Fabrication and Characterization of Hybrid Aluminum (Al6061) Matrix Composite Reinforced with SiC, B_4C and MoS_2

By

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Office of graduate studies

Adama Science and Technology University

January, 2021

Adama, Ethiopia

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Co Adviser: Dr. C.Venkatesh

A Thesis Submitted to the Department of Mechanical Design and Manufacturing Engineering

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APPROVAL PAGE

We, the undersigned, members of the Board of Examiners of the final open defense by **Ayalew Abebe** have read and evaluate his/her thesis entitled "Fabrication and Characterization of Hybrid Aluminum (Al6061) Matrix Composite Reinforced with SiC, B_4C, and MoS_2" and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirement of the Degree of Master of Science in Mechanical design and Manufacturing Engineering.

Name	Signature	Date
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____________________	________________	_________________
External Examiner		

DECLARATION

I hereby declare that the work which is being presented in this thesis entitled "Fabrication and Characterization of Hybrid Aluminum (Al6061) Matrix Composite Reinforced with SiC, B_4C, and MoS_2'' in partial fulfillment of requirements for the award of the degree of masters of science in Manufacturing Engineering is an authentic record of my own work carried out from October 2019 to Janury 2021 under the supervision of Dr. Devendra Kumar Sinha and Dr. C. Venkatesh, Department of Mechanical Design and Manufacturing Engineering, Adama Science and Technology University, Ethiopia.

Any portion embodied in this thesis has not been submitted by me for the award of any other degree or diploma. All relevant resources of information used in this thesis have been duly acknowledged.

Name	signature	date
Ayalew Abebe Emiru	________________	________________

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge and belief. This has been submitted for examination with our approval.

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Date of submission: <u>January, 25th, 2021</u>

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NOMENCLATURE

%Wt	Weight percentage
Al6061/ 6061Al	Aluminum 6xxx series alloy
AMMCs	Aluminium metal matrix composites
ASTM	America society of test material
CMCs	Ceramic matrix composites
D	Specimen diameter
Dc	Diameter of crucible
Ds	Diameter of stirrer
FAM	Finite element method
G	Gage length
HAMMC	Hybrid Aluminium metal matrix composite
HMMC	Hybrid metal matrix composite
HRS	Hollow rectangular steal
MMCs	Metal matrix composites
OM	Optical microscopy
PM	Powder metallurgy
PMCs	Polymer matrix composites
R	Fillet radius
RPM	Revolution per minuet
RSH	Rice husk ash
SEM	Scanning electron microscope
SEM	Scanning electron microscope
UTM	Universal testing machine
UTS	Ultimate tensile stress
VHN	Vickers hardness number
XRD	X-ray diffraction microscope

ABSTRACT

In the current perspective, the acceptance of single and hybrid reinforced Aluminum alloy composites rises day today for general purpose and engineering applications as a result of their desirable properties like high strength, low density, better wear, and corrosion resistance. This work aimed at fabrication of aluminum alloy (Al6061) based hybrid composite reinforced with MoS_2, SiC, and B_4C powders via stir casting method and investigate the influence of reinforcements on the microstructural, density, porosity, tensile, hardness, and wear resistance behavior of the base alloy. The reinforcement has been added by varying B_4C and SiC to 3%, 6%, 9%, and 12%. But the percentage addition of MoS_2 has been restricted to 4% in each specimen except the one which is non-reinforced. In each composite except non-reinforced, constant 84% of Al6061 was used to know the effect of reinforcements exactly. The hardness of the prepared hybrid aluminum matrix composite improved with the rise in percentage composition of B_4C. With the addition of 12% of B_4C and 4% of MoS_2, the hardness of Al6061 was improved by about 22.06%. On the other hand, the ultimate tensile strength of the hybrid Al6061 composites found to be increased by the addition of B_4C, SiC, and MoS_2. By the addition of 12% of SiC and 4% of MoS_2, ultimate tensile strength was improved by 22.63%. As the load increases from 10N to 50N in the step of 20N, the coefficient of friction and wear loss increases. At 50N load, the maximum weight loss was 0.0032g for non-reinforced specimen and the minimum weight loss was 0.0016g for double reinforced specimen (Al6061/12%B_4C/4%MoS_2) at this load. The advances in mechanical and tribological properties of B_4C, SiC, and MoS_2 hybrid reinforced aluminum alloy (Al6061) provide a practical and technical record in the area of composites for automotive, commercial, military and aerospace applications.

Keywords: Aluminum alloy (Al6061), Silicon carbide (SiC), Boron carbide (B_4C), Molybdenum disulfide (MoS_2), Stir casting, Hybrid Aluminum Matrix Composite (HAMC).

CHAPTER ONE

INTRODUCTION

1.1. Backgrounds of the Study

At present, metal matrix composites (MMCs) are broadly utilized in industrial sectors, medical sectors, construction sectors and others like Automobile industries, aircraft industries, Marine time industries, Medical industries and construction equipment's due to desirable properties MMCs, like better strength, high wear resistance, light in weight, good thermal conductivity and low thermal expansion (Rajasekar et al. (2018)). The modifications in manufacturing technology had a large influence on the development of composite materials.

Metal that commonly used as matrix in the fabrication of MMCs are Aluminium alloys (Madeva et al., 2017; Bhaskar et al. 2017), Magnesium alloys (Karthick et al., 2017; Arabinda et al., 2019), Titanium alloys (Faming et al., 2020; Imayev et al., 2018) etc. on the side, materials which used as reinforcement in the production of MMC'S are Aluminium oxide (Al_2O_3), Silicon carbide (SiC), Titanium bromide (TiB2), Titanium carbide (TiC), Molybdenum disulfide (MoS_2), Titanium nitride (TiN), Boron carbide (B_4C), , Fly ash, Agricultural waste and other (Rahat et al., 2017; Rao and Ramanaiah, 2017; Srinivasan et.al, 2017).

MMCs contain metallic characteristics of base alloys (such as ductility, conductivity and toughness) and ceramic properties of reinforcements (such as superior strength, high wear resistance, high thermal stability and high modulus) (Yadav et al., 2016). Thus, hybridization using different reinforcement's tips to greater tensile, shear and compression strength, better service temperature potentials and less wear loss.

