, and low cost are only a few of the characteristics of composite materials made from aluminum. These are used in a variety of technical applications, including cylinder block liners, automobile drive shafts, automotive pistons, and bicycle frames (Ivona Camelia Petre, 2017).

For the manufacture of a variety of technical goods, natural plant fiber composites have been produced. These materials offer advantages including biodegradability and ecological stability. Due to its recyclability,ecological protection, reusability, and mechanical qualities, bamboo fiber resources have drawn considerable interest as a means of reinforcing composites (R. Harikumar, 2020).

The cross-section of a bamboo stem is not continuous, and the structural characteristics of the bottom, half (larger-diameter), and upper (smaller-diameter) parts vary. It is evident that the bamboo samples' age and moisture content significantly affect the bamboo's compressive strength. In comparison to bamboo with a high moisture level, bamboo with low moisture content has better compressive strength.

This research focuses on the effects of BSAP on monolithic aluminum with three secondary reinforcements -- MoS_2, B_4C and Al_2O_3. This is a unique undertaking since combinations of four (Tetra hybrid) reinforcements are rarely used with aluminum matrices. This study aims to measure the changes in mechanical and physical properties of pure Aluminum caused by the various weight percentages (0, 2.5, 5, 7.5, & 10) of BSAP proportions. There is no research work done on Aluminum metal matrix with BSAP and other reinforcements through the powder metallurgy production route.

1.2. Problem Statement

Due to the weak mechanical properties; hardness, compressive strength, and tribological characteristics; low wear resistance, of pure aluminum alone, new materials had to be developed. Graphite (Gr), silicon carbide (SiC), aluminum oxide (Al_2O_3), Boron carbide (B_4C), Molybdenum disulfide (MoS_2) particles and other single reinforcements are used in the majority of MMC research; only a small number of researchers have focused on the combination of several reinforcements (hybrid composites).

Some of the ceramic reinforcements that are used to improve the aforementioned weaknesses of pure Aluminum are rarely abundant and as a result they are expensive. So, replacing these ceramic reinforcements with easily available, cheap, and eco-friendly materials of natural fiber reinforcementssuch as bamboo.

The fabrication of aluminum matrix composites using liquid metallurgical processing techniques results in porosity, an unfavorable interfacial bonding response, and significant energy usage. Additionally, there are issues with cost and property improvement when making AMCs solely from these ceramic reinforcements.

Therefore, it is preferable to employ powder metallurgy and replace some of the ceramic particle reinforcements with plant extracts like bamboo ash powder of choosing the correct mixing ratio to obtain AMCs that have superior and tailorable features with cost reduction and are environment friendly. In this study, four reinforcements—B_4C, Al_2O_3, MoS_2, and

BSAP— were employed along with pure aluminum as the matrix to develop and analyze the AMCs' mechanical, tribological, and physical properties.

1.3. Objective

1.3.1. General objective

The objective of this paper is to analyze the effect of bamboo powder on the mechanical and tribological properties of Aluminum composite reinforced with Boron Carbide, Molybdenum disulfide, and Aluminum oxide.

1.3.2. Specific Objectives

1. ExtractionandpreparationBambooashfinepowderfromthestem.
2. Preparation ofAl/(5%B_4C, 2.5%Al_2O_3, 2%MoS_2)+BSAP tetra hybrid reinforcedaluminummatrixcompositesusingvariouswt%ofBSAPvia Powdermetallurgy (P/M) route.
3. Investigating the effects of the main process parameters (compacting pressuresandsinteringtemperatures)onphysical properties(density,porosity)andmechanical properties(hardness,compressivestrength)ofthedeveloped hybrid composite samples.
4. Evaluating and comparing the tribological (wear) and corrosion characteristic behaviorof tetra hybrid reinforced aluminummatrixcomposites.
5. Comparingthemechanical and tribologicalperformanceofthehybridcompositeswiththeunreinforced monolithic metal.

1.4. Significance of the study

This research work has the following significance

- To continue reduction of production costs for hybrid aluminum matrix composites
- To advance our understanding of powder metallurgy processes used to create composites with aluminum matrix.
- To find echo-friendly materials for engineering applications.
- To contribute new ideas for other researchers as input in the field of study.
- To reduce the dependency on rarely abundant compounds by replacing them with

renewable ones.

1.5. Scope of the study

This research work consists of an introduction, problem statement, literature survey that covers the problems, processing methods, and recently published work in the field of AMCs with reinforcements B_4C, Al_2O_3, MoS_2, and BSAP particulates. Primarily, this study presents an introduction to composites in general and AMCs in specific. Secondly, a literature survey of recent research into the field of AMCs reinforced B_4C, Al_2O_3, MoS_2, and BSAP with particles, Gr fine powder, and Agro-industrial solid waste suchas sugar cane bagasse ash. Thirdly, the techniques and testing procedures include thepreparation of composite powders and selected optimal compositional mixtures, details,and parameters of the high energy ball milling technique, the consolidation of powdercomposites into solid compacts, the sintering temperature, and then density and porosity measurement, Vickers hardness, compression testing,corrosion measurements, and pin on disc wear testing. Finally, a conclusionand recommendations for future work on the most important improvements and findings ofAMCs are discussed.

1.6. Limitation of the study

Many reinforcements are used in AMC; the ceramic reinforcements that are used in this work are selected based on physical and chemical properties. And also, availability is considered.

This study is limited to powder metallurgy route because the other metal matrix composite production methods are costly, energy consuming, complex process parameters and changes in chemical and physical properties can occur.

The milling time is selected to be 2 hrs. to reduce the chance of agglomeration. The pressing pressure is bounded between 40 and 60 MPa to have a better property and to control machinery damage. The sintering temperature is also limited to 594 ^oC max due to not exceeding 90% of the melting point of the matrix material which is Aluminum; 660^oC.

1.7. Organization of the Thesis

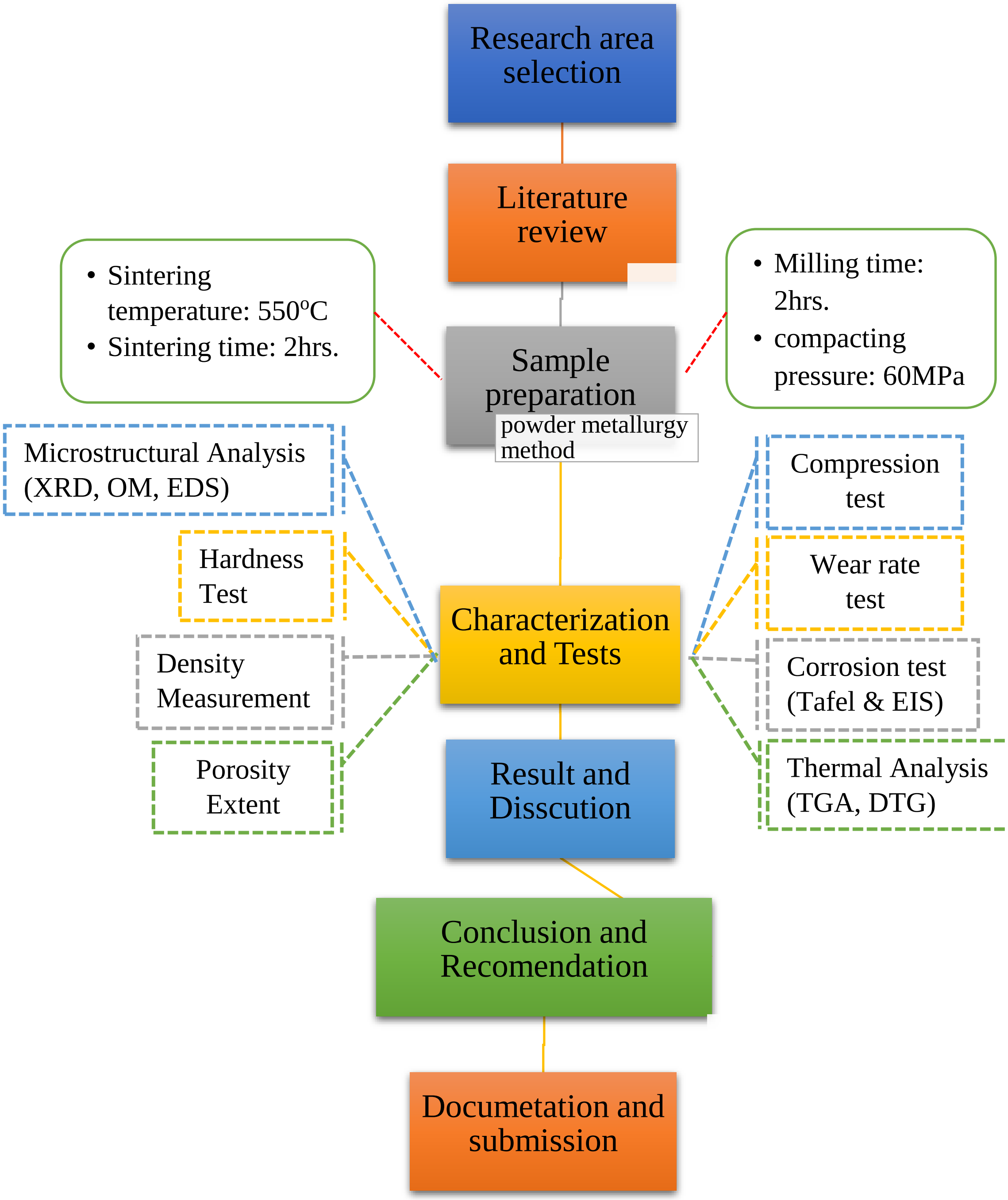


Figure 1: Organization of the research

CHAPTER TWO

2. Literature Review

2.1. Composite materials

Two or more different types of materials are combined to create composite materials. The fundamental building blocks, matrix, and reinforcement, each have unique qualities and their merger results in a completely new substance (Murlidhar Patel1, 2020). A composite material system is made up of two or more constituents together in a proper and organized way. A composite product's constituents can be separated because the contact between them differs in form and chemical makeup. The components of a composite cannot dissolve in one another (Kala, 2014). Compared to its basic parts, it possesses special, novel, and distinctive features. Most current technologies require materials with unique and odd combinations that have better qualities than those of ordinary materials.

Based on the chemical composition of the matrix phase, a composite can be categorized. Ceramic matrix composites (CMCs), Carbon-Carbon matrix composites (CCM), polymer matrix composites (PMCs), and metal matrix composites are among the classifications (MMCs) (Ashebir et al., 2022; Kala, 2014).

Base metal (matrix) and inclusions (reinforcement) are both important in composite materials. Furthermore, the combination of reinforcement strength and matrix ductility aids in maintaining the ideal characteristics of MMCs. It is possible to choose a matrix made of materials like iron, aluminum, copper, titanium, lead, magnesium, silver, tin, nickel, zinc, and so on based on their good oxidation and corrosion resistance. The most popular matrix materialsare titanium (Ti), magnesium, and aluminum (Al). This is due to their good resistance to corrosion, low density and, remarkable mechanical qualities (Ikubanni Peter P., 2020).The reinforcement material can be incorporated into a metal matrix to create a metal matrix composite, and the resulting composites have superior characteristics (Arun Kumar Sharma, 2020).

For aluminum matrix composites (AMCs), pure aluminum or aluminum alloy serves as the base metal (matrix), and ceramics (Alumina (Al_2O_3), Silicon carbide (SiC), Boron carbide (B_4C), Silica (SiO_2), Aluminum nitride (Al-N), and so on), industrial waste (red mud and fly ash), and agro-waste (rice husk ash, corn cob ash, coconut shell ash, and so on) have all been used as reinforcement materials. Recently, combinations of reinforcing elements (such as mixing SiC and Al_2O_3, SiC and B_4C, etc.) have been used in place of employing a single reinforcing material (single reinforcement like SiC), allowing for the development of new hybrid composites with improved characteristics and performance (Ikubanni Peter P., 2020).

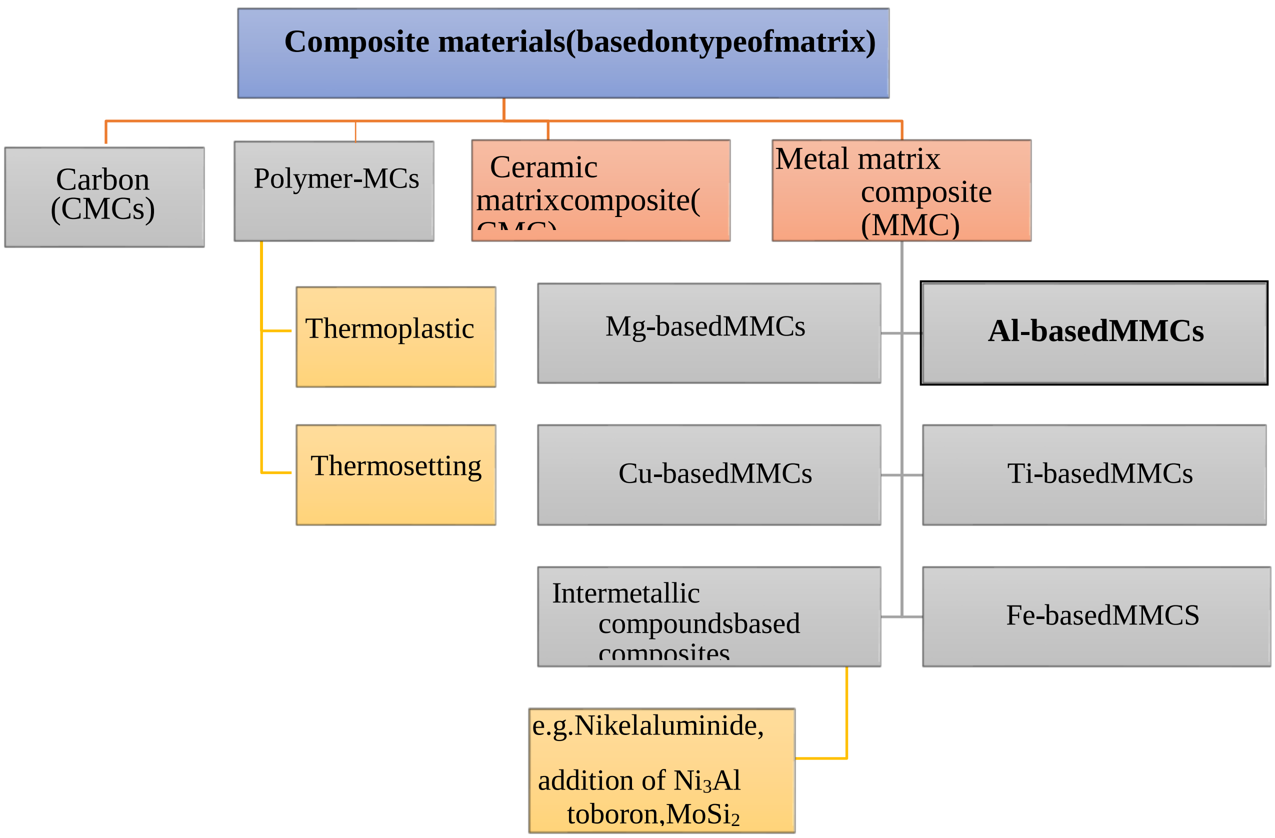


Figure 2: classification of composites based on matrix materials(Ikubanni Peter P., 2020)

2.1.1. Metal matrix composites

For applications that require a balance of high strength, elastic modulus, specific stiffness, strength-to-weight ratio, and ductility, particulate reinforced metal matrix composites (PRMMC) are the most promising choice(Arun Kumar Sharma, 2020). According to Deuis, et al., (Deuis, 1996) MMCs have a significant increase in mechanical strength and toughness when compared to alloys, MMCs can therefore endure compressive and tensile stresses. This is made possible by the dispersion of applied force from the phase of the reinforcement to the ductile matrix. From many of the sub-classes of metal matrix composites Aluminum matrix composites take the preceding.

2.1.1.1. Aluminum-basedmatrix composites

Aluminum or aluminum alloys are used as a matrix in aluminum metal matrix composites, which are then reinforced with other solid wastes like bagasse ash, bamboo ash or hard ceramic materials like SiC, Al_2O_3, B_4C, Ti_2B, TiC, etc. (Aktar Zahid Sohag, 2020; Annigeri, 2018; Arun, 2015). Aluminum is recognized as a major material because of its promising qualities, including lightweight, a high strength to weight ratio, resistance to corrosion and wear, and workability. An aluminum matrix is stronger, harder, more resistant to wear and corrosion, stiffer, and more thermally stable when hard ceramic elements are dispersed inside it.Aluminum as single element has low strength and elasticity as shown in table 1.

Table1: physical properties of aluminum

Properties Unit Value		
Density	g/cm^3	2.7
Melting point	°C	660
Brinell's Hardness	HB	45
Ultimate Tensile Strength	MPa	130
Yield Strength	MPa	276
Modulus of Elasticity	MPa	68.9
Thermal conductivity	W/m-K	167
Coefficient of Thermal Expansion	m/°C	23.6×10^{-6}

There is a lot of interest in aluminum metal matrix composites because of the improvement in features such as lightweight and greater strength to weight ratio, corrosion resistance, wear resistance, and low thermal coefficient. Due to their low density, superior mechanical qualities, and high levels of corrosion resistance, aluminum alloys also exhibit favorable features when employed as a matrix. Due to their numerous uses in the production of automotive components (such as brake discs, drums, back plates, engine blocks, pistons, and gearbox parts), aerospace components (such as rotating blade sleeves in helicopters, fan exit guide vane in gas turbine engines, and flight control hydraulic manifolds), and other industries, research has primarily focused on composites with aluminum and its alloys as a matrix (Aynalem, 2020; Michael Oluwatosin Bodunrin, 2015).

2.1.2. Reinforcements

2.1.2.1. Ceramic reinforcements

In comparison to standard Al and Al alloy, ceramic particle reinforced aluminum metal matrix composites (CPRAMMCs) offer superior features, such as enhanced hardness, improved strength to weight ratio, tensile and compressive strength, creep and fatigue resistance, etc. (B. Ramgopal Reddy, 2018).

When SiC and alumina were added to aluminum, as Singh (Jaivir Singh, 2021) conducted an experimental investigation to determine how the metal would behave mechanically, he concluded that as the weight percentage of reinforcement increased, so did the mechanical properties such as yield strength, hardness, and ultimate strength. But concurrently, elongation is reduced and the material's behavior changes from ductile to brittle. Kuma and Singh (Gurpreet Singh & Sanjeev Goyal, 2016) compared the mechanical characteristics of hybrid metal matrix composites based on aluminum. The results showed that the newly created composite with SiC and B_4C particles outperformed the SiC, graphite-reinforced composite in terms of tensile strength, ultimate tensile strength, hardness value, and flexural strength.

SiC, B_4C, Al_2O_3, and other ceramic particles can improve the mechanical and tribological characteristics of the basic aluminum or its alloy matrix. SiC and $A1_2O_3$ are inexpensive particle reinforcements that have been employed to lower the price of aluminum or aluminum alloy MMCs during the past ten years as reported by Z. Guo et al. (Z. Guo, 2018). When the weight percentage of reinforcement increases, so do the composites' hardness, porosity, and density. When compared to reinforced composites with particle sizes of 45 and 29, the homogeneous distribution of SiC particles is attained in the composite with a particle size of 110 micron; nevertheless, considerable agglomeration is seen when the particle size is smaller than 110 micron (I. M. El-Galy, 2017).

Kandpal et al. (B. C. Kandpal, 2017) uses 5, 10, 15 and 20 wt.% Al_2O_3 to reinforced the Al alloy matrix and found that as the alumina content in the matrix increases, so do the micro hardness and tensile strength. The ductility decreases as the weight percentage of alumina in the AA6061 matrix rises. Rao and Padmanabhan (Padmanabhan, 2012) observed that the distribution of the B_4C particulate in the matrix phase is uniform. They found that The B_4C particle is evenly distributed throughout the matrix phase, and when the amount of B_4C particles in the matrix phase rose, the composites' hardness and ultimate compression strength increased, but their density reduced.