Among different types of metal alloy, aluminum alloys are light in weight, high corrosion resistance, good electrical and heat conductivity and are of the most favorite materials in the production of MMCS as matrix material. Several Aluminum alloys (e.g. 1xxx, 2xxx, 5xxx, 6xxx, 7xxx and other) are selected in the production of composites. Out of them, 6xxx series of aluminum alloys have good machinability and extrude-ability and use mostly as a matrix material in the production of AMMC (Halil et al., 2019). Aluminum metal matrix composite

(AMMC) is the one which is applicable for several applications because of its low density, high specific strength, high stiffness, better wear resistance, low thermal coefficient of expansion, and high temperature application.

In Aluminum alloy matrix composites, silicon carbide (SiC) (Ajay et al., 2018), boron carbide (B_4C) (Shashi et al., 2019), aluminium oxide (Al_2O_3) (Ghanaraja et al., 2017), Molybdenum disulfide (MoS_2) (Bhargavi et al., 2014), graphite (Mukesh et al., 2019), titanium carbide (Ravi et al., 2017), fly ash (Govinda et al., 2020) etc. were used as reinforcement material.

The production methods for metal matrix composites can be classified based on primary production procedures such as solid form or liquid form or semi-solid form. According to the production processes, metal matrix composite production method can be categorized as Solid state methods (powder metallurgy), liquid state processing (such as stir casting, stir squeezed casting) and semi-solid state method (spray deposition) (Ramanathan et al., 2019). stir casting method was used this work, to fabricate the composite specimen because of its simplicity and economical way of producing large to small scale MMC components.

The main objective of this work is to produce hybrid Al6061 matrix composite materials which have improved mechanical and tribological properties than parent metal by adding B_4C, SiC and MoS_2 particles to Al6061 alloy. Al6061 alloy is selected as matrix material due to good formability, machinability, weldability, corrosion resistance and good general purpose alloy used for a wide range of structural applications and welded assemblies including truck components, railroad cars, marine applications, agricultural applications, Aircrafts components, Automotive parts, medical equipment, machine parts, and storage tanks etc. (Davis, 2001).

In this study, non-reinforced (Al6061 alloy), double reinforced (Al6061+SiC+MoS_2 and Al6061+B_4C+MoS_2) and triple reinforced (Al6061+B_4C+SiC+MoS_2) composite materials are fabricated by stir casting methods and mechanical properties, such as hardness, tensile strength, and percentage of elongation, and tribological properties such as wear and coefficient of friction were investigated by relating to their microstructures. Microstructural analyses were also performed by optical microscopy (OM).

1.2. Composite Materials

A composite is a structural material that consists of two or more combined ingredients that are combined at a macroscopic level and are not soluble in each other (kaw, 2006). Composite materials are anisotropic and inhomogeneous materials. Composite materials usually present unique properties in which the strength-to-weight ratio is high (Siti et al., 2019). Composite materials consist of two phases; the continuous phase which is called “matrix” and discontinuous phase which are called “reinforcements”. The matrix phase in composite material have the role of binding fibers/reinforcements together; Transfers loads and stresses within the composite structure; supports the overall structure, protects the composite from incursion of external agents such as humidity, chemicals, etc. (Haghshenas, 2016). On the other hand fibers/reinforcements provide stiffness, strength, thermal stability, and other structural properties in the composites. The discontinuous phase is usually harder and stronger than the continuous phase (Sathish et al., 2014). Matrix phase provides shear, low density and thoghness.

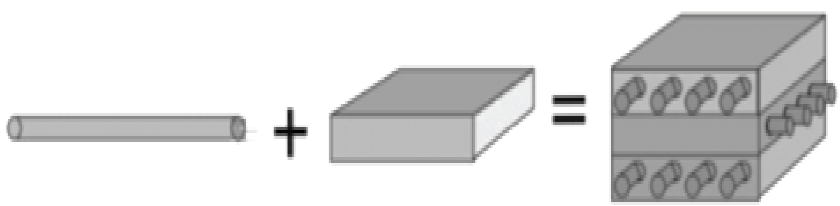


Figure 1.1.Composition of composite (Yadav et al., 2016)

1.3. Various considerations in fabrication of metal matrix composites

To fabricate better quality metal matrix composite via stir casting mechanism, stir process parameters, selection matrix reinforcement materials, production process, properties of metal matrix materials and challenges should be properly considered.

The detail of various considerations that should be put in account in fabrication of MMCs is shown in Figure 1.2 as cause and effect diagram.

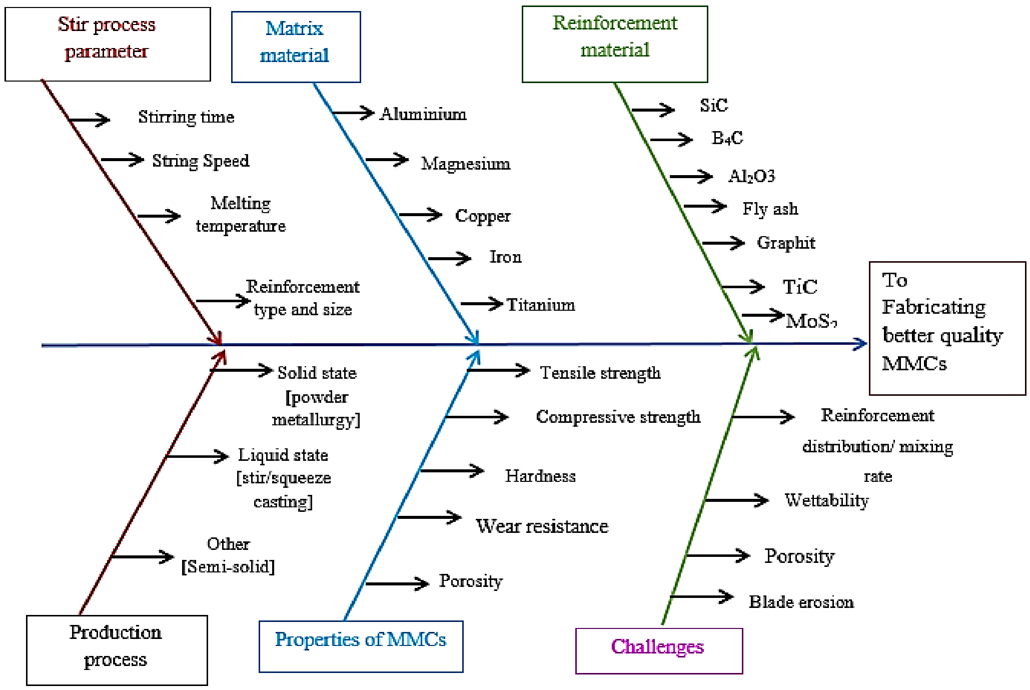


Figure1.2 Fish bone diagram for producing better quality MMCs by stir casting process.