Marimuthu and Berchmans (Berchmans, 2013) prepared and characterized Al-Mg-B_4C (3 and 7 wt. %) PRAMMCs. They observed as the weight percentage of B_4C particle in the alloy matrix rises, it has been observed that the composite's hardness and tensile strength improve. The effect of particles size on the abrasive wear and hardness of B_4C particulate reinforced AMMCs are evaluated by Nieto et al. (A. Nieto, 2017) To strengthen the AA5083, they employed B_4C particulates in three distinct particle sizes: micrometric B_4C particulate (B_4C), submicron B_4C particulate (sB_4C), and Nano-metric B_4C particulate (nB_4C). They discovered that bigger B_4C particulate reinforcements are more susceptible to particle pull-out, which negates the benefit of enhanced hardness. Because of its high hardness and larger interfacial area, which prevented nano-B_4C particles from pulling out, the AA5083+nB_4C composite exhibits exceptional wear resistance. In comparison to AA5083, it increases hardness by 56% and abrasive wear resistance by 7%.

2.1.2.2. Bio-based reinforcements

Science has been on the lookout for lightweight, strong materials that can survive the demanding conditions of today's high-tech applications in a variety of industries, including aviation, automobiles, sports, and more. Aluminum metal composites (AMCs) reinforced with bio-based fibers of various origins have been found in studies to be a suitable advanced material due to the enhanced physical and mechanical qualities that can be obtained. Although they improve the physico-mechanical and wear behavior of the aluminum alloy matrix, such reinforcements may be solitary (use of one reinforcement) or hybridized (use of more than one reinforcement with generated particulate materials) (Ikubanni Peter P., 2020; M., 2018).

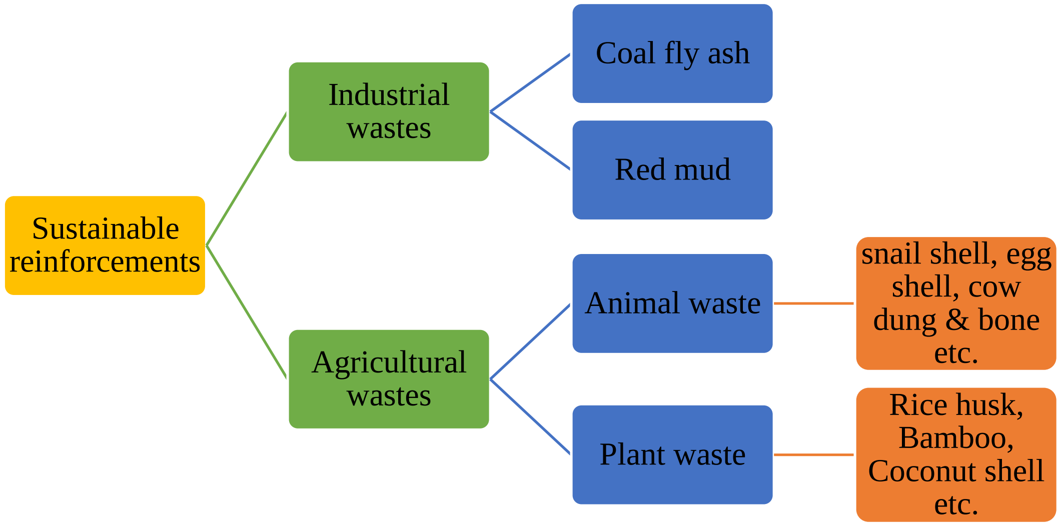


Figure 3: Classification of sustainable reinforcement materials(Ikubanni Peter P., 2020)

Much interest has been developed in the use of alternative materials for particle reinforcements for MMCs due to the requirement for sustainability in the manufacturing of components and materials. Waste-to-wealth, or the recognized need for sustainability, has encouraged study into the use of waste materials as reinforcing. Typically, these waste products are divided into industrial and agricultural wastes as shown in the Figure 2 above(Ndudim Ononiwu, 2020)

In the case of agro-based reinforcements that produce solid-liquid interfaces during fabrication, particularly when liquid state or semi-liquid state production processes are used, the problem of wettability and the interfacial bonding between the reinforcement and Al matrix is a subject of concern. The wetting activity between the agricultural-based reinforcements and the aluminum matrix determines the strength of the reinforced composites. Although several researchers have employed a variety of ways to enhance this, further study is still needed to solve this issue (Parveez et al., 2021).

Anil Kumar, Haber, et al. (Anilkumar et al., 2011) studied the mechanical characteristics of Al6061 composites reinforced with fly ash and discovered that these qualities degrade with increasing fly ash particle size, including tensile strength, compressive strength, and hardness. The ultimate tensile strength, compressive strength, and hardness of the composite rise as fly ash particle weight fractions increase and ductility declines.

2.2.Composite production route

Composites may be produced from the aluminum matrix using a variety of techniques. The cost-effectiveness and mechanical performance, including tensile strength, impact strength, hardness, and fatigue, are significantly influenced by the manufacturing procedures. The classification of fabrication techniques as solid state, liquid state, or other type depends on how the matrix is handled. In solid-state processing, the matrix and reinforcement materials bind together as a result of mutual diffusion occurring under pressure at a high temperature. MMCs produced via the solid-state approach can also be deformed by the use of forging, extrusion, and other cold- or hot-working processes. The dispersion of the reinforcement phase into the molten metal matrix is a component of the liquid state process, which is followed by the solidification process. It is often divided into two techniques: casting and infiltration, where reinforced particles are combined directly with molten metals. Infiltration involves soaking the preformed reinforcement phase in the molten matrix (Priyaranjan Samal, 2020). The schematics of the process of manufacturing are presented in Figure 3below.

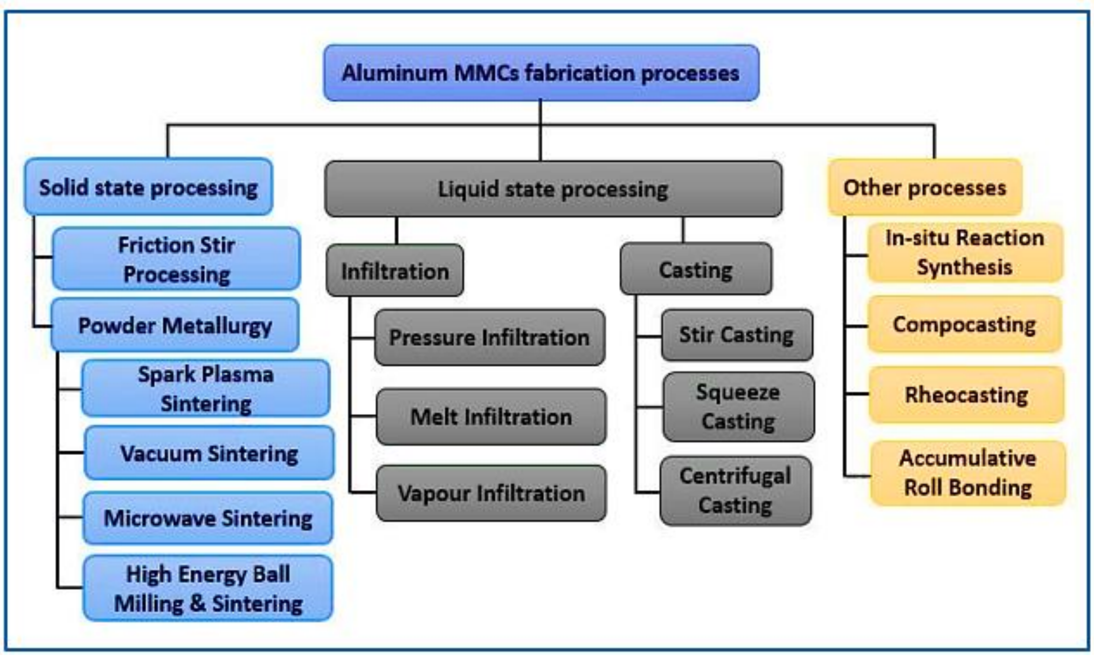


Figure 4: AMCs fabrication process chart(Priyaranjan Samal, 2020)

2.2.1. Powder metallurgy

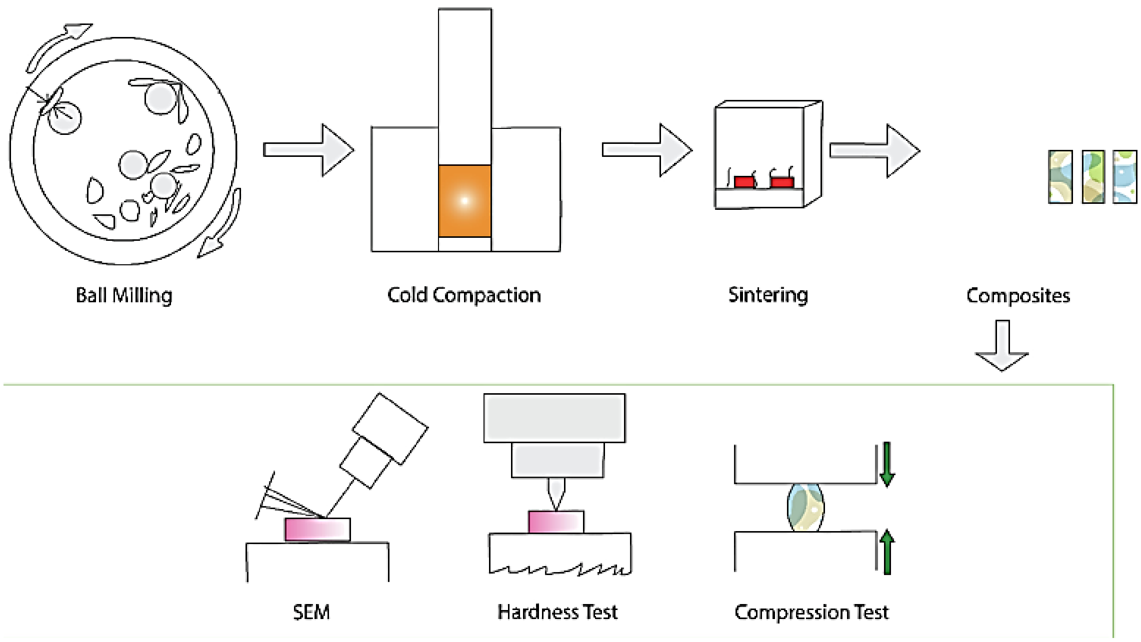


Figure 5: Schematic diagram of powder metallurgy process

The process of making components from metallic powders in powder metallurgy involves compressing the powder into the required form and heating it to a temperature below the melting point to create solid-state bonding of the particles into a hard, rigid mass known as sintering (Slipenyuk, 2004).

The primary benefit of powder metallurgy is the solid-state mixing of the matrix and reinforcement, which solves the issue of non-wetting between the reinforcements and liquid metal and prevents the creation of any unwanted phases. Contrary to conventional MMC fabrication procedures, where agglomeration of particles is the primary issue in the fabrication of particulate reinforced metal matrix composites, powder metallurgy allows for uniform distribution of reinforcement in the matrix and greater control of microstructure (Priyaranjan Samal, 2020).

Metal powders are used as catalysts or in different chemical and metallurgical processes because powders have a high surface area to volume ratio. Economical, distinctive, and captive applications are the three basic justifications for employing PM. Materials like reactive metals and refractory metals, which are challenging to treat using conventional methods, are examples of captive uses for PM. Processing using powder metallurgy gives several benefits. When compared to alternative metal forming processes, the PM process is more resource and energy efficient. Making complex-shaped items with powder metallurgy is affordable and requires less machining(Kaviarasu & Ravichandran, 2021).

Parts made of powder metal have a smooth surface and can be heat treated to boost their strength or wear resistance. The PM method offers part-to-part repeatability and is appropriate for manufacturing at moderate to high volumes. For self-lubrication or filtering, regulated micro-porosity can be offered as needed(Chak et al., 2020).

For automotive applications such as diesel engine pistons, piston rings, connecting rods, drive shafts, braking discs, and cylinder liners, ceramics are frequently employed as reinforcing materials (Slipenyuk, 2004)(W. Brian James, 2015).

The difficult problem in the creation of particulate-reinforced metal matrix composites is the uniform dispersion of particles within the matrix without agglomeration and with minimal interfacial reactions. The primary drawback of the deposition method is that it requires a lengthy procedure and should only be utilized with discontinuous reinforcement. Agglomeration of reinforcement and undesirable interfacial interactions are casting process limits, which are mostly caused by higher processing temperatures. Powder metallurgy has been able to resolve the issues with the aforementioned methods (Slipenyuk, 2004).

The benefits of powder metallurgy over other processes include the solution of the interfacial reaction problem, which is made possible by the process's extremely low processing temperatures. Over the past ten years, as shown in Figure 5, powder metallurgy has effectively solved the issues brought on by the aforementioned procedures(Chak et al., 2020).

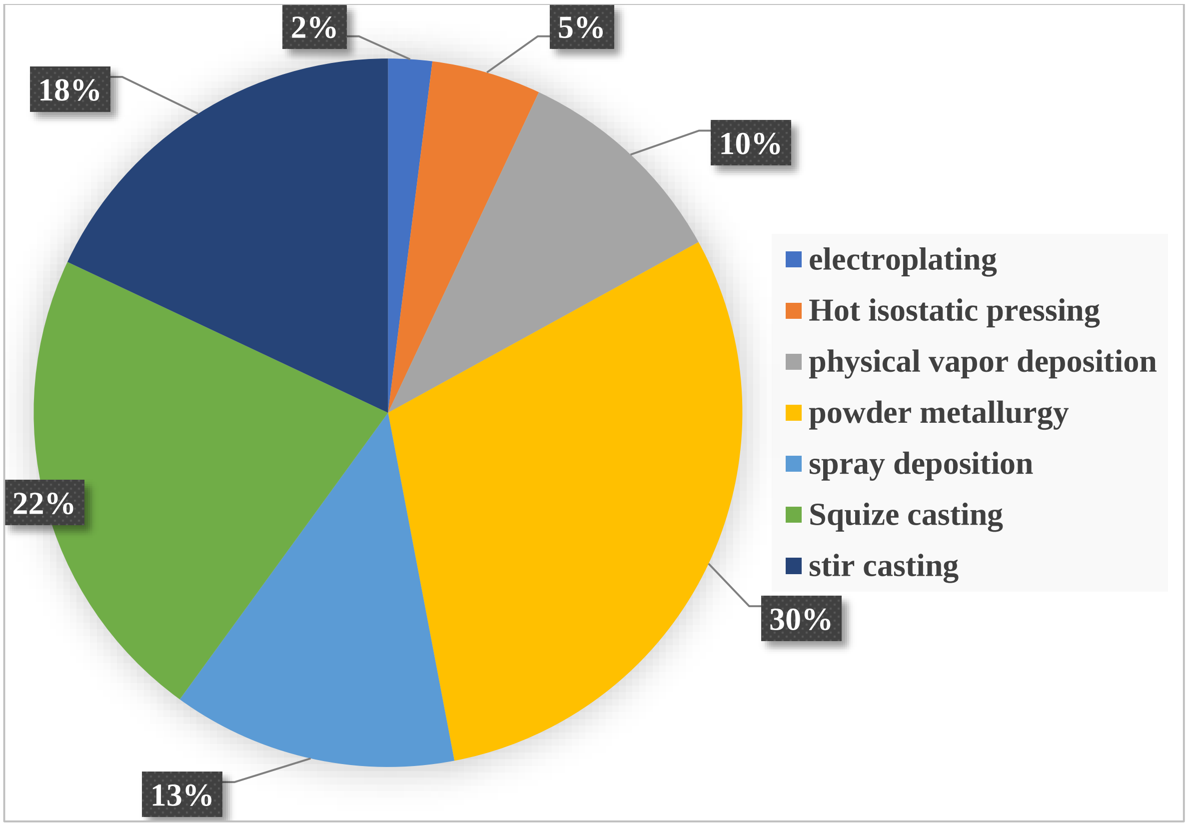


Figure 6: Research Studies conducted on fabrication routes of MMCs for the last 10 years(Chak et al., 2020)

i. Powder blending

Slipenyuk et al.(Slipenyuk, 2004), reported that the matrix-to-particle size ratio (PSR), which results in a finer microstructure and superior mechanical characteristics, should be close to 1. Additionally, they noted that if the PSR is higher than this number, agglomeration will occur as a result of the matrix's reduced surface area, which is insufficient for a uniform distribution of the reinforcement particles.

ii. Powder compaction

Compacted in solid dies, intricate, multilayer PM components won't have uniform green density throughout. While it is normally desired to create a density that is as uniform as feasible across the compacted component, taller parts and parts with many levels are more likely to have denser zones that are not next to one another. Only a portion forms that can be expelled from the die chamber may be compacted in stiff dies. In general, parts having undercuts, reverse tapers, threads, and similar features are not useful. These characteristics are created by post-sintering machining procedures(Slipenyuk, 2004).

Table 2: Compaction pressure for different MMCs(Chak, 2018)

No	Metal matrix composites	Compaction pressure (MP)
1	Al/10 wt% SiC–Cu	180
2	(3Ni + Fe)-Al2O3	750
3	SiCp/Al-10 wt%Si and SiCp/Al-12 wt%Si	30 at 540-570 ^{o}c (hot pressed)
4	Al/SiC	200 – 300
5	Al/Al2O3	440
6	6711Al/SiC	400
7	Cu-graphite	700
8	Al/SiCp	80Ton
9	Al/SiCp	200
10	Al–SiC–B4C	150
11	NiFe–CNT and Ni3Fe–CNT	300

iii. Sintering Temperature

Sintering temperature is the primary determining factor in powder metallurgy process to have best output of the produced components. A key factor is the choice of sintering temperature. The range to choose the sintering temperature is (0.7 – 0.9)T_m where, T_m is the lowest melting point from the compositions (Kumar et al., 2021)The primary process of sintering involves heating the green compact to a temperature below the melting point of the matrix. As a result, the matrix powder melts and reacts with other components, such as reinforcement, to form a liquid between the particles that engulfs the more refractory phase.

2.3. Bamboo as reinforcement

Trees, especially with high strength, are renewable materials with a long application history in human society in the application of structural and furnishing (Xiaofeng Sun, 2020). To improve and provide better material properties and structural performance, compared to raw woods, machined wood or bamboo are produced in factories. This includes laminating, plying, and layering.

In light of the importance of climate change and the environment, experts are interested in switching from synthetic to natural fibers. Animal fibers having protein, such as silk, wool, and hair, are categorized as natural fibers. Plant fibers, such as bamboo, sisal, hemp, and flax, are also considered natural fibers (Subash et al., 2017). Plant fibers are primarily composed of lignin, pectin, cellulose, and hemicellulose. The kind of cellulose and crystallinity determine the effectiveness of plant fiber reinforcing. Plant fibers may be divided into seven categories: grass, stem, wood, fruit, seed, bast, and leaf. When compared to other plant fibers, bamboo, which is a member of the grass family Bambusoideae, offers a number of benefits, including low cost, low density, rapid growth, stiffness, and high mechanical strength. There are three types of bamboo extraction methods; Chemical, mechanical and combined methods.

In places like Africa, South America, and Southeast Asia where bamboo is a naturally occurring resource, bamboo goods are mostly produced. China presently exports more bamboo than any other country in the world, making up more than half of the total trade, according to International Network for Bamboo and Rattan (HUNTER, 2003).

More than 1,500 species and 90 genera of bamboos may be found around the world, spanning 36 million hectares (ha) of land and growing at heights up to 4000 meters above sea level in the tropical and subtropical region between 46° north and 47° south latitude. There are around 43 species of bamboo in Africa, which occupy over 1.5 million hectares (Amsalu Tolessa, 2017).

The kind of bamboo species, the location, the age (maturity), and the portions of the bamboo all have different chemical compositions. The physical and mechanical capabilities of bamboos, as well as how they are treated and used, are greatly influenced by the variety of bamboo's chemical makeup. The short and branching forms of hemicellulose are really constructed of carbohydrate polymers that are composed of simple sugars monomer to produce the linear structure of cellulose (Amsalu Tolessa, 2017).

Typically, the term "ash" is used to describe inorganic materials like metal ions, silicates, sulfates, or carbonates. The actual composition varies across wood species and is also impacted by the local constituents. The percentage of inorganic compounds, commonly known as ash, is made up of Ca, K, Mg, P, Mn, Fe, Si, Al, and Na salts (Amsalu Tolessa, 2017).

Bamboo culm has a hollow cylindrical structure, and the inner side of every culm is divided by several diaphragm-like structures that appear to be rings from the outside. Branches grow from the internode (space between two rings) (Amede & Hailemariam, 2021). The culm wall of bamboo consists of many vascular bundles, providing strength to the culm. The number of internodes can be defined by the height of the culm. The microstructure of bamboo culm consists of many vascular bundles embedded in parenchyma tissue and distributed across the wall thickness. Vascular bundles and bundle sheaths are the main parts of this plant, reinforcing the bamboo culm and connecting the nodes to the culm.

Manufacturing industries have increasingly adopted natural fiber composites as an alternative to traditional composite materials. The biodegradability and eco-stability of these replacements contribute significantly to their attractiveness. Bamboo fibers, in particular, are beneficial for the reinforcement of composites due to their ecological protection, reusability and recyclability, as well as their mechanical qualities (R. Harikumar, 2020; Zakikhani et al., 2014). Of the many tropical and subtropical regions that bamboo species grow in around the world - Asia being the notable leader with 65% of global production - Africa has seen increased activity among its native species, as shown on Figure 6(Amsalu Tolessa, 2017; Wang & Chen, 2017). Research into using bamboo from African nations for building materials is gradually being conducted (M A P Handana, 2020).

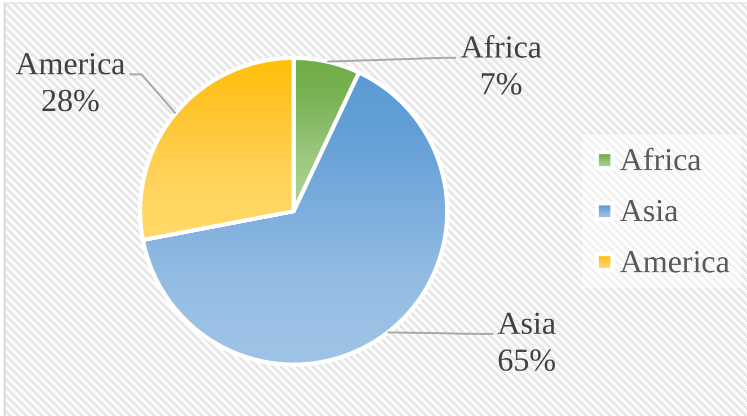


Figure 7: contribution of bamboo as a continent

Each bamboo culm has a hollow cylinder-like structure, and its inner side is separated by a number of diaphragms that, from the outside, look rings as shown in Figure 7. The "internode" is the area between two rings, and it is from this area that branches develop. Each node's distance changes depending on the species. Bamboo has several vascular bundles that provide the culm wall its strength. The height of the culm can be used to determine how many internodes there are. In order to define bamboo species, it is crucial to consider their average size, density, and number of vascular bundles. Bamboo culms' physical characteristics, which reflect their utility, are determined by their anatomical structure.(Banik, 2020; Wang & Chen, 2017). On average, bamboo that has low moisture content produces a stronger compressive force than those specimens that have higher levels of moisture(Dong, 2018; M A P Handana, 2020).

There are several different types of mechanical extraction techniques, including the steam explosion process, crushing, grinding, rolling in a mill, and retting. These techniques are used to harvest bamboo fiber for usage in many industries to create composite materials reinforced with bamboo fiber (Subash et al., 2017; Zakikhani et al., 2014).

According to Pravinkumar M. (M., 2018), Bamboo has a compressive strength that is about between 40 and 80 N/mm2, which is twice to four times greater than the average for wood timber species.

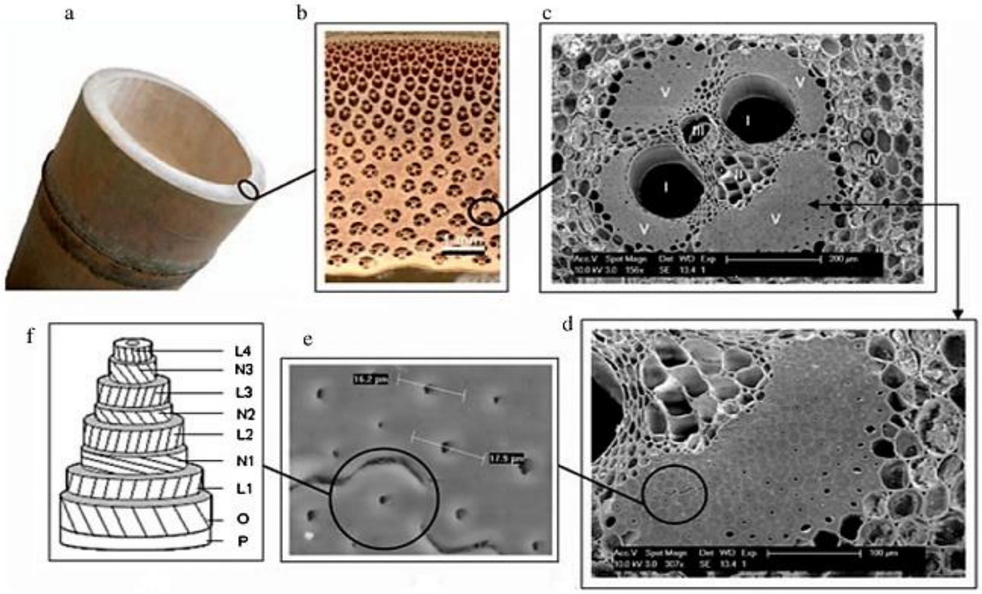


Figure 8: Bamboo plant and its cross-sectional microscopic images

Also, Bamboo has an average tensile strength of 160 N/mm2, which is frequently three times more than the majority of conventional construction-grade timbers. In comparison to compressive strength and even tensile strength of the same bamboo species, shear stress parallel to the grain is around ten times weaker. However, bamboo has a shear strength that is sometimes twice as high as that of common timber species. Most bamboo species have bending strengths that range from 50 to 150 N/mm2; on average, this makes bamboo twice as strong as most common construction timbers. Different test procedures, sample quality, and the bamboo under test's moisture content all contribute to variations within the same species.

2.4. Solid Lubricants as reinforcement

Solid lubricants are employed when liquid lubricants are unable to meet the demands of the required applications. Due to their weight, sealing issues, and environmental factors, oils, greases, and other liquid lubricants are not used in many applications. On the other hand, solid lubricants are less expensive and have less weight than systems that rely on grease lubrication. Since lubricants also evaporate in high vacuum, the liquid lubricants are unable to function, rendering the gadget inoperative. The oxidation or decomposition of liquid lubricants occurs at high temperatures. Liquid lubricants become viscous or harden at cryogenic temperatures and are unable to flow.

M. Asif (M Asif, 2011) has examined the dry sliding wear behavior of aluminum alloy-based composites, reinforced with silicon carbide particles and solid lubricants such as graphite/antimony trisulphide, and evaluated the creation of aluminum-based hybrid metal matrix composites for heavy-duty applications. The findings showed that the hybrid composite had a lower wear rate than the binary composite. As the load rises, the wear rate lowers as the speed increases.

Most PM components have pores. When metal powders are utilized to create self-lubricating bearings, where oil is impregnated into the surface-connected pores of the components, this is advantageous. Oil leaks from the pores of the bearing surface as it gets hot from frictional heat. The oil is drawn back into the pore channels by capillary action when the bearing cools. Parts' physical, mechanical, magnetic, thermal, wear, and corrosion characteristics are impacted by the porosity of PM components.(W. Brian James, 2015)

One of the lubricant materials is molybdenum disulfide, better known as MoS_2. All of its characteristics are unique because of its distinctive structure. The main components in boosting the material productivity are the features of MoS_2, which serve as the foundation of the compound. Because of how many and varied its applications are, this material's trustworthiness is maintained. Nevertheless, MoS_2 is a great material for many applications and sectors.

The substance molybdenum disulfide is good for a variety of industrial uses. However, its uses are so many and varied that they are being noticed in a variety of industries, increasing the material's productivity and legitimacy.

The hexagonal planes of the S atoms on each side of the hexagonal plane of the Mo atoms make up the crystal structure of molybdenum disulfide (MoS_2). Strong covalent bonds between the S and Mo atoms cause these triple planes to stack on top of one another. However, the layers are held together by weak Van Der Waals force, allowing the layers to be mechanically separated to create 2-dimensional sheets of MoS_2.

'Molybdenite' is a naturally occurring mineral in which MoS_2 is present. MoS_2 has a solid, lustrous, dark look when it is present in quantity. Due to the sheets' weak interlayer contacts, MoS_2 is also used as a lubricant since it allows for easy sheet-to-sheet sliding. Although MoS_2 is used as a substitute to graphite in high-vacuum applications, its maximum working temperature is lower than that of graphite. Bulk MoS_2 is a semiconductor with a 1.2eV indirect band gap, and as such, the optoelectronics sector is only really interested in it. Due to the hardness and abrasiveness of reinforcing elements like alumina particles, these materials are referred to be tough to manufacture materials. The wear resistance of composites is further increased by adding MoS_2 reinforcement as hybrid reinforcement. This is due to the mechanically mixed layer, which is stable and rich in MoS_2, which avoids metal-to-metal contact and lessens composite wear. In the absence of the lubricant phase, the mechanically mixed layer's instability reduces the hybrid composite's wear resistance (Chethan K N, 2018).

Depending on the percentage added, molybdenum disulfide increased the mechanical characteristics. It is discovered that the addition of molybdenum disulfide increases the hardness. The addition of molybdenum disulfide to the composite is also proven to increase its wear resistance. Since it is used in more than 50% of automotive parts, especially in engine blocks, pistons, liners, drive shafts, and rocker arms, it is helpful in the application of modern self-lubricating composite.(J. S. David Joseph, 2019)

According to David, Sathish et al. (J. S. David Joseph, 2019) the addition of MoS_2 improved the hardness of the composite and this is due to the uniform distribution of MoS_2 and its high ability to resist penetration because it has a strong ionic bond between molybdenum and Sulfur. The density of the composite also showed an increase with molybdenum disulfide addition. The reason is the density of molybdenum disulfide is higher than aluminum, and the uniform distribution of molybdenum disulfide and the lesser particle size of molybdenum disulfide made them fill inside the pores.

The creation of oxide layers, which guard against pin wear, is thought to be the reason why an increase in sliding velocity causes a decrease in wear rate. As a result of the increased pressure between the mating surfaces caused by the load increase, the wear rate increased at lower sliding velocities, causing more material to be removed as debris. The highest wear rate was observed at 0 wt.% MoS_2 at the highest load of 29.43 N and highest sliding velocity of 3 m/s. Whereas the lowest wear rate was observed at 10 wt.% MoS_2 medium load of 19.62 N load and highest sliding velocity. This demonstrates that the wear performance of aluminum composites will be significantly impacted by the inclusion of molybdenum disulfide. The improvement in wear resistance is the result of the lubrication provided by molybdenum disulfide.

The addition of solid lubricant should not exceed the allowed quantity and that it may be used in conjunction with other ceramic reinforcements, which in turn reduces their resistance to wear. When the amount of solid lubricant increases, the material's hardness falls as a result of the compound's increasing porosity (S., 2018).

Due to its superior self-lubricating qualities, graphite is included as reinforcement in the majority of studies to lower wear rate and friction. However, relatively few attempts have been made to use MoS_2 as a strengthening element in self-lubricating aluminum matrix composites. The main benefit of MoS_2 over Gr is that it can display its solid lubricant properties even in a vacuum environment since it doesn't require any additional assistance, such as air (oxygen), to do so (S., 2018).

As Ravichandran, Mohanavel(M.Ravichandran, 2021) studied the hybrid composites of AA7075 and 2 wt% MoS_2 with secondary reinforcement of AlN became more porous as the weight percent of AlN rose. The change in the mechanical, physical, and thermal characteristics of AA7075, MoS_2, and AlN are what causes the hybrid composites with an AA7075-2% MoS_2 matrix to become more porous. The increase in porosity of hybrid composites is also caused by the agglomeration of the reinforcing particles. And also, Vickers hardness and the TS of the hybrid composites made up of AA7075 and 2 weight percent MoS_2 matrix rose as the AlN weight percentage increased. AlN has a harder surface than AA7075. As a result, the hybrid composites comprising AA7075 and 2 weight percent MoS_2 are substantially harder. AlN in the matrix is what causes the rise in hardness. And due to the uniform distribution of AlN and MoS_2 and the grain refinement and interfacial bonding between the AA7075 and AlN are the reasons for the improvement in TS.

2.5. Applications of MMCs

Some of the proven commercial applications of AMMCs areas given below:(Mavhungu et al., 2017; Moona et al., 2018)

I. Brake rotors made form aluminum composites (AlSi7Mg+SiC particulates) for Germanhigh speed train ICE-1 and ICE-2 developed by Knorr Bremse AG.
II. The braking systems (discs, drums, calipers or back-plate) of Volkswagen made from particulate reinforced aluminum alloy.
III. AMMC continuous fiber reinforced pushrods produced by 3M for racing engines. These pushrods weigh 40% of steel.
IV. AMMC wires also developed by 3M for the core of an electrical conductor.
V. Pistons, brake rotors, calipers, liners and propeller shafts manufactured by Duraclan, Martin Mareitta, GKN and Lanxide using Al-SiC particle composites.
VI. Connecting rods of Nissan using Al-SiC whiskers composites.
VII. Piston rings of Toyota using Al-Al2O3 composite.
VIII. Connecting rods of DuPont and Chrysler using Al-Al2O3 composite.
IX. Pistons and connecting rods of Martin Mareitta using Al-TiC particle composite.
X. Engine blocks of Honda using Al-Al2O3-carbon fiber hybrid composites.
XI. Brake rotors of Lotus Elisse, Chrysler and Volkswagen using Al-SiC particle composites.
XII. Rear brake drum, drive shaft and engine cradle of General Motors using Al-SiC particle composites.

2.6. Summary of literature

As a summary, the addition of different ceramic and solid lubricant reinforcements in aluminum matrix composites had been reported. Some researchers focus on the improvement of mechanical properties of AMCs and get improved results. The others tried to improve the wear performance and corrosion resistance of AMC by adding solid lubricants and hard ceramic materials and succeeded. Some of the researchers used a single reinforcement and others used double sometimes triple reinforcements to get the necessary optimum results. The use of plant extract reinforcements also reported for the improvements of mechanical tribological and corrosion resistance of Aluminum matrix composites. The results were improving some properties not all, so to improve the hardness, compressive strength, wear, corrosion properties and reduce density and porosity of the Aluminum matrix composite addition of different reinforcements with different quality should be employed.

2.7. Research Gap

From previous literature, it is obvious to understand that ceramic particles reinforcement materialssuch as; B_4C, SiC, Al_2O_3, MoS_2, graphite, and plant extracts such as rice husk ash, Bamboo leaf ash, coconut seedpod ash etc., had used to influence the physical, mechanical, andtribological properties of hybrid aluminum matrix materials (Aktar Zahid Sohag, 2020; Arun, 2015; B. Ramgopal Reddy, 2018; Murlidhar Patel1, 2020; S., 2018). There is no researchwork performed to study the behavior of a combination of bamboo ash powder, Alumina, Boroncarbide, and Molybdenum disulfidefineparticulatesastetrahybridreinforcement with the pure Aluminum matrix material.Thepresentworkwillfocusonthefabricationofhybridaluminummatrixcomposite materials with pure Al as matrix material and bamboo ash powder, alumina, boroncarbide, and molybdenum disulfidefineparticulatesashybridreinforcements.Thephysical,mechanical,andtribologicalbehaviorofthehybrid composites will also be investigated.

There is also no researchon the fabrication of bamboo stem ash powder, Alumina, Boroncarbide, and Molybdenum disulfidefineparticulates hybrid reinforced aluminum compositefabricated using powder metallurgy process. In this work, HAMCs had been prepared bypowdermetallurgymethodwithdifferentweightpercentages of bamboo stem ash powder. Further investigation includes process parameters of powder metallurgy such as bamboo stem ash extraction method, sintering temperature, sintering time, and pressing pressure in the production process were analyzed.

CHAPTER THREE

3. Materials and Methodology

3.1. Materials

3.1.1. Bamboo ash powder extraction

Bamboo with the age of 1.5 to 2 years is cut and let dry in sun for about a week. After a week the bamboo stem was put in the oven for about 24 hrs. at 85 ^{o}c to remove the remaining moisture. The dried bamboo then was burned in an open air to reduce equipmentdamage and then calcined at 800 ^{o}C for 2 hr. The calcined powder sieved using 100-micron sieve. The necessary characterizations were conducted before the powder was mixed with the matrix and secondary reinforcements.

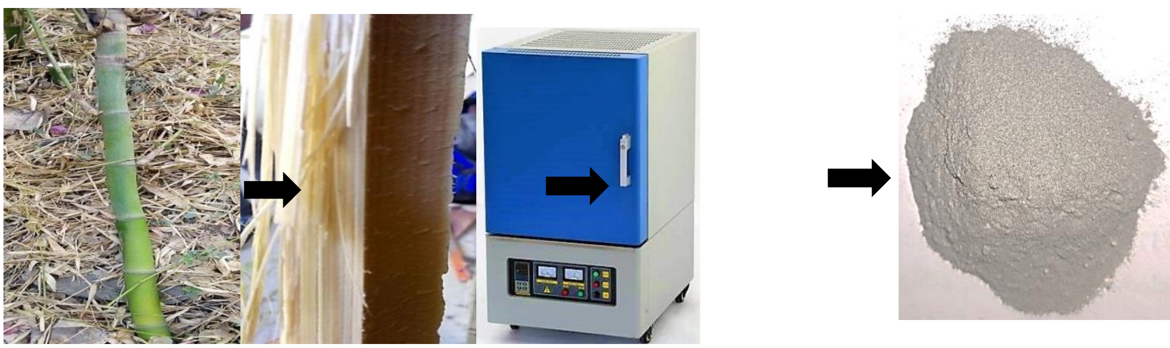


Figure 9: BSAP extraction process

3.1.2. Materials selection

The materials that are used in this research are selected depending on different parameters or properties. The physical, chemical and thermal properties are listed in Table 3below.

3.1.3. Sample Preparation

Pure Aluminum powder for matrix, Al_2O_3, B_4C, and MoS_2 has been purchased from the local market. After preparation of the BSAP and weighing the appropriate amount of the powders, mixing is performed using a High Energy Ball mill for 2 hrs. with a composition ratio as shown in table 3. After the mixing process is done, using a 20mm diameter die and punch pressing of the test sample is done at 60 MPa holding for 20 min to ensure the compaction process. The pressed pellet then sintered at 550 ^{o}C for 2 hrs. The necessary characterizations and tests performed and analyzed.

Table 3: Some physical & mechanical properties of the reinforcements

Property	Al_2O_3	B_4C	MoS_2
Melting point	2,072 °C	2,763 °C	2,375 °C
Density	3.95 g/cm3	2.52g/cm^3	5.06g/cm^3
Hardness	15 – 19 MPa	26 - 30 Mpa	2256 MPa
Mechanical strength	300 – 630 MPa	350 – 650 MPa	600 – 900 MPa
Thermal conductivity	20 – 30 W/mK	31 – 90 W/mK	~35 W/mK
Molecular mass	101.96 g/mol	55.25g/mol	160.07 g/mol
Appearance	White	Blackish grey	Black or lead gray crystal

Table 4: Sample composition design in weight percent

Material	Weight percentage (wt. %)					
	BP-00	**BP-01**	**BP-2.5**	**BP-5**	**BP-7.5**	**BP-10**
Al	100	90.5	88	85.5	83	80.5
B_4C	0	5	5	5	5	5
Al_2O_3	0	2.5	2.5	2.5	2.5	2.5
MoS_2	0	2	2	2	2	2
BSAP	0	0	2.5	5	7.5	10

(a)

(b)

Figure 10: produced samples for (a) mechanical testes (b) wear test

3.2. Methodology

3.2.1. Powder metallurgy process

1. **Powder mixing and blending**

The powders, mixture of Al/5%B_4C+ 2.5%Al_2O_3 + 2%MoS_2 + (2.5, 5, 7.5, and 10 wt.% of BSAP), were mixed using a high energy ball milling machine with constant speed of 320 rpm for about 2 hrs.