1.4. Statement of the Problem

Now a day's, manufacturing industries, such as automotive industries, aerospace industries, marine industries, etc. are focused on the production of lightweight and high strength components using cost-effective composite materials instead of steel. Aluminum is the third most abundant element in the earth's crust and it is a lightweight metal with a specific weight of 2.7 gm/cm^3; it is about one-third of that of steel. The use of aluminum in automotive parts such as car rotor drum, clutch, engine block, connecting rode, car body, shafts, gear train, and other parts reduces dead-weight and energy consumption. In other words use of heavy metals in automotive components boosts the overall weight and fuel consumption of the automotive. Because of aluminum alloy have low density and availability, it is extensively used for different application beside automotive use. Even though aluminum attracts the user due to its lightweight and availability in abundance, still it's mechanical and tribological properties such as tensile strength, compressive strength, hardness, and wear resistance need an improvement to encounter the required applications. Therefore, to overcome the limitation in mechanical, physical, and tribological properties, the present work deals with the fabrication of a novel hybrid aluminum alloy matrix composite reinforced with boron carbide, silicon carbide, and molybdenum disulfide.

1.5. Objectives

In line with the above justification the study addresses the following general and specific objectives.

1.5.1. General Objective

The general objective of this thesis work is to fabricate and characterize the properties of hybrid Aluminum (Al6061) Metal Matrix Composite reinforced with SiC, B_4C and MoS_2 by varying wt. % each.

1.5.2. Specific Objectives

- To fabricate hybrid metal matrix composite from Al6061 alloy matrix and Sic, B_4C and MoS_2 reinforcements using stir casting method.
- To measure theoretical density, actual density and porosity of developed composite.
- To investigate the microstructure of developed composite through Optical Microscope.
- To test mechanical properties such as tensile strength and hardness of prepared hybrid composites.
- To investigate tribological properties of hybrid composite using Pin-on-Disc tribometer and also investigate wear morphology of the worn samples by SEM.

1.6. Scope of the Research

The scope of this research work is to successfully fabricate non-reinforced (Al6061 alloy), double reinforced (Al6061+SiC+MoS_2 and Al6061+B_4C+MoS_2), and triple reinforced (Al6061+B_4C+SiC+MoS_2) hybrid aluminum matrix composite materials using stir casting method and prepare the specimen for test. Besides, analyze the effect of the weight percentage variation of B_4C, SiC MoS_2 on physical properties (like density and porosity), mechanical properties, (such as tensile strength, and hardness), and tribological properties (wear loss and coefficient of friction at different load). The characterization of the microstructure of Al/SiC/B4C/MoS2 composite via optical microscope and wear morphology via scanning electron microscopy (SEM) was also performed.

Finally, a short and precise conclusion is made about fabrication method, physical, mechanical, tribological properties, and microstructural characterization of the developed composite.

1.7. Limitation of the Work

- The specimens which were manufactured through stir casting process have undergo brittle characteristics. Therefore, the developed aluminum matrix composite is not applicable for applications where the materials are subjected to high impact loading.
- Due to imperfectness of the string mechanism, some clustering of reinforcements was observed. This leads to failure of specimen and initiation of crack during preparation the tensile test specimen. This results in poor tensile strength of the composite.

1.8. Significance of the Study

Now a day's, manufacturing industries such as automotive industries, aerospace industries, etc., focused on the production of lightweight components using cost-effective composite materials instead of steel and aluminum alloys. The proper choice of cost-effective reinforced material decreases the cost barrier of vehicles or other machines. The research gives important attention to the reduction of fuel consumption of vehicles by reducing the dead weight of the vehicle.

This research work has the following advantage;

- It will be used as an alternative source of low cost and lightweight materials.
- It will reduce the weight of the machine, for example, the use of this hybrid composite reduces the weight of the vehicle and decreasing fuel consumption.
- Significant improvement in mechanical and tribological properties of the machine component.
- It will substitute the material which is used in some parts of motor vehicles such as connecting road, valves, shafts, rotor drum/disk, etc. with comparable Properties.
- As teaching aid and reference material for technological education and further researches in developing composites.

1.9. Beneficiaries

Different industries such as; automotive industry, construction industries, aerospace industries, and other industries the one which uses heavy metals to produce machine components will get benefit with this work. Researchers and students also will get benefit for farther investigation on composite materials.

1.10. Structure of the thesis

This research paper consists of five chapters; the essences of each chapter are discussed as follows. The first chapter is the introduction of the study. It includes a background of the study statement of problem, objectives, the scope of the research, limitation of the work, and the organization of the report.

The second chapter focused on different literature work completed by different authors that emphasize on study of metal matrix composite material.

The third chapter deals with materials and methods used to accomplish this thesis work. This section comprises Matrix and reinforcement materials, Fabrication Equipment, Testing equipment, Composition preparation for composite fabrication, the process of the composite fabrication method, and others.

The experimental result of mechanical, microstructure and tribological properties of the manufactured specimens Al6061+SiC+B_4C+MoS_2 composite have been presented and discussed in Chapter four.

Finally, Chapter five presents the conclusion of experimental results and recommendations for future works.

CHAPTER TWO

LITERATURE REVIEW

2.1. Chapter Overview

This chapter gives a full literature survey of aluminum metal matrix composites. A Review of different literatures was helps to have better understanding of some common sense of this thesis work area. The outcomes of various studies by international researchers on composite materials are discussed in the present chapter. The chapter gives detail discussion about previous works related to metal matrix composite in subtitle of Composite materials characteristics and classifications, metal matrix composites, advantages, matrix and reinforcements used in the production of MMCs, Production process of MMCs, recommended process parameters for stir casting and Recent Research developments on Aluminum Al6061 alloy Matrix Composites. At the end, based on the discussion made, Literature summary is presented in with literature gap.

2.2. Characteristics of Composite Materials

The properties of composites are strongly relying on the properties of their constituent materials (both continuous phase and discontinuous phase), their distribution and the interaction among them. The properties of composite also depend on the weight percentage of reinforcement constituent in the matrix material. Apart from the nature of the principal materials properties, the geometry of the reinforcement (shape, size and distribution) influences the properties of the composite to a great extent. The orientation of the reinforcement also affects the properties composites. The shape of the reinforcement phase (which may by spherical, cylindrical, or rectangular cross-sectioned prisms or platelets), the size and size distribution (which controls the texture of the material) and volume fraction determine the interfacial area, which plays an important role in determining the extent of the interaction between the reinforcement and the matrix. Concentration, usually measured as volume or weight fraction, determines the contribution of a single constituent to the overall properties of the composites (Chandramohan & Marimuthu, 2011). Composite manufacturing methods and manufacturing variables also play avital role on the quality of composites

2.3. Classification of Composite Materials

Generally composite materials can be classified in to two main categories based on the nature of exists indicated in Figure 2.1. These are naturally existing or valuable composite called natural composites and manmade or synthetically existing composite called synthetic composites. Natural composites exist in both animals and plants. Well known examples of natural composite are wood (lignin is a matrix and hemicellulos is a reinforcement) and bones.

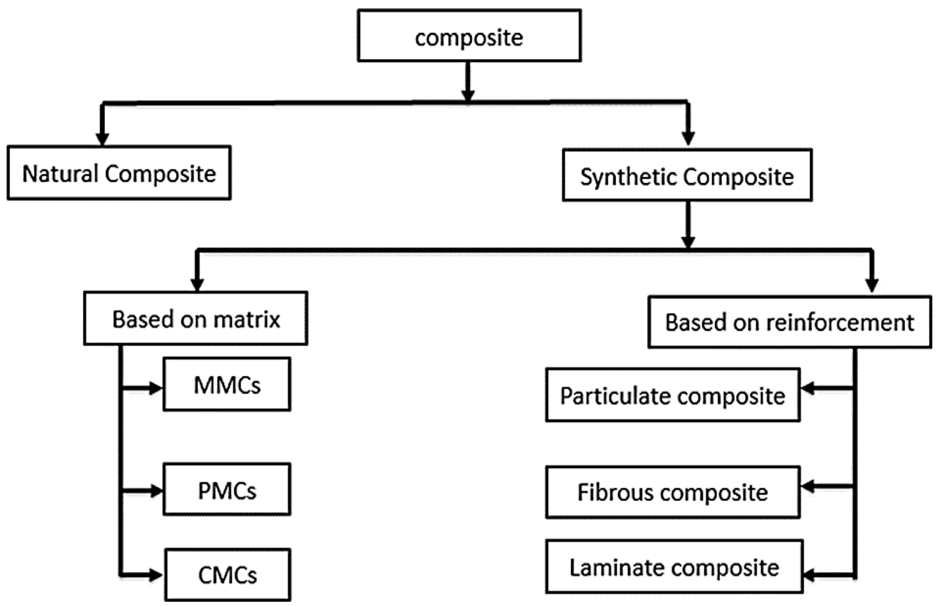


Figure 2.1. Classification of composite material

Based on the type of matrix material used, synthetically made type of composite can be classified as metal matrix composites (MMCs), polymer matrix composites (PMCs) and ceramic matrix composites (CMCs). Man-made composite materials can also be classified as Particulate Composites, Fibrous Composites and Laminate Composites based on the reinforcing material structure (Callister, 2007).

2.3.1. Particulate Composites

Particulate Composites consist of a matrix reinforced by a dispersed phase in the form of particles is shown in Figure 2.2 a. They are usually isotropic because the particles are added randomly. Particulate composites have advantages such as improved strength, increased operating temperature, oxidation resistance, etc. (kaw, 2006). Particles used for reinforcing include: ceramics and glasses, metal particles, and amorphous materials (Callister, 2007).

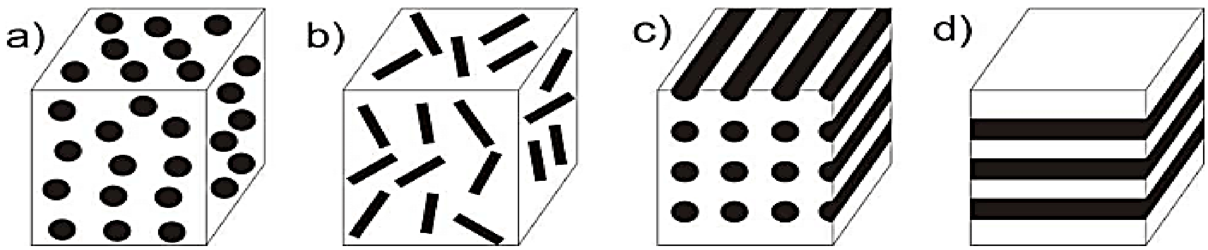


Figure 2.2. a) Particulates b) Whiskers/ short fibers c) Fibers d) Layers/ plates (Przemysław et al., 2013).

2.3.2. Fibrous Composites

A. Short-fiber reinforced composites. Consist of a matrix reinforced by a dispersed phase in form of discontinuous fibers (length < 100*diameter) as shown Figure 2.2 b.
B. Long-fiber reinforced composites. Consist of a matrix reinforced by a dispersed phase in form of continuous fibers as shown in Figure 2.2. c.

2.3.3. Laminate/ Structural Composites

When a fiber reinforced composite consists of several layers with different fiber orientations, it is called multilayer composite as shown Figure 2.2. d.