2. **Compaction process**

The blended powder compacted in a uniaxial hydraulic pressmachine to obtain a solid green sample at room temperature.The test samples were compacted using a 60 MPa compaction pressure.

3. **Sintering process**

The sintering process takes place in a muffle furnace for about 2hrs. at a temperature of 550 ^{o}C. The samples were covered with aluminum foil to reduce oxidation and inclusion of unwanted impurities at the time of heating and cooling.

3.2.2. XRD analysis

The XRD characterization of the BSAP powder and the composite were performed using X-Ray Diffracto-meter (XRD) from SHIMADZU Corporation (Japan) Model: XRD-7000 MAXIma and were analyzed using Origin and Xpert high score plus soft wares.

3.2.3. Thermal analysis

The thermal analysis is done on Differential Thermal gravimetry Model: DTG - 60H SHIMADZU Corporation (Japan) thermal analyzer and the results are drawn and interpreted using Origin software.

3.2.4. Density and porosity analysis

Using the Archimedes principle and the ASTM standards, the density of the composite was determined. The specimen was initially discovered as a sintered mass and measured (dry weight). Thereafter, for a total of two hours, the specimen was kept in a 70°C temperature of hot water bath to facilitate the pores filled by water. The mass was measured and then weighed to determine its saturation. Finally, a water-filled beaker was used to quantify the suspended mass after the weight of the composite compacts was determined while the specimen was suspended in the water. Using the Archimedes principle, we can determine the weight of sintered, wet, and submerged samples in this case (Annigeri, 2018; Ndudim Ononiwu, 2020).

3.2.5. FTIR spectroscopy

The fingerprint area in FTIR spectroscopy is part of the spectrum that normally lies between 400 and 1500 cm-1. The term "mid-infrared" is also occasionally used to describe this area. The term "fingerprint region" refers to the region of the spectrum that may be used to identify and characterize the molecular structure of a sample because it has a distinctive pattern of peaks.

The bending and stretching vibrations of various chemical bonds and functional groups in a molecule give rise to a significant number of peaks in this spectrum. The pattern of peaks in the area is unique to each molecule since each one has a different arrangement of bonds and functional groups, making it an effective tool for identification and characterization.

3.2.6. BET

One approach for calculating a solid material's precise surface area is the BET method. The BET method is popular and usually regarded as one of the most precise and sensitive ways to determine a solid's specific surface area. In addition to the surface area pore size and pore volume of the can be found from BET. The reduction of the pore size and pore volume in the composites were measured.

3.2.7. Hardness test

The resistance to persistent indentation is indicated by a material's hardness. An indenter is used to assess a material's hardness by pressing it into its surface while being subjected to a certain weight for a predetermined amount of time. Using a low power microscope, the area of the indentation made in the test material is measured. The test material is determined to be softer the greater the indentation the indenter leaves on the surface of a workpiece (specimen) when applying a specific test force.

3.2.8. Compression test

Compression testing machines are used in compression tests to analyze the behavior of materials under escalating compressive loads. Compression tests check at a material's reliability, robustness, and integrity. To assess the compression qualities of the material being tested, pressure is applied to a specimen during the test using compression platens or unique instruments installed on a testing machine.

Results from the test are shown in the form of a stress-strain diagram, which also shows the yield point, the elastic limit, the proportionality limit, and, in certain situations, the compressive strength.

3.2.9. Wear test

Wear is a process of removal of material from one or both of two solid surfaces when their surfaces are in solid contact during sliding or rolling under a load. In order to make the best choice of material for a specific application, it is necessary to know the wear resistance of the material because wear is the main cause of material wastage.

3.2.10. Corrosion test

The material's composition, manufacturing method, exposure to a particular environment, and other environmental factors all affect the sort of corrosion that develops in MMCs. For the purpose of creating methods to stop or lessen corrosion damage, it is crucial to understand the processes of corrosion in MMCs. The corrosion test performed on BioLogic SP300 model potentiostat.To quantify the corrosion property of metal matrix composites, there are different method of measuring or testing. The mainly used are the following.

1. **Tafel plot**

A Tafel plot is a graphical representation of the electrochemical behavior of a material in a corrosive environment. It is named after the German chemist Julius Tafel, who developed the plot in 1905. The Tafel plot is obtained by measuring the current density (I) and the corrosion potential (E_{corr}) of a sample material in a corrosive solution and plotting the logarithm of the current density against the overpotential (η), which is the difference between the measured potential and the corrosion potential.

2. **PEIS**

Corrosion testing and research frequently employ the EIS approach. The major goal of EIS in corrosion testing is to offer details regarding the electrochemical behavior of metallic materials in diverse settings, including the rate of corrosion, the mechanism of corrosion, and the efficacy of corrosion prevention methods.

3.2.11. Optical Microscope imaging (OM)

The Optical Microscope imaging is done on Huvitz microscope mainly for the corroded samples to see the corrosion effect of on the tetra hybrid reinforced aluminum composites. Form the images we can differentiate which type of corrosion happened on the composites.

3.2.12. Scanning Electron Microscope (SEM)

A scanning electron microscope (SEM) is a kind of electron microscope that scans a sample's surface with a concentrated stream of electrons to create high-resolution pictures of the surface. The Scanning Electron Microscope test is done using ACCEL VOLT 10.0 model JCM-6000plus testing machine. The results are analyzed using ImageJ software.

CHAPTER FOUR

4. Result and Discussion

4.1. Characterization of BSAP

4.1.1. Phase analysis

From the XRD graph of BSAP Figure 11 after calcined at 800 ^{o}c, we can see that the cristallinity of the powder is increased as calcined at elevated temperature. This is due to the crystals got enough energy to rearrange themselves. The peaks at 26.63 (011), 49.95 (112) belongs to quartz hexagonal structure silica in agreement with (JCPDS card No. 85-1780) and the peaks at 12.69 (026) 27.39 (240) (JCPDS card No. 71-0261) belongs to silica (quartz). In addition the peaks at 42.76 and 60.45 belong to cristobalite silica (JCPDS card No. 89-3434) (Shanmugam et al., 2020). The peaks of Al_2O_3, Fe_2O_3 and CaO appeared in small amount. Other unidentified peaks also were shown.This shows that BSAP is rich in silica which is ceramic reinforcement for Aluminum and its alloys.

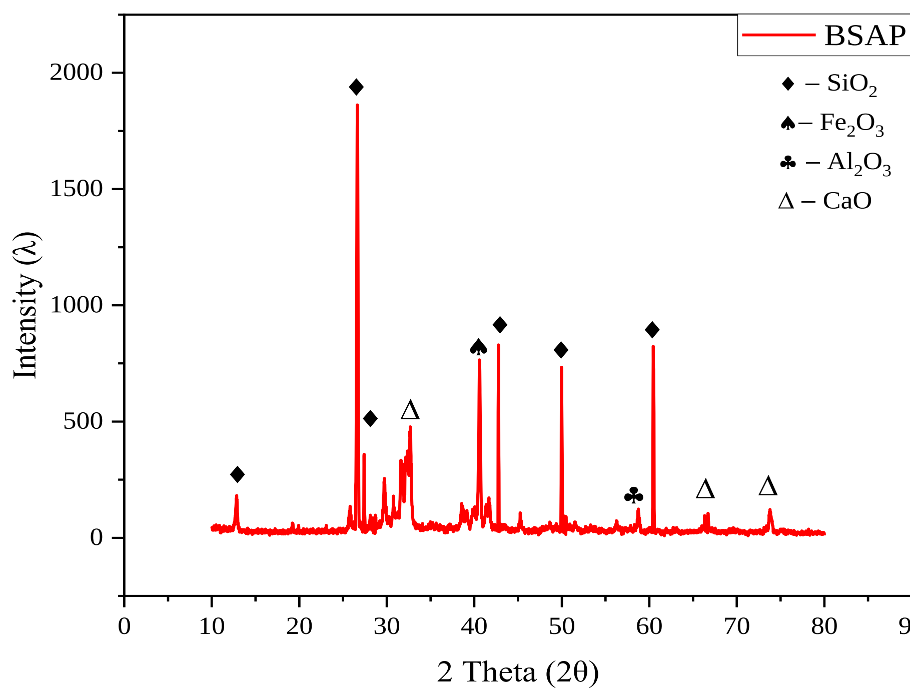


Figure 11: XRD graph of bamboo stem ash powder

4.1.2. XRF analysis

The X-ray Florescence (XRF) test in Table5reveals that the BSAP contains SiO_2 as a majority, which is a hard ceramic compound that can be used as reinforcement for metal matrix composites, followed by Al_2O_3,$Fe_2O_3$and CaO. The presence of these ceramic and metallic oxides compounds makes BSAP good replacement for some rare and expensive ceramic reinforcements.

Table 5: XRF analysis of BSAP

Compound	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	P_2O_5	TiO_2	MnO	SO_3
Percentage(%)	71.28	10.13	7.17	5.43	1.75	2.35	1.02	0.56	0.16	0.15

4.1.3. FTIR analysis of BSAP

The FTIR spectra in Figure 12 shows the infrared ray spectrum of BSAP. The peak at 461 belongs to Al-O bending vibration, 1034 cm^{-1} can be attributed to asymmetric stretching vibration of Si-O-Si bonds(Ashebir et al., 2022; Li et al., 2014).The peak at 617 cm^{-1}belongs tobending vibration of Si–O–Si. The peak at 786 cm^{-1} associated to the symmetric vibration of silica. The peak spectrum at 2166 cm^{-1} is attributed to stretching vibration of Si-O bonding(Darmakkolla et al., 2016). This shows BSAP functional groups and there is no Si-OH bonding which acts as corrosion agent.

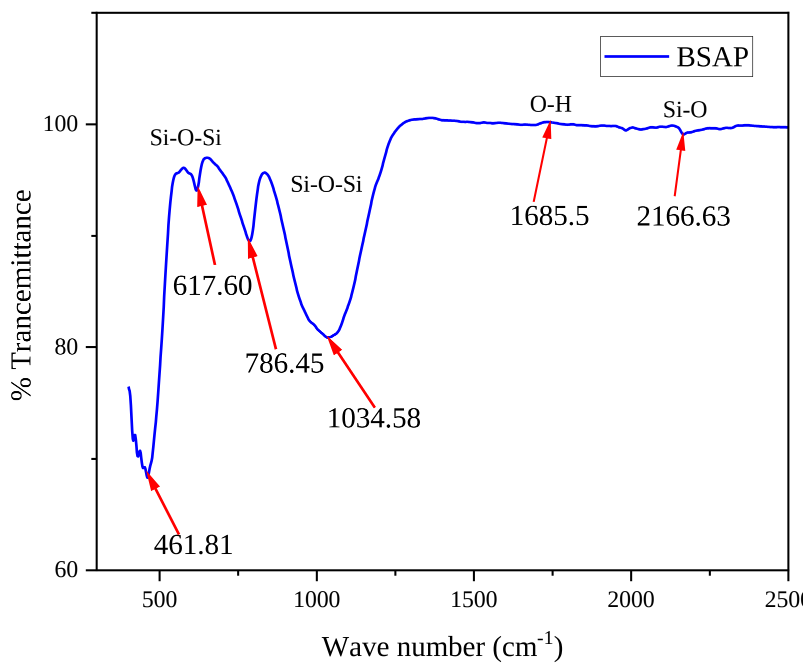


Figure 12: FTIR spectra of BSAP

4.1.4. Thermal analysis of Bamboo Powder

Thermo-gravimetric analysis (TGA) was used to examine the weight change of BSAP materials as a function of temperature, whereas differential thermal analysis (DTA) was used to examine the phase shifts of BSAP materials as a function of temperature. The thermal analysis, in general,was used to determine the calcination temperature of the powder.

The experimental graph in Figure 13 had shown that when heated at a rate of 20 ^{o}C/min, the powder experienced 6.85% mass loss upon reaching 100 ^{o}C - attributed to external trapped water and moisture evaporation from the powder. At temperature ranging from about 200-463 ^{o}C, organic compounds' volatilization caused an additional 94.69% in mass loss. During this period, two endothermic peaks were observed on the DTA curve due to the breakdown of volatile substances into three primary components - cellulose, hemicellulose and lignin (Shanmugam et al., 2020). Moreover, BSAP thermal patterns between 463-900 ^{o}C has small mass loss, about 0.504%, and it is almost stable (Juan Pablo Márquez Costa, 2019). This shows that there are thermally stable contents like SiO_2, Al_2O_3, CaO and others are available in the powder (Ashebir et al., 2022).

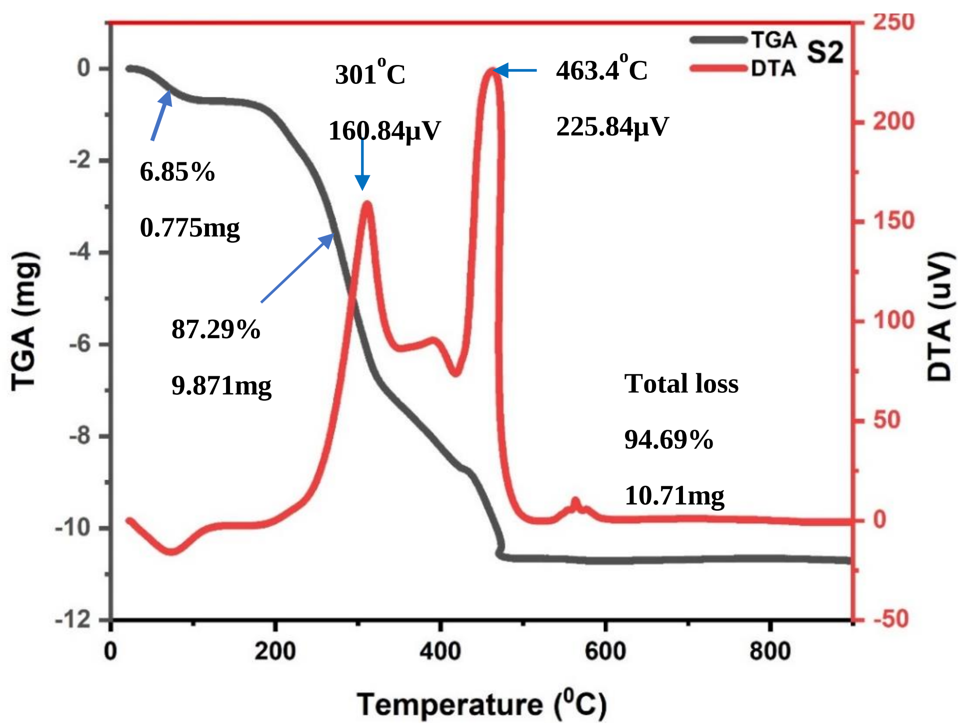


Figure 13: TGA/DTA graph of BSAP

4.2. Characterization and test of the composites

4.2.1. Phase analysis

The X-Ray Diffraction graph of the prepared samples Figure 14 reveals that the addition of BSAP does not appear to affect the phase of the matrix (aluminum). This is likely because there is no unwanted interfacial chemical reaction between the matrix and reinforcements observed. The small peak related to (011) crystallographic plane of SiO_2 at 26.63 degrees is shown for BP-7.5 & 10 samples; this is due to a comparatively low weight concentration ratio when compared to aluminum levels, which take precedence in XRD tests. The peaks of the other reinforcements also haven't appeared in the XRD graph due to the dominance of the matrix in quantity. In general we can say that BSAP can be a good replacement of costly ceramic reinforcements to reinforce Aluminum and its alloys to improve different properties and so that it can be used in the applications of automotive and aircrafts (Ikubanni et al., 2021).

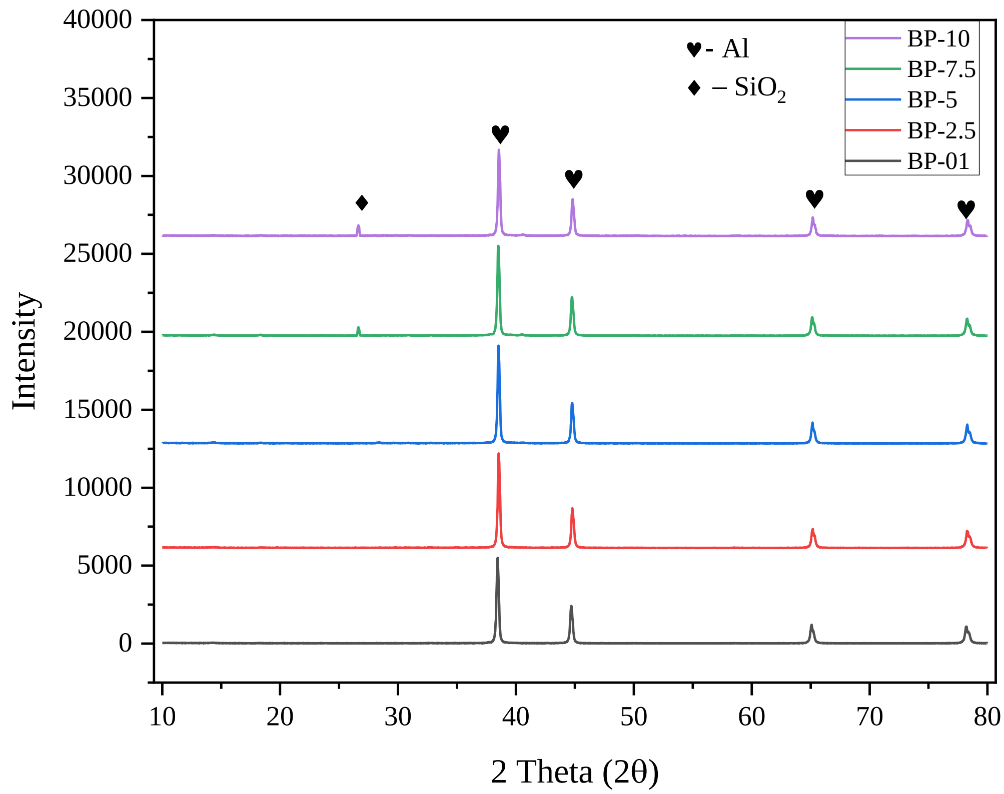


Figure 14: XRD graph of the HAMC composites

4.2.2. Thermal analysis of the composites

The thermal analysis of the composites in Figure 15tells that the addition of BSAP have slight effect on the thermal properties of the composites. From TGA curve in Figure 15 (a) which contains 0 wt.% of BSAP,when the temperature of thematerial increases from 80 °C to 300 °C there was an increase in mass about 0.01 – 0.02% and the reason for this might be introduction of impurities from the heating atmosphere. Heating from 300 ^oC up to 660 ^oC increase the weight gain of the material and this might be due to the formation of oxide layer on the surface of the material as W. Smeltzer(Smeltzer, 1956) mentioned. Beyond 662 ^oC there is a higher rate of weight gain, and the reason for this is the total oxidization reaction of Aluminum and Oxygen (Park et al., 2019). This causes a total of 1.37 mg increment in the mass of the material. When we see the DTA curve in Figure 15 (a) there are three exothermic reactions and one endothermic reaction. The endothermic reaction occurs at 737.4 ^oC has a value of 12.6 µV and is due to the oxidization of the matrix material. The first exothermic peak occurs at 38.64 ^{o} C with the value -1.61 µV and this is due to the inclusion of impurities from the atmosphere of the heating. The highest exothermic reaction occurs at 662.5 ^oC (-38.89 µV). The reason for this might be the property of the reinforcements to absorb energy rather than phase change because the three reinforcements have lower thermal conductivity and higher heat of fusion. The third exothermic reaction appears at 860.8^oC (-4.62µV) and this is due to thermal degradation of aluminum to form Al_2O_3(Leon-Patino, 2000).