2.4. Metal Matrix Composite

Metal matrix composites (MMCs), as the name indicates, a composite that utilize metals as a matrix material. Super-alloys and alloys of aluminum, magnesium, titanium, and copper, are employed as matrix materials. Typical reinforcements include graphite, silicon carbide, boron carbide, molybdenum disulfide, aluminium oxide etc. The reinforcement may improve specific stiffness, specific strength, abrasion resistance, creep resistance, thermal conductivity, and dimensional stability (Callister, 2007; kaw, 2006).

2.4.1. Applications of Metal Matrix Composites

Metal matrix composite has many applications in engineering at present day. The development of MMCs forced many industries to adopt metal-based composites over alloys and pure metals due to its superior properties than its alloys and pure metals. Some of industrial applications of metal matrix composites are discussed as follow (kaw, 2006).

A) In aircraft and aerospace industries

The space shuttle uses boron/aluminum tubes to support its fuselage frame. The use of this composite decrease the mass of the space shuttle by more than 320 lb (145 kg), and also reduced the thermal insulation requirements because of its low thermal conductivity. Hubble Telescope of space shuttle uses carbon-reinforced aluminum. Wings and supporting structure in airlines, components of military aircrafts and cargo are also produced from MMCs (Pulkit et al., 2019).

B) In automobile industries

Metal matrix composites are now used in automotive engines that are lighter than their metal complements. Also, because of their high strength and low weight, metal matrix composites are the material of choice for gas turbine engines.

Automobile manufacturers use MMCs for their products. For example, some engine components have been introduced consisting of an aluminum-alloy matrix reinforced with aluminum oxide and carbon fibers; this MMC is light in weight and resists wear and thermal distortion. Metal-matrix composites are also employed in drive shafts, extruded stabilizer bars, and forged suspension and transmission components (Callister, 2007).

Components such as pistons, connecting rods, engine blocks, brake rotors, current collectors, propeller shafts and brake disc are manufactured from aluminum matrix composites (Pulkit et al., 2019). Figure 2.3 shows connecting rods made of aluminum matrix composite reinforced with aluminum oxide.

Figure 2.3. Connecting rods made of Al-Al_2O_3 (Przemyslaw and Aleksander, 2013)

C) In Military industries

Precision components of missile guidance systems need dimensional stability, So that the geometries of the components cannot change during use. MMCs such as SiC/Aluminum composites satisfy this requirement because they have high micro-yield strength (kaw, 2006).

Metal matrix composite also applicable in Marin industries, Sports and recreation sectors, Electrical transmission equipment's, Rail transport companies etc. due to its desirable properties.

2.5. Matrix and Reinforcements Used in the Production of MMCs

Figure 2.4 shows various matrix and reinforcement used in the production of metal matrix composites.

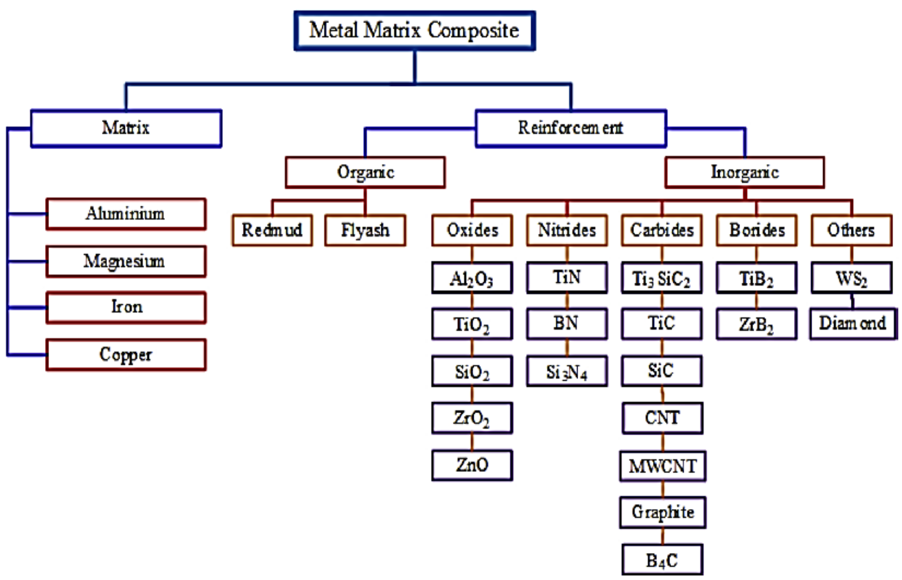


Figure 2.4. Various matrix and reinforcement materials used for the production of MMCs (Ramanathan et al., 2019).

2.6. Production methods

The production methods for metal matrix composites can be categorized based on primary processes such as treating the metal matrix in a liquid or a solid form or others (including semi-solid, in situ and others). According to the production processes, metal matrix composite can be categorized as Solid state processing/ such as powder metallurgy/, liquid state processing/such as stir casting, stir squeezed casting/ and other techniques (Ramanathan et al., 2019). From various types of MMCs fabrication processes/methods, stir casting is regarded as the most productive, economical and relatively simple (Madeva et al., 2018). Table 2.1 gives comparison between various production processes in terms of different aspects.

Table 2.1. Comparative evaluation of the different techniques used for DRMMC fabrication (Hashim et al. 1999)

Method	Range of shape and size	Damage of reinforcement	Cost
Stir casting	Wide range of shapes; large size up to 500kg	No damage	Least expensive
Squeeze casting	Limited to preform shape; up to 2cmheight	Sever damage	Moderately expensive
Powder metallurgy	Wide range but restricted size	Reinforcement fracture	expensive
Spray deposition	Limited shape but large size	-	expensive

2.7. Process Parameters

To fabricate quality single or hybrid reinforced metal matrix composite material; stir or squeezed-stir casting is used frequently. Squeezed-stir casting Process parameters, such as melting temperature, die temperature, string speed, string time, reinforcement percentage, reinforcement preheating temperature, squeezing pressure etc., have a great role in the production of good quality MMCs. The recommended process parameter ranges for stir and stir-squeezed casting is indicated in Figure 2.5. The suggested range of process parameters are based on the results found by different researchers as discussed by Ramanathan et al. (2019).