Figure 15 (b) – (e) show the thermal behavior of the composites after the introduction of different weight percent of BSAP. Form theTGA curves of the figures we can see that at 25 ^oC 100% of weight. Up to 100^o C there is no significant weight loss or gain observed. From 100^oC up to about 600 ^oC there is slight weight loss and this might be due to evaporation of moisture and other impurities trapped in the composites. As compared to BP-01, the addition of BSAP increase the thermal stability of the composites. From about 590 ^oC up to 660 ^oC there is small weight gain occur. Beyond about 660 ^oC there is high rate of weight gain due to oxidation reaction. Even if the four samples have the same trend of increment of mass, as the percentage of BSAP increase the weight gain slightly increase. This might be due tothe presence of metal oxide in the plant extract facilitate the oxidation process. The DTA curves of the composite samples in Figure 15 (b) – (e) show no exothermic reaction and higher endothermic reactions at about 682 – 685ºC. This is due to the phase transformation or oxidization of the matrix material. The phase transformation temperature increases as compared to BP-01 (0wt.% of BSAP) and this might be due to the presence of BSAP. And also, the endothermic reaction energy increase from 220 – 330 µV which is far high from BP-01 (12.6 µV). this is due to the presence of oxides in the plant extract that can support the formation of oxide (Singh et al., 2015). The addition of B_4C MoS_2 and Al_2O_3 increase the thermal stability of the composites in addition to the inclusion of BSAP (Fayomi et al., 2019). In general,Table 6 can summarize the thermal behavior of the tetra hybrid reinforced composites.

The range of thermal stability increases with the addition of hybrid reinforcement particulates. Tetra hybrid reinforced aluminum matrix composites were stable at the temperature range of 100 to 662 ℃ above the range of stability for the base metal (pure Al). All the composites show excellent thermal resistance and material stability at a higher temperature. The findings of this workare further can be related to previous researches (Ashebir et al., 2022; Kumar et al., 2021).

Table 6: summary of thermal property of the composites

samples	Total weight gain (in milligrams)	TGA (stable region) (in ºC)	DTA (Phase change) (in ºC)
BP-01	1.47	100 – 662.5	662.58
BP-2.5	2.02	100 – 661.97	685.1
BP-5	2.08	100 – 662	682
BP-7.5	3.0	100 – 663.5	676
BP-10	3.19	100 – 662.1	685

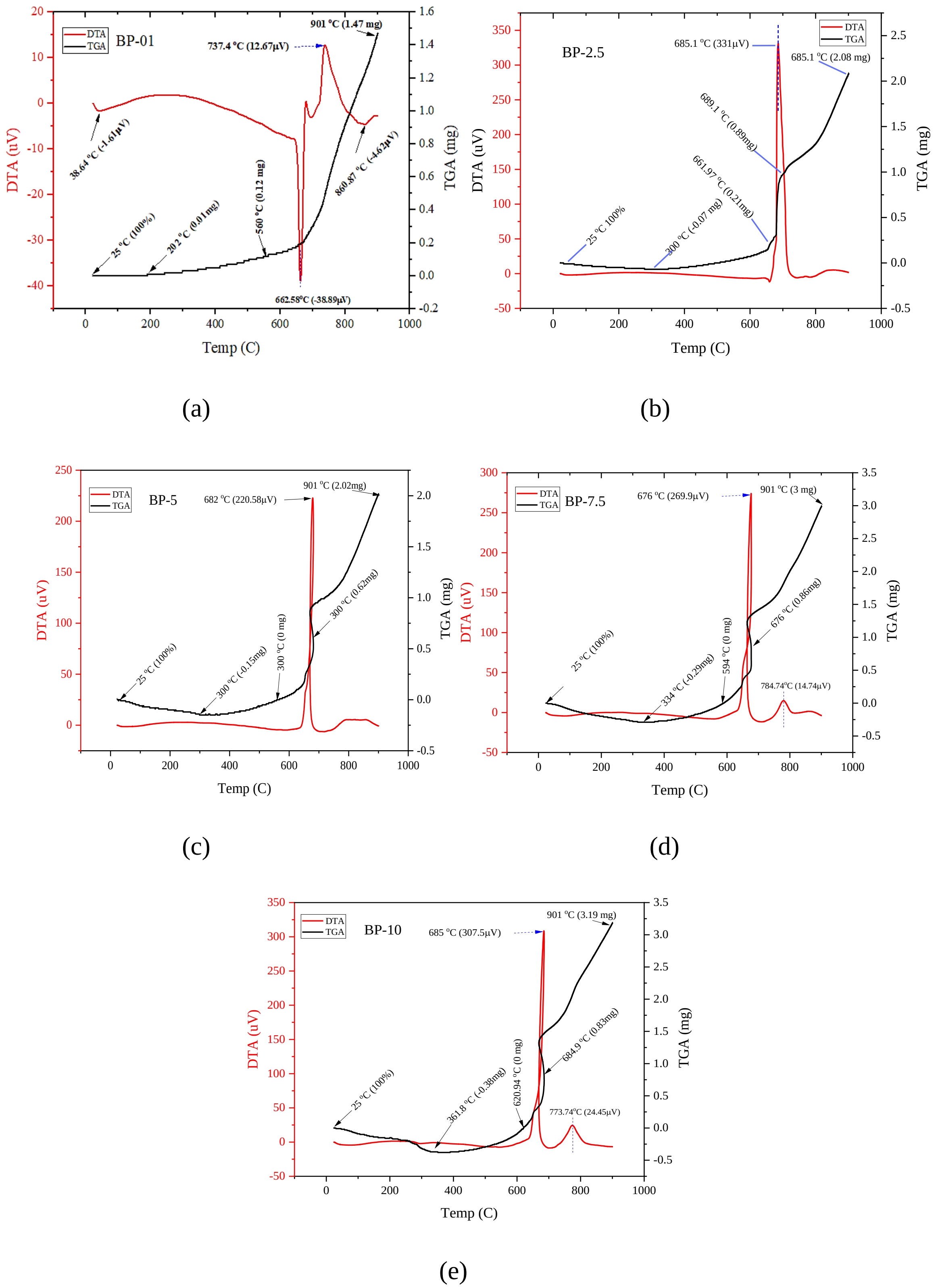


Figure 15: thermal analysis graph of the composites (a) BP-01 (b) BP-2.5 (b) BP-5 (d) BP-7.5 (e) BP-10

4.2.3. Brunauer-Emmet-Teller (BET)

Table 7: Brunauer-Emmet-Teller (BET) test data

Sample	Surface area (m^2/g)	Pore volume (cm^3/g)	Pore size (nm)
BP-01	594.542	0.04531	0.2361
BP-7.5	321.519	0.01537	0.1584

The BP-01 sample is higher than the BP-7.5 in terms of surface area, pore volume, and pore size. The presence of hard particles like B_4C and Al_2O_3 in the BP-01 sample may be responsible for its high specific surface area. According to the information in Table 7, the materials also contain micropores with diameters and volumes of 0.1584 nm and 0.01537 cm^3/g for BP-7.5 and 0.2361 nm and 0.04531 cm^3/g for BP-01 respectively. The BP-7.5 sample has 7.5 wt.% BSAP primary reinforcement, which reduce its surface area and micropore density. This is brought on by an improvement in the uniform dispersion of particulates throughout the matrix. And BSAP helps improve rearrange of particles inside the base material, increasing its hardness and reducing its porosity.

4.2.4. Density and Porosity analysis

Using the Archimedes principle, we can determine the weight of sintered, wet, and submerged samples in this case (Annigeri, 2018; Ndudim Ononiwu, 2020).

Table 8: Density and porosity of test samples

Sample	Theoretical density	Experimental Density (gm/cm3)	Porosity (%)
BP-00	2.7	2.5596	0.0049
BP-01	2.7694	2.4595	0.0183
BP-2.5	2.7232	2.4468	0.0161
BP-5	2.6799	2.4464	0.0128
BP-7.5	2.6302	2.4423	0.0102
BP-10	2.5844	2.3601	0.0187

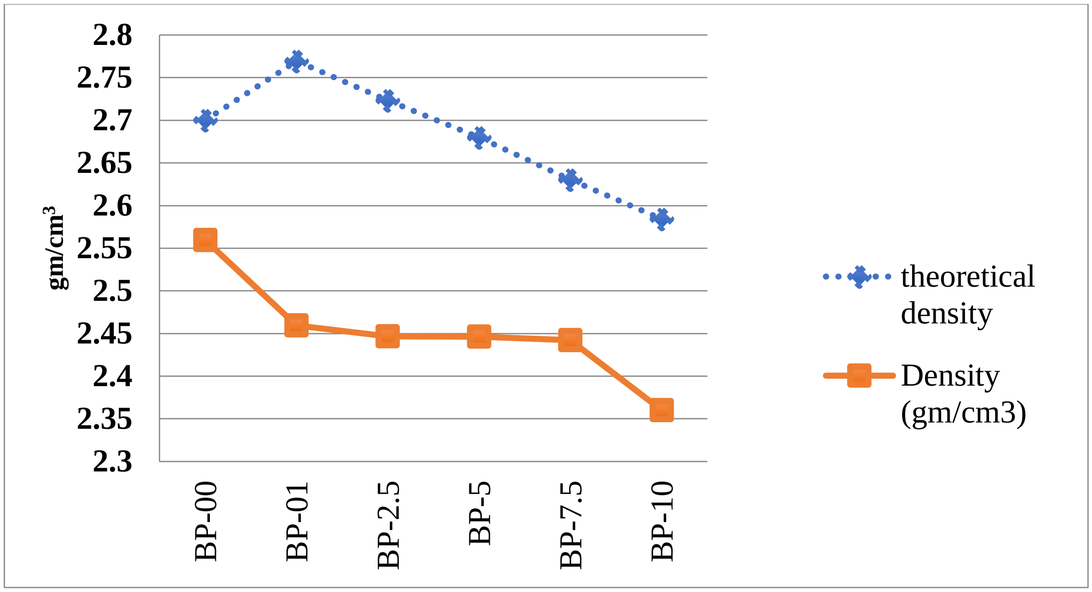


Figure 16: Experimental and Theoretical Density of test samples

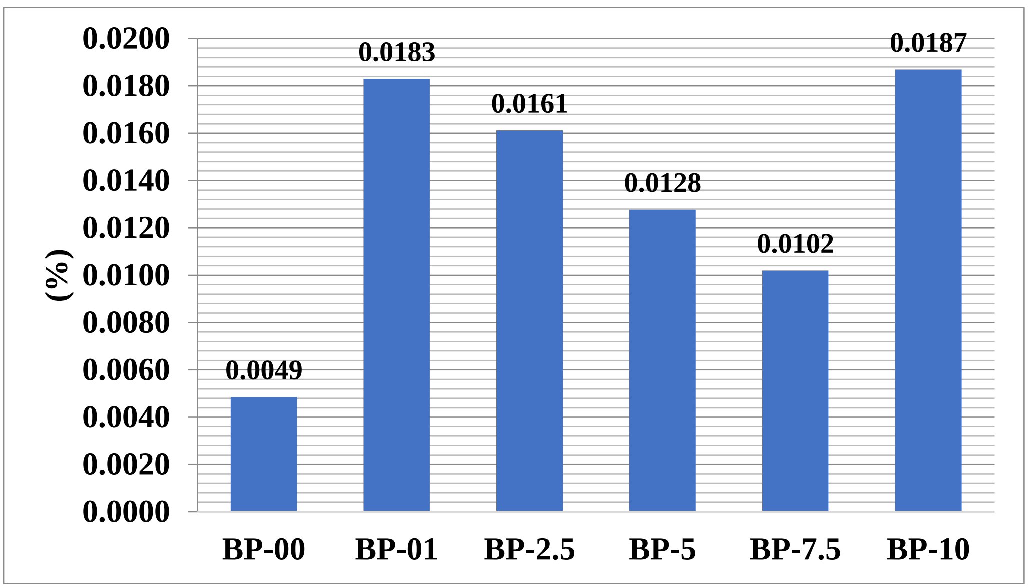


Figure 17: Porosity graph of the composites

Table 8shows the theoretical density, experimental density and porosity of the produced samples. The graph in Figure 16 reveals that introducing up to 10 wt.% BSAP reducethe density of the composites lower than pure aluminum, resulting in lighter weights. This is beneficial for aircraft, cars, and ships since it knocks payloads and lowers fuel consumption.When we see BP-01 (0 wt.% BSAP) of the theoretical density increases due to the addition of higher density reinforcements (Al_2O_3& MoS_2) which are harder materials. Even if in the experimental density it has lower density than pure aluminum, it has higher value of experimental density. BP- 01 has lower value than pure aluminum, is because of the weight percentage of higher density materials (Al_2O_3& MoS_2) and percentage of lower density material (B_4C) balanced and as a result the total density is lower than pure Aluminum. Porosity also another factor for the reduction in density. The theoreticaldensity of the composites with the addition of BSAP reduce linearly as the weight percent of BSAP increase. This is due to the reduced density of BSAP. Similarly, the experimental density is reducing as the weight percentage of BSAP is increased. This is due to the addition of lower density reinforcements (BSAP &B_4C). Up to the addition of 7.5 wt.% BSAP the density reduction is slight but when we introduce 10 wt.% BSAP the density falls lower as compared to the other composites. This is due to the pores nature of the plant extract(Dong, 2018).

In the porosity graph Figure 17, the composite with 0 wt.% BSAP (BP-01) has a higher porosity compared to the other composites. BSAP functions as filler and tempering agent when milled using high energy ball milling, which can boost cohesion between particles - leading to lower agglomeration. The porosities of the composites from 2.5-7.5 wt.% of BSAP have reduced gradually, while 10wt% causes an abrupt increase in porosity due to the pores nature of the plant extract and can absorb air and moisture (Dong, 2018). In addition, particle size is the other factor for the increasing of porosity; BSAP has higher particle size compared to matrix material and some of the reinforcements(Shanmugam et al., 2020).

4.2.5. Hardness test analysis

The hardness of the composites in Figure 18, increased as the composition of the bamboo powder increased up to 7.5 wt.% (BP-7.5) by 5.45 times, or 544.9% as compared to pure Aluminum.The BP-7.5 AMC sample has a maximum hardness value of 305.7 HV. This is due to the addition of BSAP fine particle. These fine particles fill the inter-molecular void and increase the surface area of the composites. As the sintering temperature increase beyond $400^{o}C$ there is a tendency to form oxide layer on the surface of aluminum matrix composites. The formation of this oxide layer increases the hardness of the composites (Smeltzer, 1956). The hardness of the composite decreased when we added 10 wt.% of BSAP, and this is due to delamination of the reinforcement (BSAP) because of exceeding the optimum weight that has to be added in the composite. The micro-hardness of the tetra hybrid composites was raised beyond the composites with single and double reinforcements, which was above that of the matrix metal, by the addition of smaller grain sizes, higher modulus powders, and multiple reinforcements. The expensive and less abundant conventional ceramic reinforcements can be optimized by replacing them with low cost and available materials like BSAP which is important for the development of hybrid aluminum metal matrix composites. This is an important development because agro-industrial solid materials like BSAP, which are low density, lightweight, and easily available, create a clean and safe environment (Parveez et al., 2021).The use of two or more reinforcing materials in HAMCs allows for the optimization of some features while also potentially lowering costs (Ramanathan et al., 2019). The most important hardness influencing factors are volume, size, and kind of reinforcing particles (Kulkarni et al., 2019). So, we can say adding BSAP in aluminum matrix composite have a great role in the increment of hardness of the composites with a reduced cost and weight.

Table 9: Vickers hardness test result

Samples	Average Hardness (HV)
BP-00	56.1
BP-01	166.1
BP-2.5	241.8
BP-5	253.4
BP-7.5	305.7
BP-10	222.54

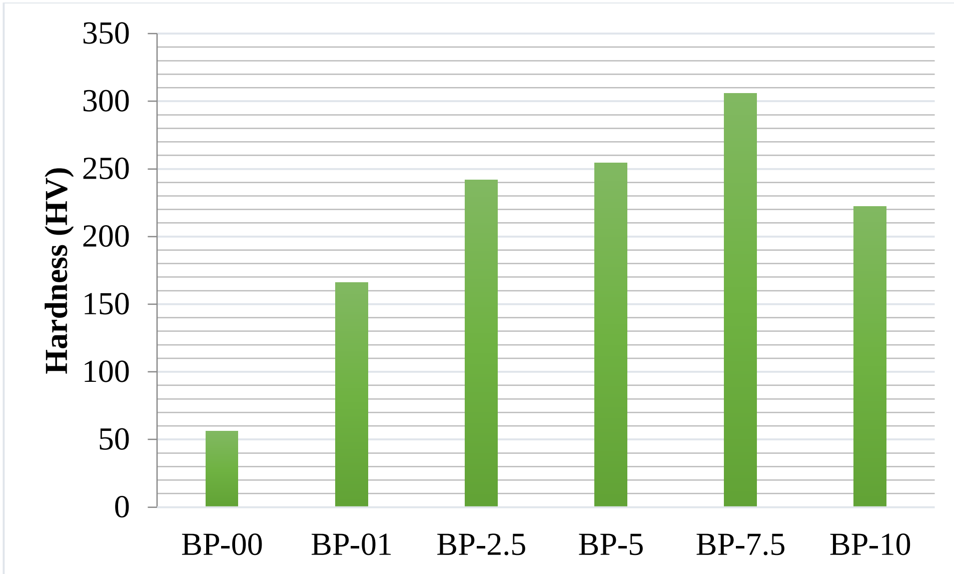


Figure 18: Vickers Hardness of the composites

4.2.6. Compression test

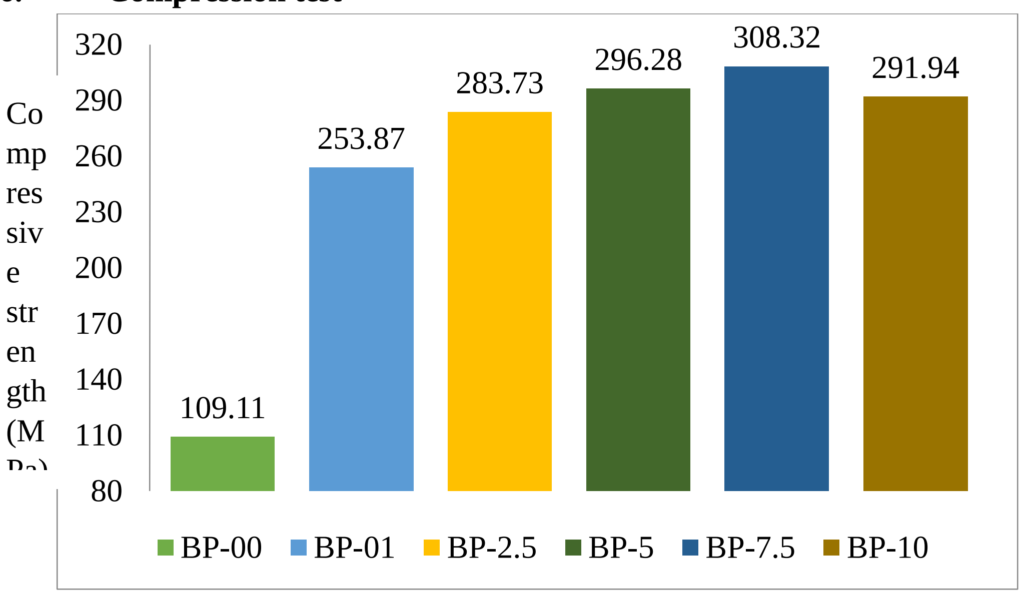


Figure 19: compressive strength of the composites and pure Aluminum

As can be seen fromFigure19 the compressive strength (CS) of the composites, as compared to the pure Aluminum, increase as the weight percentage of BSAP increase. The increase in the CS is due to the addition of the particulated BSAP and the secondary reinforcements (Sahu & Sahu, 2020). The compression strength has been demonstrated to increase with the usage of hybrid reinforcement. The inter-particulate space between the matrix (Al) and BSAP particles shrunk, which raised the dislocation pack (Ashebir et al., 2022). Since BSAP contain high strength ceramic material which is SiO_2(Silva et al., 2021) and found from XRF analysis, it affects the CS of the composites positively (Ashebir et al., 2022). The maximum compressive strength is found at 7.5 wt.% of BSAP introduced in the hybrid reinforced composite which is 308.32 MPa and this is 2.825 times the pure Aluminum. After the addition of 7.5 wt. % the compressive strength falls down. The reason for the fall down of CS of the composites is that as the percentage of the plant extract increase, the inter-particle physical bonding of the composites weakens. so, we can say the addition of BSAP on aluminum metal matrix can improve the compressive strength and can be used for components in need of high compressive strength like aircraft main frame, engine block, and other structural applications.

4.2.7. Wear test

1. **Effect of load on weight loss of composites**

The primary determinant of composite wear during sliding is the applied load. Pure Aluminum metal and the composite materials both experience increased wear loss as applied stress increases. There is a threshold transition load beyond which the wear rate sharply increases, according to previous research (Manivannan et al., 2018). In practice, moderate or oxidative wear happens when applied loads are below this threshold value, and severe or metallic wear happens at higher loads, which is followed by increased plastic deformation. As the load is increased from 10 to 30 N, the wear loss of Al rises. Wear degrading with higher loads is what contributes to the increase in wear loss. Al's temperature increases during sliding wear, seriously harming any surface asperities and reducing Al's hardness. The hardness, as well as the sharpness of a material's surface, influence its wear resistance.By acting as load-bearing components, the reinforcements B_4C, MoS_2, and Al_2O_3 as well as BSAP particles in the composites raise the compressive strength and hardness of the HAMC as compared to pure Aluminum. These enhanced characteristics increase the HMAC's subsurface anti-wear and plastic deformation resistance. The hybrid composite's wear surface hence produces relatively little wear debris. On the hybrid composite surface, the B_4C and Al_2O_3 particles also extend over the wear surface and aid in the formation of a stable tribo-layer. Up to a certain degree, supplementary reinforcement like BSAP help to prevent wear loss in HAMCs; after that point, the wear loss starts to increase.The improvement of the wear resistance of the composites by adding BSAP is due to the formation of oxide layer formed by the addition of the BSAP which contain metallic and ceramic oxide in it. Wear decreased from pure Aluminum to the composite samples with the addition of tetra hybrid reinforcement particles up to certain limits, and as the wt % of the tetra hybrid reinforcements increased above this optimal limit, the wear loss increased (Reddy et al., 2020; Suresh, 2020). After the optimal limit of the load the reinforcement and the matrix start to delaminate. This result to increase the weight loss of the composites. The minimum weight loss is registered on BP-7.5 sample is 0.0010 micron on 10 N loading and 0.0022 micron on 30 N loading.

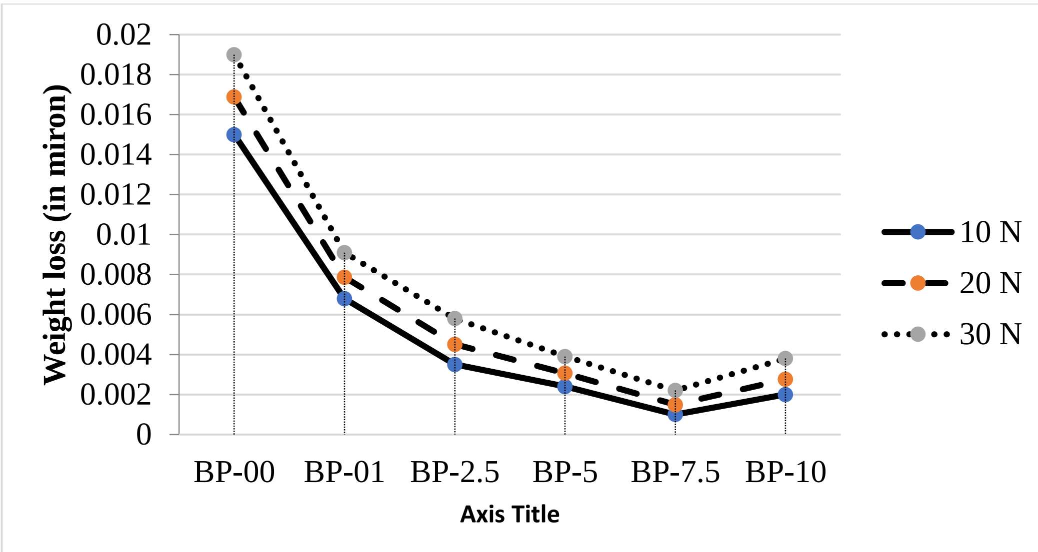


Figure 20: Effect of load on weight loss

2. **Effect of sliding distance on weight loss of the composites**

The difference in wear loss concerning the weight % of tetra hybrid reinforcements for 500, 1000, and 1500 m of sliding distanceare shown in Figures 21. In composites containing BSAP particles, wear loss is reduced by the solid lubricating property and oxide formation properties of BSAP. In sliding surfaces, the MoS_2 particles also spread off the contact surface and create a mixed layer that prevents metal-to-metal contact. Al_2O_3 has been shown to have a solid lubricating effect due to its hexagonal crystal structure, making it a suitable for reducing wear loss similar to BSAP(B. C. Kandpal, 2017). The formation of a tribo-layer between the sliding surfaces in composites reduces wear loss. At greater loads, this layer helps to avoid micro-cutting and scratching. Wear loss increases from 500 to 1500 m of sliding distance for all the tetra hybrid composites. The presence of the hard particles of B_4C also the other reason for the reduction of the weight loss in the composites(Gurpreet Singh & Sanjeev Goyal, 2016). In addition to these hard particles of Al_2O_3 and B_4C and solid lubricant MoS_2, the inclusion of BSAP has great effect on the improvement of tribological properties of the composites, since as the weight percentage of BSAP increased the wear loss decreases. The minimum weight loss due to sliding distance happens at BP-7.5 0.0049 micron on 10 N loading and 0.006 micron on 30 N loading.The wear loss of BP-7.5 is considerably less as compared to other composite samples. On the other hand, the wear loss rises as the proportion of BSAP grows up to 10 weight percent. In contrast to the other four composite samples, BP-10's wear loss does not diminish as the sliding distance increases; this may be because of the aggregation of tough BSAP particles. However, BP-10 has a higher wear resistance than the matrix material (pure Al). These patterns align with prior study findings from earlier studies (A. Nieto, 2017; Adediran et al., 2020; J. S. David Joseph, 2019; Manivannan et al., 2018). This result also in agreement with other physical and mechanical property tests in this research.

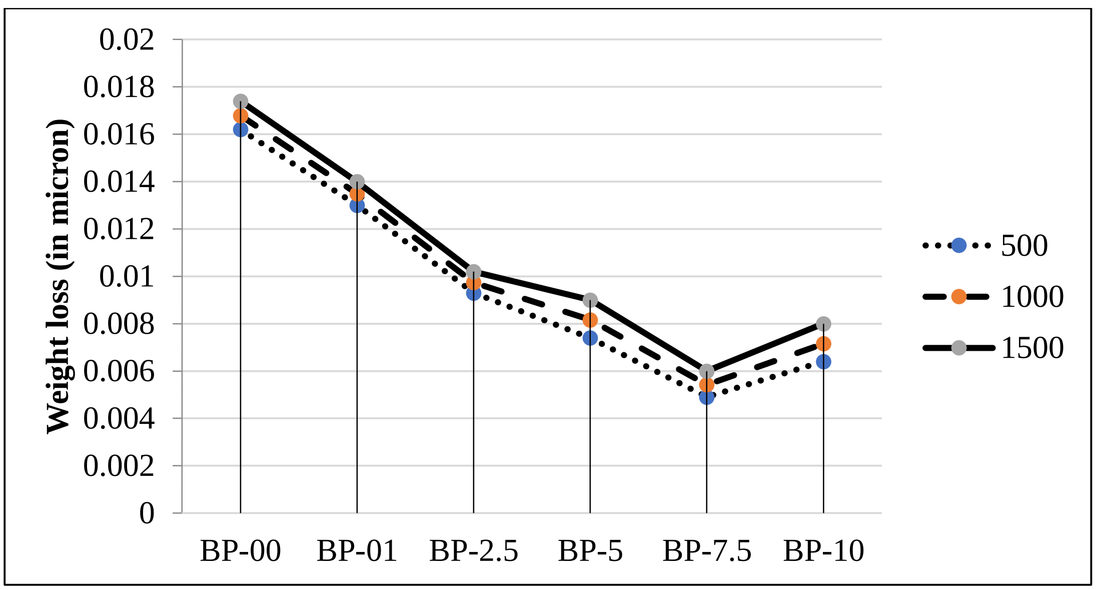


Figure 21: Effect of sliding distance on weight loss

3. Effect of sliding speed on weight loss of the composites

Figure 22 shows the influence of sliding speed on wear loss. The wear loss lowers as the sliding speed is increased from 1.5 to 4.5 m/s with 1.5 m/s increment. Material removal through fracture of the reinforcement and matrix due to high frictional force and transferring material layer is also seen at lower sliding speeds (1.5 m/s). The oxide-like transferred layer has been seen at moderate (3 m/s) and higher (4.5 m/s) speeds, reducing direct interaction with the hard counter surface. At low and moderate speeds, adhesion and abrasion wear dominate, while localizing melting wear at high speeds. The incorporation of BSAP increases the wear resistance of composites by forming a protective layer between the pin and counter face and the inclusion of BSAP also has a significant effect on the wear behavior. However, an increase in the BSAP content beyond a limiting value can deteriorate the tribological properties of these composites. Therefore, true optimization of a tribological system (of the hybrid composite and counter phase) can be achieved by selecting appropriate reinforcement contents (Gurpreet Singh & Sanjeev Goyal, 2016). A decrease in wear loss with an increase in sliding speed is mainly caused by the solid lubrication of MoS_2 particles, which are released during sliding and form a tribolayer at the contact surfaces. With 10 wt% of BSAP, the wear loss tends to increase. This tendency may be attributed to a decrease in the fracture toughness of the composites (Ravindran et al., 2013; Sahu & Sahu, 2020)

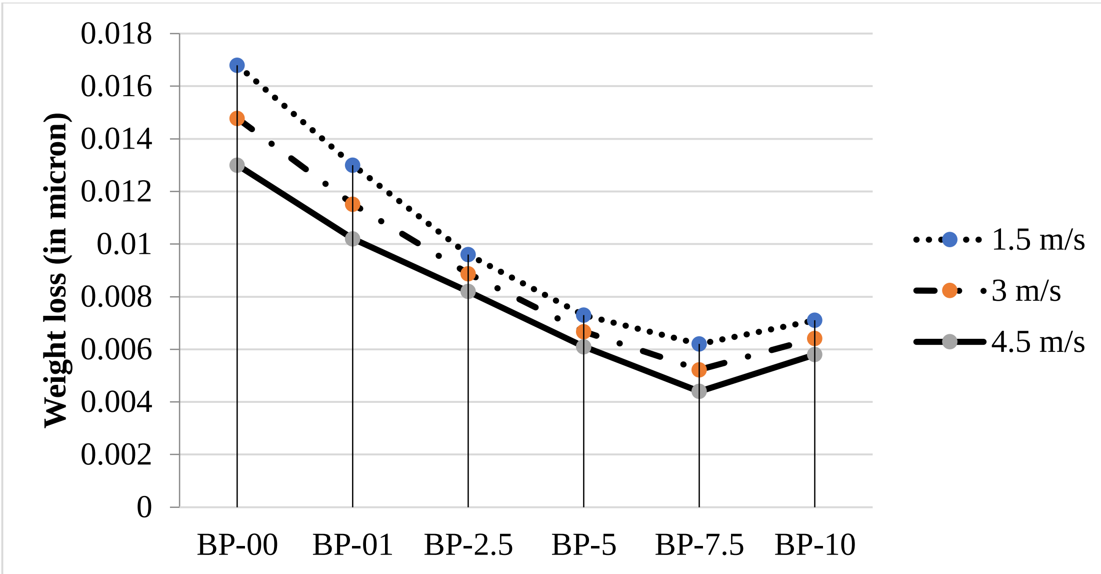


Figure 22: Effect of sliding speed on weight loss

4. Effect of loading on CoF of the composites

The coefficient of friction rises with increasing load, as seen in Figure 23. At lower loads, the tribo-layer film was found to be more stable than at higher loads, as the film was damaged at a quicker rate as the applied load grew, which greatly increased the CoF. The coefficient of friction decreases with rising weight percentage of BSAP increased up to 7.5 wt%. This outcome is the consequence of mainly BSAP being present in the Aluminum matrix composites, which serves as a solid lubricant material on the surface and causes the creation of a solid lubricant-rich layer on the tribo-surface, lowering friction by preventing metal-to-metal contact on the sliding surface.The presence of MoS_2 is also another reason for the reduction of coefficient of friction.When the percentage of BSAP was above 7.5 wt%, the friction showed an increasing trend due to fracturing of the oxide layer within the surface, which weakens worn surfaces. Abrasion through the decohesion of sliding surfaces causes contact between the composites and counter face. As a result, the coefficient of friction increased. Figures show that the maximum speeds at various weight percentages of the hybrid reinforcements have been linked to an increase in the coefficient of friction with an increase in load.

It has been observed that for the base matrix and its reinforcements, the coefficient of friction was low at starting loads. But for any given weight, BP-7.5 has the lowest friction coefficient. As a result, the applied load increases together with the coefficient of friction. The coefficient of friction starts to rise as BSAP continues to rise. It has also become clear that, in contrast to the load, the coefficient of friction drops as the sliding speed and weight percentage of BSAP rise due to decreased frictional force.

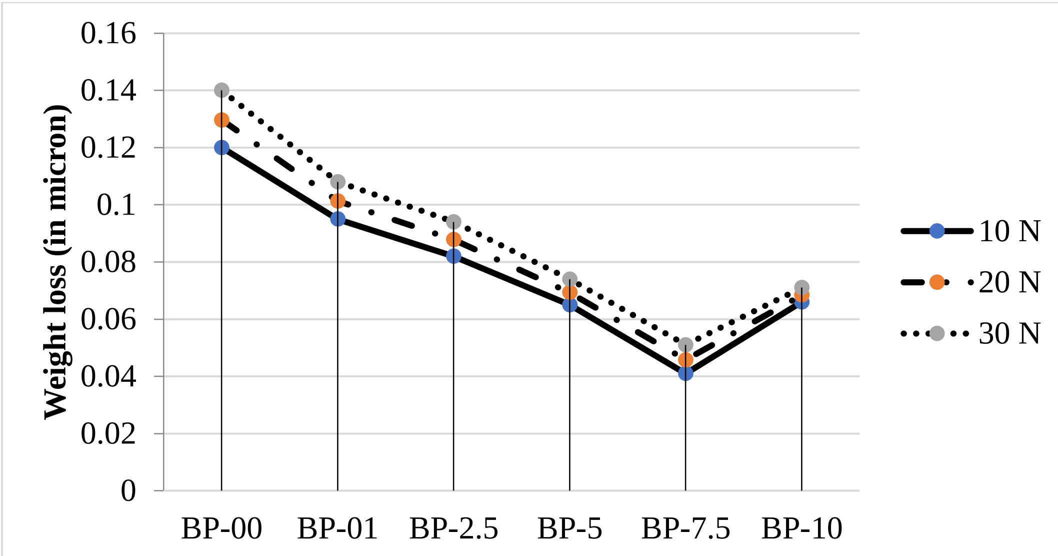
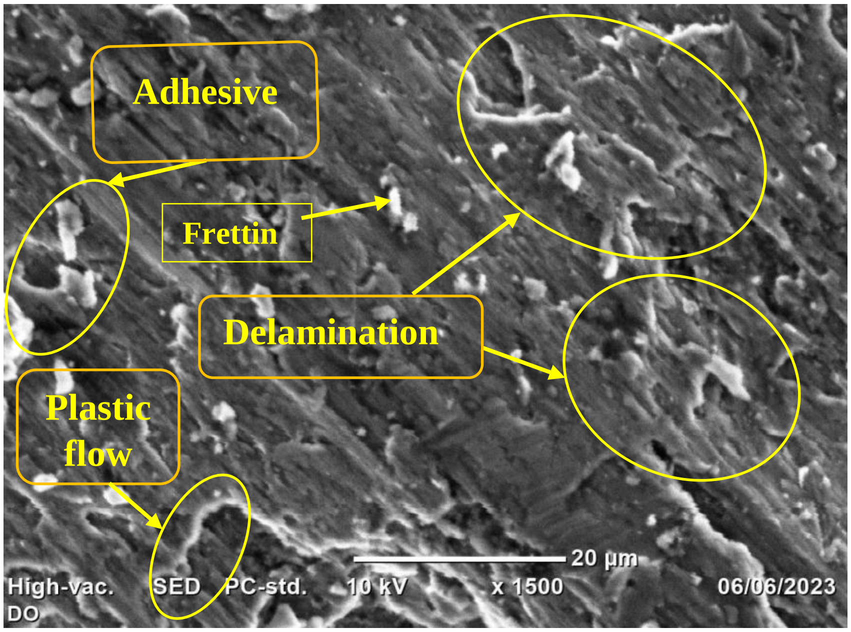


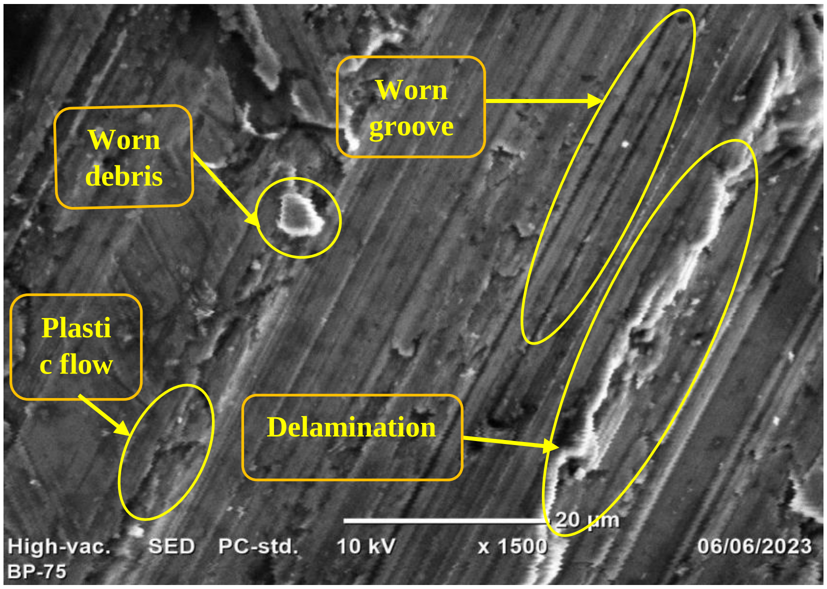
Figure 23: Effect of load on COF

5. SEM image of the wear surfaces of the composites

In the case of aluminum MMCs, a variety of wear mechanisms, including delamination, abrasive, adhesive, fretting, etc., were documented (Kanthavel et al., 2016). The delamination mechanism is the excessive fracturing characterized by deep grooves and huge flake-sized debris. Adhesive wear was defined as the onset of plastic deformation and the manifestation of pits and prow (Karun et al., 2016). However, compared to the delamination process, the pits in cases with adhesive wear were often smaller. Parallel grooves indicative of abrasive wear was produced by micro-cutting and micro-ploughing. The SEM image in Figure 24 shows the worn-out surface of the pure Aluminum (a) and BP-7.5 (b) samples.



(a)



(b)

Figure 24: SEM image of wear surface (a) BP-00 (b) BP-7.5

The image in Figure 24 (a) reveals that there are different types of wear mechanism occur on the pure aluminum sample. These are delamination due to fracture, abrasive due to the contact with the hard surface of the disc which results scratching or rubbing of the surface, adhesion which is the transfer of worn-out debris to another site, plastic flow. Whereas in Figure 24 (b) the wear mechanism of the tetra hybrid reinforced aluminum matrix composite shows higher improvement. This wear resistance increment is due to the inclusion of the hard particles of B_4C, Al_2O_3 and BSAP, and also the solid lubricant MoS_2(Adediran et al., 2020; J. S. David Joseph, 2019; Suresh, 2020). The increasing in wt.% of BSAP has great influence on the improvement of the wear resistance properties of the composites.

4.2.8. Corrosion test

4.2.8.1. Tafel plot

The corrosion behavior of the tetra hybrid reinforced aluminum matrix composites analyzed using Tafel plot obtained from potentiodynamic polarization, after the immersion of the samples in a 3.5% NaCl solution for an hour. The resulting graph is presented in Figure 25 below.