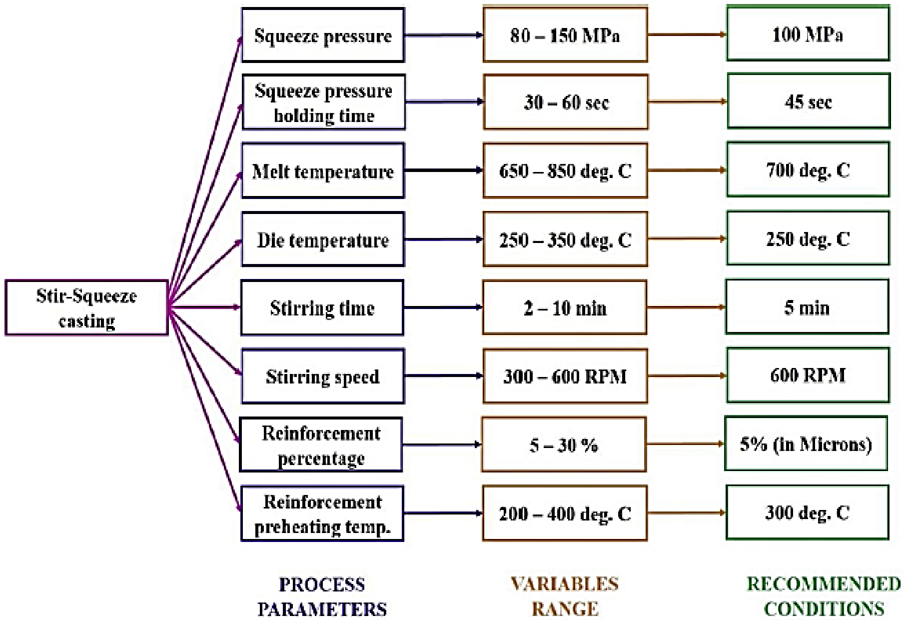


Figure 2.5. Recommended process parameters for stir-squeeze casting process (Ramanathan et al., 2019)

2.8. Wettability between Matrix and Reinforcement Material

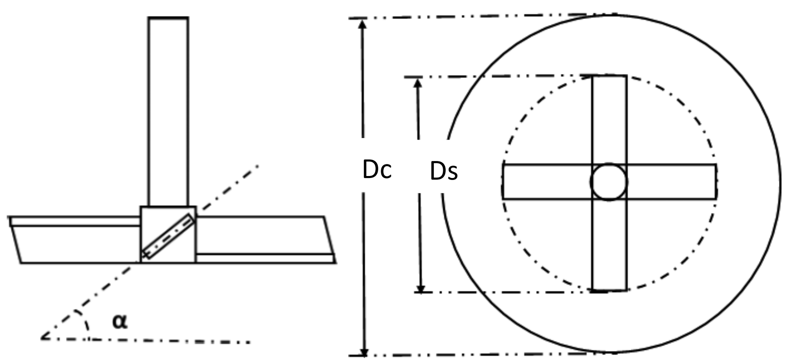
Wettability is one factor that significantly affects the properties of metal matrix composites. Wettability can be defined as the capability of a liquid (molten matrix) to spread over a solid surface (reinforcement). It also describes as the degree of close contact between liquid and solid. A number of methods have been taken to improve the wettability of the reinforcement particles with a liquid matrix material, such as; (Hashim et al. 1999).

1. The coating of the reinforcement particles wettable metal like Nickel and copper
2. The addition of reactive alloying elements to the molten matrix alloy such as Mg, Ca, Ti, NaC3, or Zr.
3. Pre-heating the reinforcement particle before added to molten matrix also promotes wettability.
4. Mechanical string leads to high wettability and
5. Ultrasonic irradiation of the melt.

2.9. Stirrer

In Stir casting setup a mechanical stirrer is required to form vortex for the necessity of uniform distribution of reinforcement particles into the molten matrix material and to promote wettability. Therefore, proper selection of a suitable blade angle, diameter and number is crucial to obtain good level of mixing.

To investigate the effect of impeller blade angle, researchers used water model and CFD model. The selected blade angles were 15, 30, 45, 60 and 90. In a water model, Ravi et al. (2007) investigated the effect of impeller blade angle over the distribution of solid particles in the liquid. The result shows Stirrer with blade angle (α = 30) performed well and shows uniform dispersion without accumulation of solid particles. In addition to this, stirring time plays an important role over the distribution of solid particles and power consumption by the stirrer. Figure 2.6 shows the typical image of four bladed stirrer.



Where
Dc= diameter of crucible
Ds=diameter of stirrer

Figure 2.6. Stirrer blade angle (Mohit and Raj, 2018)

Researcher were used different models for the optimization of stirring parameters. The models used by authors are water model, FEM model and experimental model. Authors were attempted to find the optimal values of stirring parameters for single stage and multistage impeller stirrer.

The position of the blade should be less than or equal to 30% of the height of the fluid from base of the crucible to avoid clustering of reinforcements particles at the bottom. And the diameter of the blade should be equals to one half of the diameter of crucible. Figure 2.7 shows the position of stirrer in the crucible during action.

$$h \leq H_O \qquad \text{Eq 2.1}$$

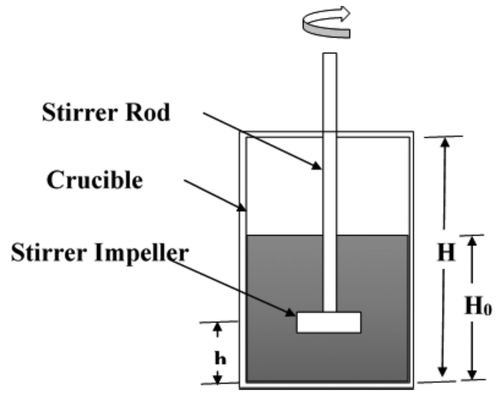


Figure 2.7. Position of stirrer in the crucible.s

Table 2.2. Optimal values of stirrer parameters

Author	Blade angle (α)	Diameter of impeller (d)	Position of impeller (h)
	^{O}C	mm	Mm
Mohit and Raj	30	0.5D	0.25H0
Prabu et al	30	0.5D	-
Ravi et al.	30	-	0.3H0
Hashim et al.	-	-	0.3H0

2.10. Recent Research Developments on Aluminum Alloy (Al6061) Matrix Composites

Aluminum matrix composites (AMCs) have significant properties than other metal matrix composites in terms of their high strength to weight ratio. This section gives a comprehensive discussion about previous works related to Aluminium matrix composite, specifically Al6061 matrix composites. It had two subsections, Single-reinforced aluminum (Al6061) alloy matrix composite and hybrid-reinforced aluminum (Al6061) alloy matrix composite. The result of mechanical properties (tensile, compression, and hardness tests) and tribological teste of some studies done by varying the wt. % of various reinforcements on Al6061 metal matrix composites were debated as follows.