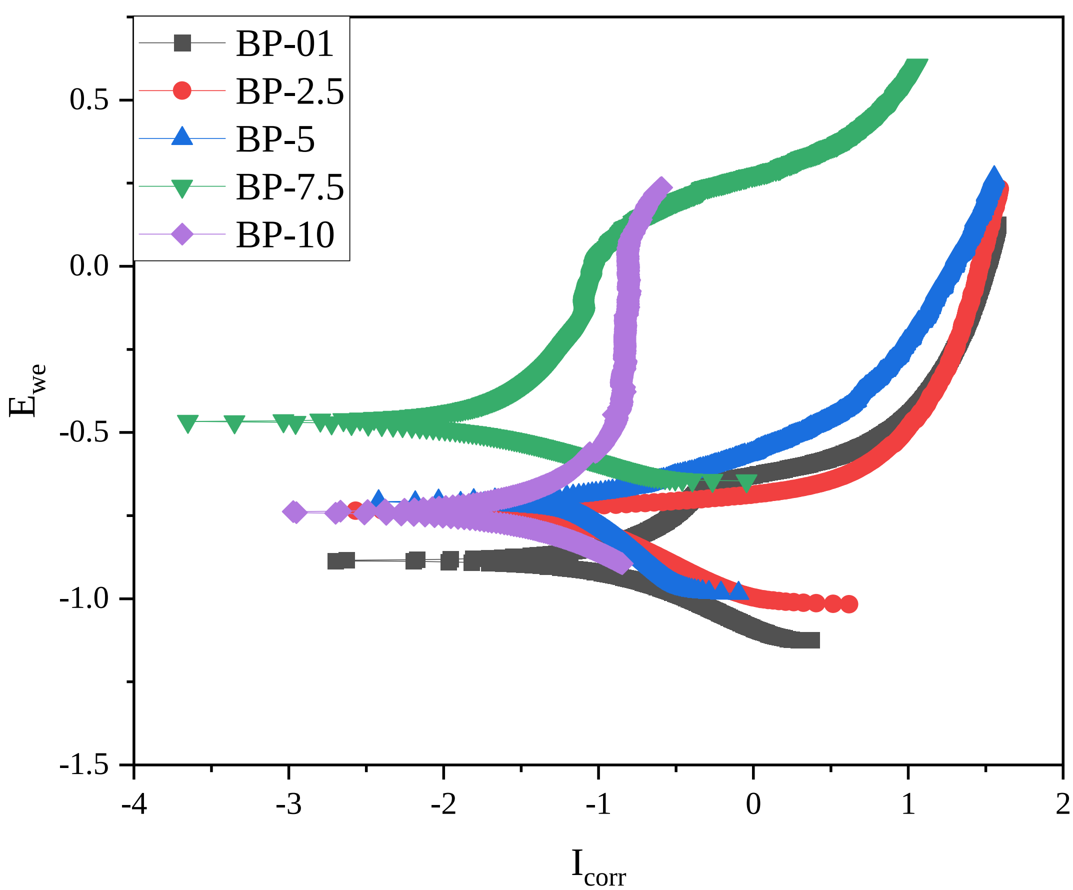


Figure 25: Tafel plot of the composites

The corrosion potential (E_{corr}), corrosion rate (C_R), polarization resistance (R_P) and corrosion current density (I_{corr}) are extracted and reported from the plot. The polarization resistance (R_P) was found using the Stern – Geary equation.

$$(R_P) = \frac{\beta_\alpha \beta_c}{2.303 Icorr(\beta_\alpha + \beta_c)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where β_α and β_c are the anodic and cathodic slopes of the polarization curves. Improved corrosion resistance may be calculated by raising the potential of corrosion while reducing current density, in addition to more uniform corrosion and a strong corrosion resistance function, high Ecorr and low Icorr suggest a low corrosion rate. The inhibition efficiency of the composites is calculated by:

$$Inhibition\ Efficiency\ (IE\%) = \frac{I^o_{corr} - I_{corr}}{I^o_{corr}} X100 \ldots\ldots\ldots\ldots \quad (2)$$

Where, I^o_{corr} and I_{corr} represents the corrosion current density values of pure Al and the specific composite, respectively.

Table 10: extrapolated corrosion data of the composites from Tafel plot

Samples	E_{corr} (mV)	I_{corr} (μA/cm^2)	β_α (mV)	β_c (mV)	R_P (Ω)	C_R (mmpy)	IE (%)
BP-00	-986.872	4.325	168.2	148.3	7.9124	1.924	0.00
BP-01	-243.831	0.34	125.3	47.8	44.1884	0.538	92.14
BP-2.5	-219.676	0.079	483.7	23.8	129.601	0.114	98.17
BP-5	-191.061	0.021	64.8	33.1	453.013	0.085	99.51
BP-7.5	-136.254	0.012	170.7	165.2	3037.805	0.024	99.72
BP-10	-163.750	0.022	66.2	42.8	513.048	0.096	99.49

From figure 26 and Table 10 the corrosion potential of pure Aluminum (BP-00) is lower and the corrosion current density is higher. This is because the Al ions in the lattice dissolve into the solution, which causes the passive layer on the metal surface to thin and eventually speeds up corrosion in the base material(Sunitha et al., 2019).This mean the corrosion resistance of Aluminum is low as compared to the composites. The composites starting from BP-01 increase the corrosion resistance up to BP-7.5. This is due to the inclusion of BSAP and other secondary reinforcements. B_4C and Al_2O_3 have resistant property to severe corrosion attack. The rate of corrosion and weight loss can be both altered by the interaction between aluminum and B_4C, B_4C particles act as a physical barrier (Arab & Azadi, 2020). According to Kanayo Alaneme et al. (Alaneme & Olubambi, 2013), Al_2O_3 thought to generate a stable inner oxide layer that serves as a shield to fend off corrosion. In addition, unlike liquid composite manufacturing processes, no unwanted intermetallic compounds are formed.This is one of the advantages of powder metallurgy. The polarization resistance (R_P) and the inhibition efficiency (IE%) show a significant increment after the addition of BSAP up to 7.5 wt.%. The maximum polarization resistance (R_P) and inhibition efficiency (IE%) are 3037.805 Ω and 99.72 % respectively. This is in relation with the XRD, the Density, porosity, hardness and compression tests. This also concedes with previous researches (Arab & Azadi, 2020; Verma & Suri, 2015). The mixed potential theory of (Katkar et al., 2011) states that the potential of composites changes in a positive direction as the reinforcing component in the composite rises. The protective surface oxide layers do, however, become more discontinuous as the weight percentage of reinforcements in the composites rises, making the sample more susceptible to chloride ions and resulting in a less stable potential. This is due to the possibility of discontinuities in the protective layer caused by the insertion of a high content of the BSAP reinforcing phase, which would increase the amount of corrosion sites(Mahdi & Ghalib, 2022).

4.2.8.2. Electrochemical Impedance Spectroscopy (EIS)

The EIS test is done via 3.5% NaCl solution immersed for an hour at room temperature. Figure 31shows the corrosion behaviourin EIS graph of the tetra hybrid reinforced Aluminum matrix composites.

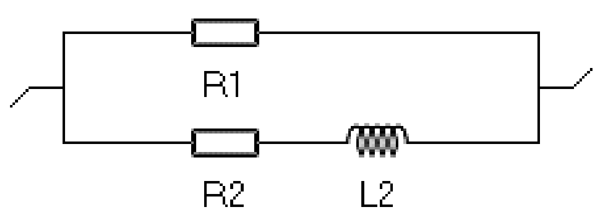


Figure 26: the equivalent Circuit diagram used to fit the EIS data

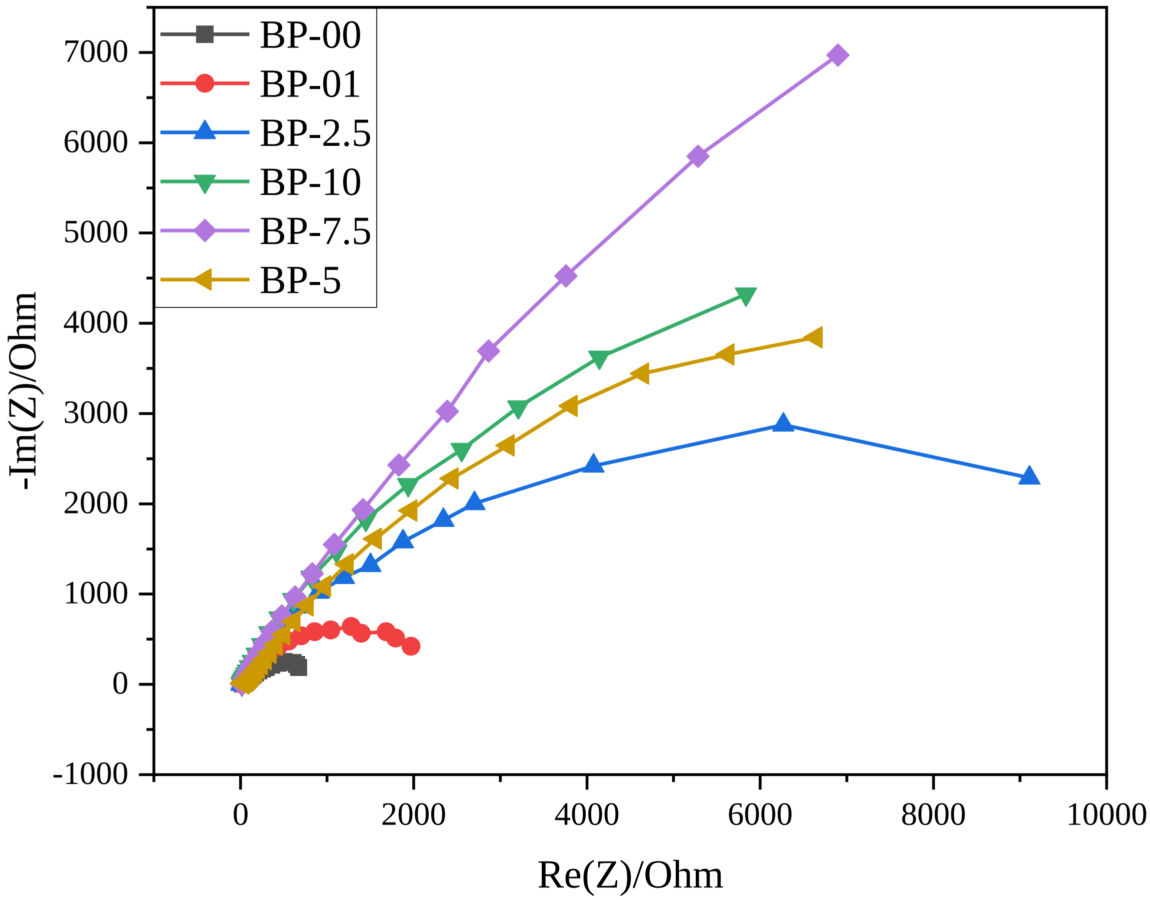


Figure 27: EIS plot of the pure Aluminum and composites samples

The best fitted equivalent circuit model in Figure 26 was used to analyse the represented spectra. Impedance spectra in Figure 27 demonstrate that composites have superior corrosion resistance than base metal because the diameter of the semicircle for composites is larger than that of the base metal in the Nyquist plot. The Nyquist plot exhibits bigger diameter and lower corrosion current as the BSAP reinforcement content in the composites increases (from BP-2.5 to BP-7.5) in the 3.5% NaCl solution. In the circuit diagram in Figure 14 R_1 represents the solution resistance, R_2 represents the resistance of the samples and L_2 represents the inductance of the samples.

Figure 28 demonstrates that both pure aluminium and composites only displayed one semicircle, with the composites' diameter being larger than that of pure aluminium. This shows that the composites have superior corrosion resistance than pure aluminium. Because the surface of the composites is more resistant to corrosion than the surface of pure aluminium, as shown in Table 11, the R2 values for HAMCs are higher than those for pure aluminium.

The anti-corrosion performance of the composites has been improved for two key reasons. Primarily, the addition of hard reinforcements (B_4C and Al_2O_3) to the Al matrix not only smooth and uniformize the composites while refining the grain, but also serves as a physical barrier layer that prevents corrosion (M. Ravikumar et al., 2021). Secondly, by evenly dispersing the BSAP reinforcement particles, the composites are strengthened and matrix dissolution is prevented, both of which greatly increase the composites corrosion resistance.

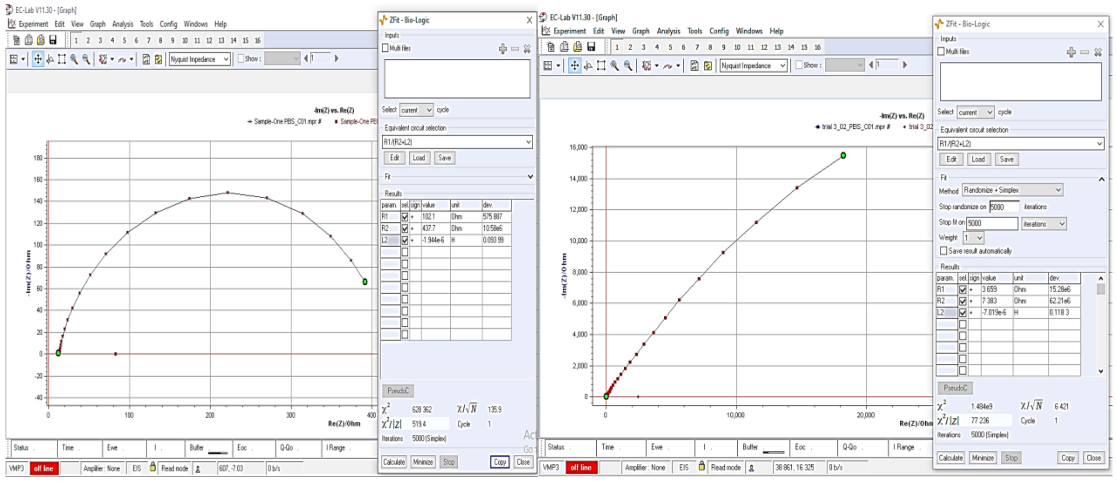
The resistance and the capacitance are the two elements that make up the impedance of a corroding metal in EIS. The resistance and the metal-electrolyte interface's ionic conductivity are connected, whereas the electrical double layer that develops at the interface is related to the capacitance.

Table 11: EIS equivalent diagram data values for pure aluminum and the composites

Samples	$R_1(\Omega)$	$R_2(\Omega)$	L_2 (H)
BP-00	102.1	437.7	1.944
BP-01	99.6	550	2.917
BP-2.5	1278	1526	3.45
BP-5	2242	3236	4.378
BP-7.5	2423	3544	9.549
BP-10	2256	3322	6.235

EIS may also be used to determine the inductance of the corroding metal in addition to these two elements. The inductance is connected to the mass transfer of corrosion products, which can have an impact on the rate of corrosion and the material's impedance.

Rapid corrosion can result in the formation of a barrier layer that alters the metal sample's impedance due to the mass transfer of corrosion products. A barrier layer serves as a physical barrier between a metal and the corrosive environment when it develops on the surface of a metal during corrosion.



(a) **(b)**

Figure 28: EIS Z fit plot of (a) BP-00 and (b) BP-7.5

By restricting the migration of corrosive species, such as oxygen and water, to the metal surface, the barrier layer can slow down or even stop the corrosion process. For example, in the case of general corrosion, the formation of a barrier layer can be due to the precipitation of corrosion products, such as metal oxides or hydroxides, on the metal surface. In the case of localized corrosion, such as pitting or crevice corrosion, the formation of a barrier layer can be due to the accumulation of corrosion products or the deposition of insoluble salts on the metal surface. The barrier layer can have different thickness and composition, depending on the type and severity of the corrosion. The barrier layer can be protective and prevent further corrosion(Huang et al., 2020; Li et al., 2022). This was shown on the composites inductance values. As the wt.% of BSAP increased the inductance of the composites increase up to 7.5 wt.%. This is due to the plant extract increase the formation of corrosion protecting layer which acts as inductor. After 7.5 wt.% the inductance value decreased and this is due to after the optimum concentration of BSAP the protective layer forming particles delaminate and corrosion agent which is Chlorine ion can penetrate and cause further corrosion.

4.3. Optimization of Pressing Pressure and Sintering Temperature on the best composition (BP-7.5) sample

Based on the compositional variation BP-7.5 has good mechanical and tribological properties. So, by having this result some mechanical and physical properties have been optimized by varying the sintering temperature and compacting pressure. The pressing pressure selected to be 40, 50 and 60 MPa, and the sintering temperature selected to be 528 ^{o}C, 561 ^{o}C and 594 ^{o}C which are 80%, 85% and 90% of the melting point of Aluminum.

Table 12: Optimized sample design

	528 ^{o}C	**561 ^{o}C**	**594 ^{o}C**
40 Mpa	528-40	561-40	594-40
50 Mpa	528-50	561-50	594-50
60 Mpa	528-60	561-60	594-60

4.3.1. Density and Porosity property

In the density and porosity analysis of the optimized sample the result reveals that the sintering temperature and compacting pressure have higher effect on the physical and mechanical properties. As shown in the Table13 and Figure 29

Table 13: Density and Porosity data of optimized sample

Sample	Dry Weight	Soaked Weight	Suspended Weight	Density (gm/cm^3)	Porosity (%)
594 – 40	3.147	3.198	1.653	**2.0369**	**0.0330**
594 – 50	3.334	3.358	1.865	**2.2331**	**0.0161**
594 – 60	3.139	3.157	1.849	**2.3998**	**0.0138**
561 – 40	3.042	3.065	1.81	**2.4239**	**0.0183**
561 – 50	3.105	3.12	1.888	**2.5203**	**0.0122**
561 – 60	2.991	3.021	1.782	**2.4140**	**0.0242**
528 – 40	3.081	3.13	1.86	**2.4260**	**0.0386**
528 – 50	3.127	3.156	1.896	**2.4817**	**0.0230**
528 – 60	3.005	3.029	1.782	**2.4098**	**0.0192**

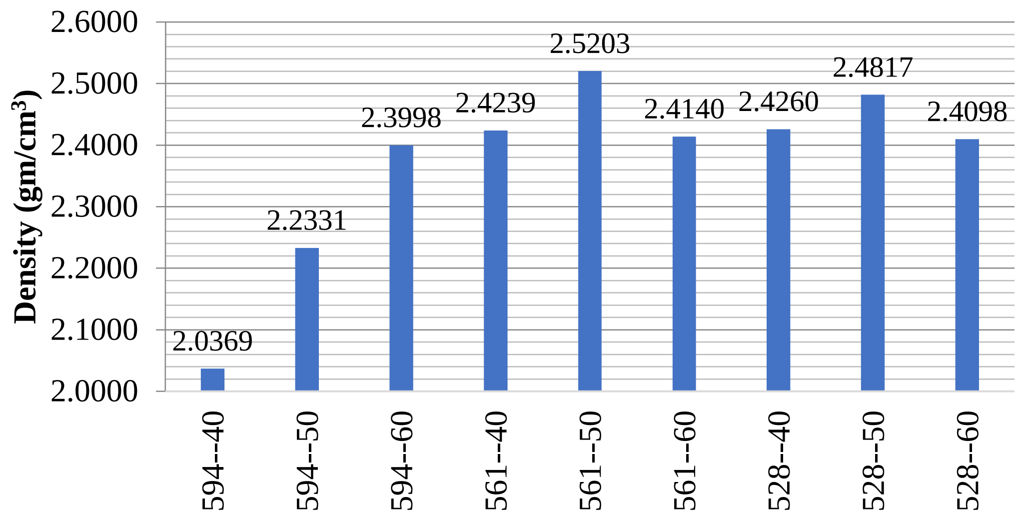


Figure 29: Density graph of optimized sample

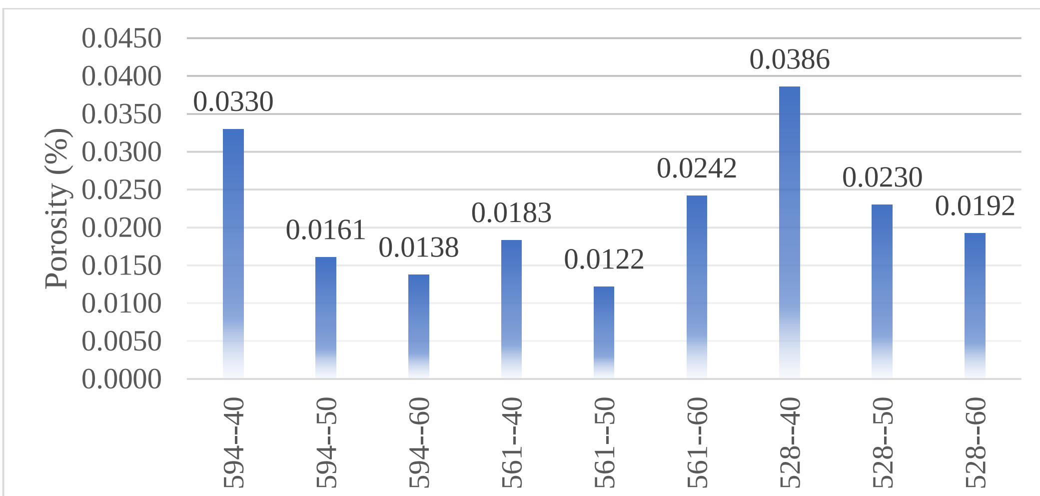


Figure 30: Porosity graph of optimized sample

As the compacting pressure is increase the density of the composites increase due to the denser and fewer defects formation due to the high pressure. But after some optimum value of compacting pressure there may be crack formation or even fracture of the compacted composites.

Similarly, the sintering temperature increment cause an increase in the increase in density and reduce porosity, because the particles get enough energy for arranging themselves in orderly manner and reduced voids. This phenomenon continues up to optimum value of sintering temperature. After the optimum value of the sintering temperature, the density reduce and the porosity of the composites increase. This is due to the formation of large grain size and as a result inter-molecular voids increase. Some of the molecules may also melt as the temperature increase (Kumar et al., 2021; Li et al., 2016).

4.3.2. Hardness test

The hardness test values as shown in Figure 31 below for the optimized composite, varies as the compacting pressure and sintering temperature varies. The maximum hardness value is seen on the sample sintered at 561 ^{o}C and pressed at 50 MPa pressure. These parameters are the optimum values of the optimization parameters.

Sintering is a process where the metal matrix composite's powder particles are heated to a temperature below their melting point, resulting in the formation of strong bonds between these particles and producing a coherent, solid mass. So, the sintering temperature plays a critical role in determining the properties of the final composite, including its hardness.

A higher sintering temperature can result in increased densification, reduced porosity, and improved bonding between the metal matrix and reinforcing constituents (e.g., ceramic particles) as can be seen in Figure 15. This, in turn, can lead to an increase in the hardness of the MMC(Priyaranjan Samal, 2020).

However, sintering at excessively high temperatures can also result in the growth of grains in the metal matrix, which may lead to a decline in its hardness (as shown the Figure 15 sintered at 594 ^{o}C). Therefore, it is essential to optimize the sintering temperature to achieve the desired properties in the metal matrix composite.

As sintering temperature, compacting pressure is also an essential factor affecting the hardness property of metal matrix composites during manufacturing process. The compacting pressure influences the density and the uniform distribution of the reinforcing particles within the matrix. Increasing the compacting pressure generally leads to higher density and improved contact between the matrix and the reinforcement, which in turn results in better mechanical properties such as hardness, strength, and Ductility.

It is well known that high compaction pressures provide excellent cold welding between neighboring particles, allowing for efficient diffusion to occur during the sintering mechanism and the creation of good interfaces with reinforcement particles. The hardnessof the composite is greatly increased by increasing the compaction pressure. Composites that are compacted at high pressures from strong interface bonds between the matrix and reinforcements, which act as barriers for dislocation movements. A strong interface between the matrix and reinforcement also causes the hard ceramic reinforcements to pin against the adjacent matrix phase, which slows down grain growth during the sintering process and also serves as a mechanism for strengthening grain boundaries.

However, there is an optimal range of compacting pressure, as applying excessive pressure can potentially cause damage to the reinforcement particles, induce residual stresses, or result in other defects that could adversely affect the hardness and overall performance of the material. Thus, it is crucial to optimize the compacting pressure for each specific MMC system to achieve the desired properties.

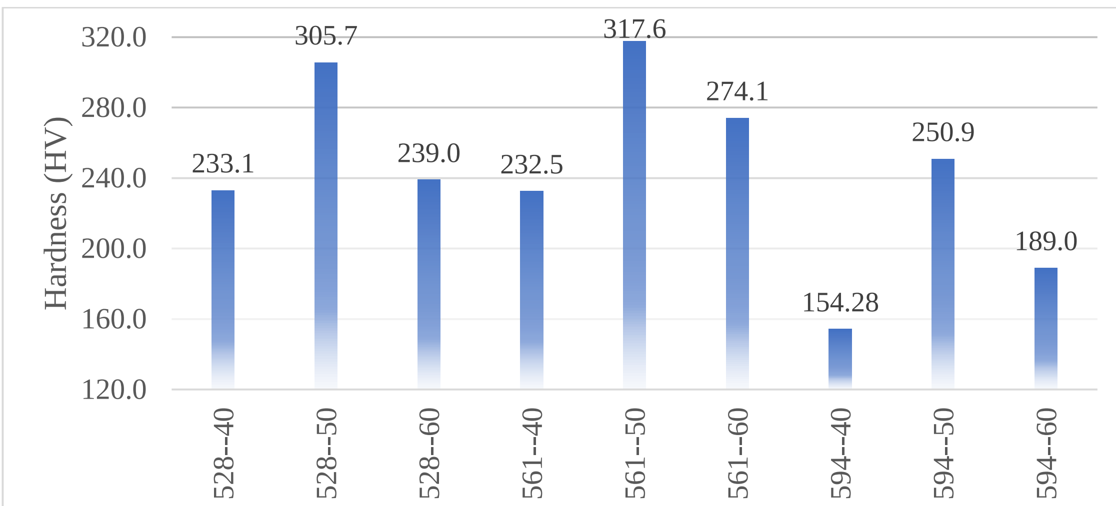


Figure 31: Hardness graph of optimized sample

4.3.3. Compression test

The compressive strength test values in Figure 32shows that the compressive strength of the optimized sample is greatly affected by the sintering temperature and compacting pressure. Sintering is a crucial step in the processing of MMCs, as it involves the consolidation and densification of the material, which ultimately determines its mechanical properties, including compressive strength.

During sintering, powders or particles of different materials are heated allowing them to bond or fuse to form a solid mass. Sintering temperature plays a vital role in determining the quality of bonding between the matrix and the reinforcement, as well as affecting the densification and microstructure of the composite.

A higher sintering temperature can improve the bonding between the matrix and reinforcement, which can lead to increased compressive strength(Priyaranjan Samal, 2020). However, sintering at excessively high temperatures can also lead to grain growth, phase transformation, or even melting of the matrix or reinforcement, which can adversely affect the mechanical properties of the composite.

On the other hand, a lower sintering temperature may result in incomplete bonding or insufficient densification, which can lead to a reduction in compressive strength. Therefore, it is essential to optimize the sintering temperature to achieve the desired balance between densification, bonding, and grain growth to maximize the compressive strength of metal matrix composites.

The optimized temperature in this way was 561 ^{o}C to get the optimized mechanical and tribological behavior. The samples produced at 550 ^{o}C had smaller values of mechanical and tribological properties. This is because the sintering temperature was lower than the optimum value.

The compacting pressure also, used during manufacturing has an impact on the metal matrix composites' compressive strength. The density, porosity, and distribution of the reinforcements within the matrix can be affected by the compacting pressure employed to mix the reinforcing fibers or particles with the metal matrix. This, in consequence, has an impact on the overall mechanical characteristics of the composite material, such as compressive strength.

As a result of helping to distribute reinforcements more evenly and reducing porosity within the material, higher compacting pressures often result in composites that are denser and stronger. Excessive compacting pressure, however, has the potential to weaken the material's compressive strength by harming the reinforcing fibers or particles. To obtain the appropriate composite characteristics, a correct bqalance of compacting pressure is also essential.

The optimized pressure in this way was 50 MPa to get the optimized mechanical and tribological behavior. The samples produced at 60 MPa had smaller values of mechanical and tribological properties. This is because the compacting pressure was higher than the optimum value. This cause the particles to delaminate and reduce the mechanical and tribological properties.

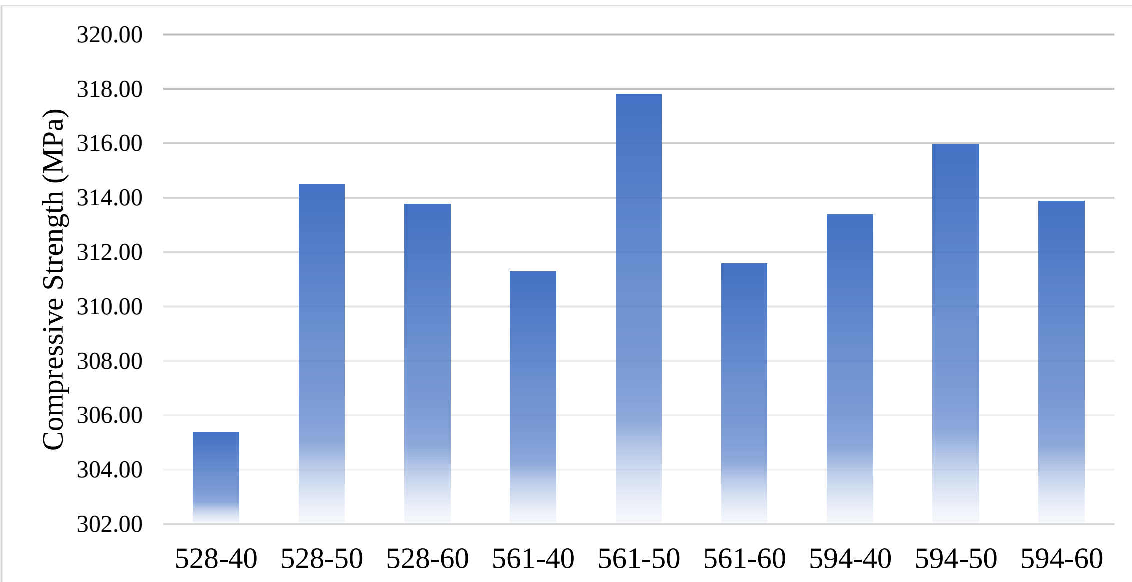


Figure 32: compression graph of optimized sample

Conclusion and Recommendation

In this study tetra-hybrid reinforced aluminum matrix composites synthesized via powder metallurgy has been studied. The findings of the tests reveals the mechanical and tribological properties of pure Aluminum improved by adding BSAP.

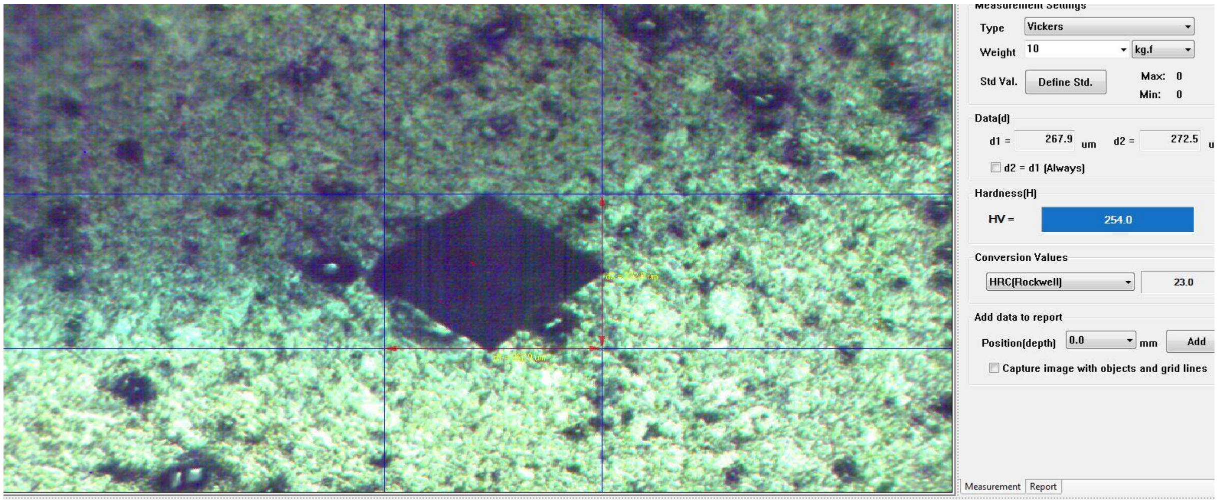
The results of the study can be concluded as follows;

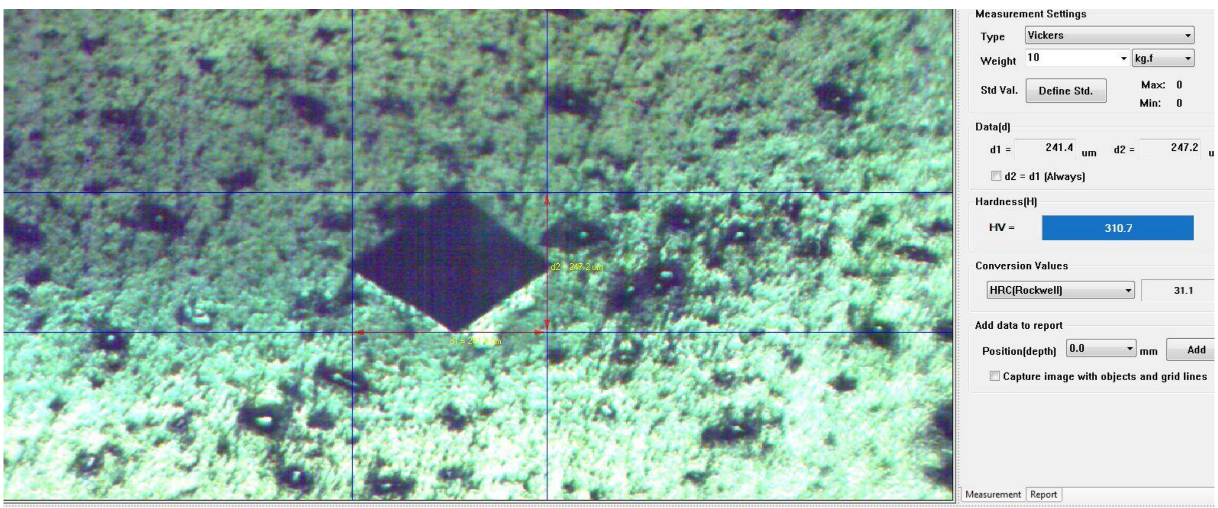
- From the XRD, XRF, FTIR graphs the natural fiber BSAP is riched in silica content that makes BSAP a good reinforcement for Aluminum and its alloys, and can replace rarely abundant ceramic reinforcements.
- The thermal analysis (TGA/DTA) graph shows BSAP is stable at high temperature and the composite can be used for reinforcing high temperature working components.
- From the XRD graph the major peaks are related to Aluminum due to mass proportion and as the weight percentage of BSAP increase the silica peaks appear. This shows that the tetra-hybrid composites were effectively synthesized through powder metallurgy process.
- Tetra hybrid reinforced Aluminum matrix composite's density and porosity marginally reduced as the wt.% of BSAP rose, while the HAMCs' hardness and compression strength improved up to 7.5 wt.% of BSAP and subsequently dropped with increases over 7.5 wt.%. Vickers hardness and compressive strength of BP-7.5 were increased over the basic material (Al) by 4.27 and 2.82 times, respectively.
- The wear resistance and corrosion resistance properties also improved as the weight percentage of BSAP increased up to 7.5 % and the drop. The corrosion inhibition efficiency of 99.72% has been recorded.
- Due to the reduced weight of the tetra hybrid reinforced aluminum matrix composite, it can be suitable for the production of automobile and aircraft body, marine components and other light weight needing parts.
- By using BSAP we can reduce production cost of components by replacing rare ceramic reinforcements and increase the mechanical and physical properties of Aluminum composites, and also keep our environment clean and green.

Recommendation

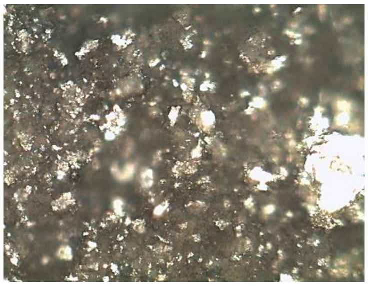
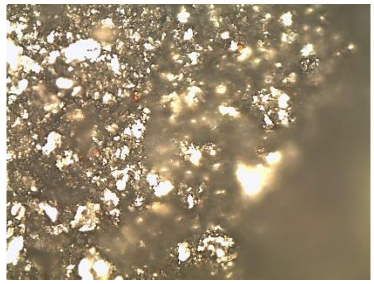
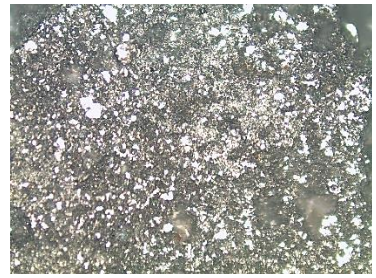
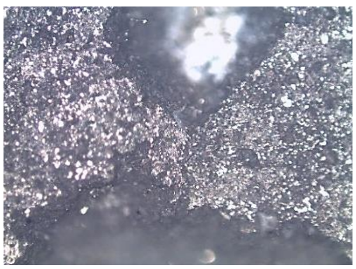
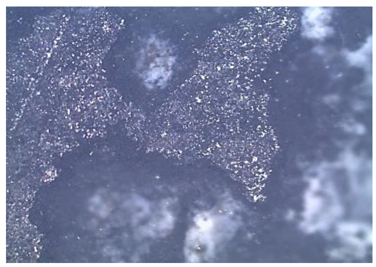
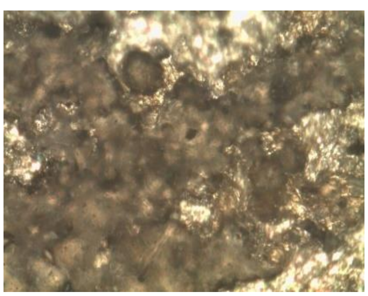
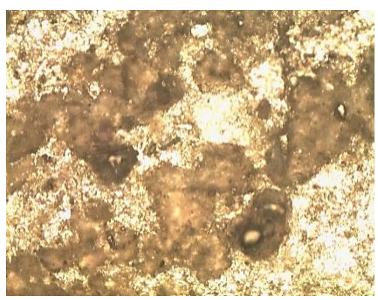
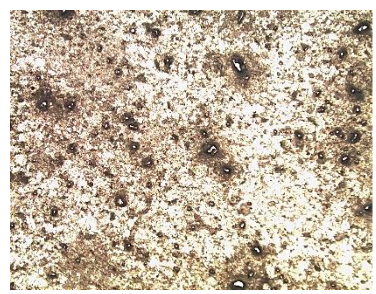
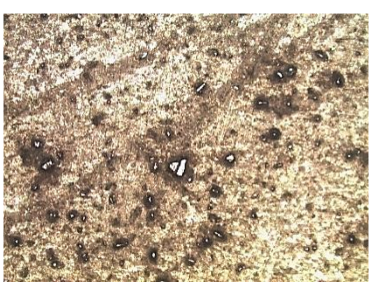
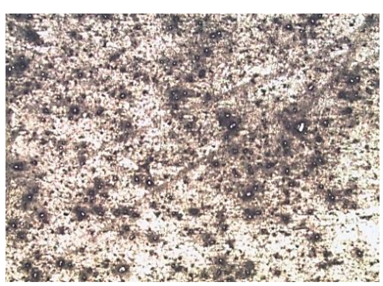
APPENDICES

Hardness test images





Optical Microscope image of the corroded samples

BP-00  20µm	BP-00  50µm	BP-00  100µm
BP-00  200µm	BP-00  500µm	
BP-7.5  20µm	BP-7.5  50µm	BP-7.5  100µm
BP-7.5  200µm	BP-7.5  500µm	

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