2.10.1. Mechanical Properties of Single-Reinforced Aluminum Alloy (Al6061) Matrix Composites

When only one reinforcement material is used to produce metal matrix composite, then the composite is called single reinforced metal matrix composite. Different researchers uses aluminum (Al6061) alloy as a matrix material with only one reinforcement to produce single reinforced composites as discussed below.

Bharath et al. (2014) evaluated the mechanical and wear properties of 6061Al-Al_2O_3 MMC's manufactured by Stir Casting. The composite was prepared by varying the reinforcement from 6-12wt% in steps of 3wt%. Afterward, Microstructural, Hardness and tensile properties of the prepared composite were determined before with and without addition of Al_2O_3 particles. Microstructural characterization of the composites has shown uniform distribution and some amount of grain refinement in the specimens. Further, the hardness and tensile properties are higher in case of composites when compared to unreinforced 6061Al matrix. The highest Ultimate Tensile strength and hardness value are 193.47MPa and 188±2VHN noticed at 12wt% Al_2O_3 addition.

Ravi et al. (2015) characterized Aluminium matrix composites (AA6061) reinforced with B_4C as fabricated by Stir casting method. The reinforcement boron carbide (B_4C average particle size of 25 μm) with Weight percentages of 0%, 5% and 10% were utilized to fabricate AMMC. The homogeneous dispersion of B_4C particles in the AMCs was noticed from the optical micrographs. The tensile strength and hardness has increased with the increase in weight percentage of B_4C particles in the composite. The maximum ultimate tensile strength and hardness is 145 MPa and 68 HV respectively at AA6061+10% of B_4C.

Karabulut et al. (2016) studied the Influence of B_4C reinforcement (average size of 10 mm) on mechanical properties of (Al6061). Four aluminum composite specimens reinforced with 5 wt%, 10 wt%, 15 wt%, and 20 wt% B_4C were fabricated using a powder metallurgy and hot-extrusion method. The composite samples were investigated to clarify the influence of different weight percentage of B_4C reinforcement on the hardness, fracture toughness, and tensile strength. The highest tensile (210Mpa) for Al6061+5 wt% B_4C and Al6061 reinforced with 10 wt% B_4C composite material has the best fracture toughness from among the specimens measured. It also observed that the hardness increases with B_4C content and the maximum hardness (70HV) occur at 20 wt% B_4C.

Moses et al. (2016) investigated the influence of process parameters on tensile strength of AA6061 + TiC aluminum matrix composites produced using stir casting. An empirical relationship was developed to predict the effect of stir casting parameters on the ultimate tensile strength (UTS) of AA6061/TiC AMCs. The factors considered were stirring speed, stirring time, blade angle and casting temperature. The UTS was high when the porosity was low and the distribution was homogenous. The present research work revealed an existence of optimum range of parameters to produce AA6061/15%TiC (mass fraction) AMCs with high UTS.

Bhaskar et al. (2017) Fabricated and characterized of Al_2O_3+Al6061 composites fabricated by Stir casting. In the present work, aluminium alloy 6061 reinforced with various percentages of Al_2O_3 particles (5, 10, 15 and 20 wt %) were prepared. After fabrication, microstructures, micro hardness and ultimate tensile strength of AMMC wear characterized. The investigation shows, Al2O3 particles were distributed homogeneously in the aluminium matrix. It also was found that both tensile strength, UTS and hardness was improved as the percentage of reinforcement increased from 5 % to 20 %. But the percentage of elongation was decreased. The maximum UTS and hardness was observed at an addition of 20% Al_2O_3 with a maximum value of 310 MPa and 89.91 VHN respectively.

Kumar et al. (2017) studied on Al6061+Graphene nanocomposites. Graphene, being one of the allotropes of carbon; although with the limited studies, shows it can be considered as nano-filler and perfect reinforcement for conventional structural materials. Graphene with different filling content (0.25, 0.5, 0.75, 1.0 weight %) is used use as reinforcement in the Aluminum matrix. The investigation shows that, addition of Graphene likely to increase the hardness values and decreasing the diametrical expansion at its optimum Graphene content in the developed composite. The highest micro hardness values is given at 0.5 wt% Graphene sintered at 500 °C have a value of 84 HV and the minimum diametrical expansion was observed at 1 wt% Graphene at a quenching temperature of 450 °C.

Rao and Ramanaiah (2017) studied the Influence of heat treatment on mechanical and corrosion properties of aluminium metal matrix composites (AA6061 reinforced with MoS_2). AA6061 as matrix material and Molybdenum disulfide (MoS_2) powder of size 3-5 mesh and with 1%, 2 %, 3%, 4%, and 5%, of MoS_2 were made through stir casting method. A systematic study of the matrix metal and AMMCs were done to evaluate the mechanical properties (hardness, yield strength and tensile strength) and pitting corrosion resistance in as cast and heat treated condition. It was observed that, mechanical properties and corrosion resistance are increase with the increase in wt. % of the reinforcement up to 4% MoS_2 further addition there is a reduction in both the conditions.

Madeva et al. (2017) studied the influence of Al_2O_3 and graphite (average particle size 90-100 μm) on the microstructure and mechanical behavior of Al6061 fabricated using liquid metallurgy method. The Al6061-Al_2O_3 and Al6061-Graphite composites were fabricated separately by introducing 9 wt. % of Al_2O_3 and graphite particulates by two stage melt stirring process. The density, hardness, ultimate tensile strength, yield strength and percentage elongation of both Al_2O_3 and Graphite composites were evaluated as per ASTM standards. It is observed that, the addition of 9wt. % graphite particles, the density of the composite is slightly decreased. It also noticed that the hardness of the alloy matrix increased with the addition of Al_2O_3 particles.

Gowri et al. (2018) tried to enhance hardness and investigated the influence of artificial aging on stir cast Al6061-B_4C and Al6061-SiC composites. This work investigated on individual effect of B_4C and SiC on the improvement in hardness with an average size of 35-40μm by varying weight percentage of reinforcements (2, 4 and 6) on Al6061 alloy. The precipitation hardening effect at 100, 150 and 200^{O}C on the mechanical properties was also investigated. Peak hardness of 85 BHN is observed with aging time with aging time of 9.30h at 100^{O}C. It was observed that, peak hardness increases to a maximum value with decrease in aging temperature and increase in aging time. As cast hardness of Al6061-6% B4C composite is 74BHN and Al6061-6% SiC composite is 69BHN when compared to 50 BHN of Al6061 alloy.

Akshay et al. (2018) characterized mechanical properties of friction stir processed Al6061-BN surface composite. Percentage of boron nitride was varied from 0 to 6wt% in steps of 3wt%. Effect of number of pass and reinforcement content on Microstructure (optical and SEM), hardness and tensile behaviour of Al6061 was evaluated. Hardness is significantly increased with increase in the concentration of boron nitride and increase in number of passes. From the Figure 2.10, it was observed that Al6061-3wt% BN increased by 14% and Al6061-6wt% BN increased by 20% when compared with Friction Stir Processed Al6061 alloy.

Subramanya et al. (2018) did experiment on microstructure and mechanical properties of rutile-reinforced AA6061 matrix composites produced using stir casting process. The composite was prepared by varying the mass fractions of the rutile average size of 10 μm particles as 1%, 2%, 3% and 4% in AA6061 matrix. Rutile-reinforced AMCs exhibited higher tensile strength and hardness as compared with parent material. The properties of the composites were enhanced with the increase in the mass fraction of the rutile particles. However, beyond 3 wt. % of rutile particles, the tensile strength decreased. With the increase of rutile particles, the hardness of specimen increases up to 50% compared with that of the base matrix alloy.

Kishore et al. (2018) studied the surface roughness in turning of in-situ Al6061+TiC metal matrix composite by Taguchi method. Al6061-10 Wt% TiC MMC rod is fabricated by using stir casting setup. It was identified that cutting speed is having highest contribution on the response surface roughness with the percentage contribution of 43%, and this is followed by depth of cut and feed rate with the percentage contribution of 31% and 26%.

Ashok et al. (2018) studied the Tensile and Compression Behaviour of aluminium alloy, Al606, Boron Carbide Reinforced MMC’s processed through Conventional Stir casting method. The composite is prepared with 9wt% of boron carbide particulates having mean sized having mean sized 8μm at processing temperature of 750°C. After the composite fabricated tensile, compressive, Hardness Microstructural test were performed. Microstructural studies revealed fairly uniform distribution of B_4C particles in 6061Al matrix was observed. The hardness of the 6061Al-9wt%B_4C composite is increased to an extent of 34.9%. The extent of improvement obtained in the 6061Al alloy after addition of 9 wt% of

B_4C particles are 15.47% (yield stress) and 9.5% (ultimate tensile strength) and 24.25% (compressive strength). On the other hand the ductility of the composites decreases with addition of B_4C particulates. Therefore, 6061Al-B_4C system could be used as replacement of steel and other ferrous materials in structural applications.

Gangadharappa et al. (2018) investigated on mechanical and wear characteristics of Al6061 red mud composites. Al6061 red composite specimens were manufactured by stir casting technique with 5%, 10%, 15% and 20% volume percentages of red mud 30-40nm size particles were used as the reinforcement. After the composite prepared investigation were performed on hardness, wear rate and co-efficient of friction. It was found that the hardness increased when the red mud content was increased in the base alloy at all the heat treatment conditions. The peak age timing which gives highest hardness was found to decrease with increased red mud content.

Madhukumar and Umashankar (2018) characterized glass particulate reinforced aluminium alloy (AL6061) metal matrix composites fabricated using melt stirring technique. The composites were prepared with different volume fraction of reinforcement 250 microns (3%, 6%, 9% and 12%). The prepared composite specimens were subjected to mechanical tests like hardness and tensile strength using Vickers hardness and uniaxial tensile testing instrument. As the results revealed that the hardness and tensile strength increases with increase in wt% of reinforcement up to 9wt% and decreased for 12wt%.

Veeresh et al. (2019) investigated the physical, mechanical and tribological properties of Al6061+ZrO_2 with a size of 200 nm nano-composites. Four casts of different percentages of reinforcement from 0 to 6 wt% in the steps of 2 were fabricated using stir casting technique. After composites were prepared various physical, mechanical & wear tests were subjected. The hardness and tensile strength of the MMCs increased by 39.88% and 47.13% respectively as reinforcement percentage increased from 0% to 6% ZrO_2. The peak hardness and UTS values were 67.8BHVand 174.9Mpa respectively and observed at 6% ZrO_2 reinforced composite. It was also found that the percentage elongation of the MMCs decreased by 50.2% as the proportion of strengthening rose from 0% to 6%.

Table 2.3. Summary of properties of Single- reinforced aluminum (Al6061) matrix composite

Year	authors	Matrix	reinforcement	Fabrication Method	Reinforcement Size	Hardness maximum	UTS
2014	Bharath et al.	Al6061	Al_2O_3	stir casting	125µm	188±2VHN	193.47MPa
2015	Ravi et al.	AA6061	B_4C	stir casting	25 µm	68 HV	145 MPa
2016	Karabulut et al.	Al6061	B_4C	powder metallurgy	10 mm	70HV)	210Mpa
2016	Moses et al.	AA6061	TiC	stir casting	-	-	230Mpa
2017	Bhaskar et al.	Al6061	Al_2O_3	Stir casting	-	89.91 VHN	310 MPa
2017	Kumar et al.	Al6061	Graphene	powder metallurgy (PM)	Al6061= 30-35 µm	84 HV	-
2017	Rao and Ramanaiah	AA6061	MoS_2	stir casting	3-5 mesh	116HV as heat treated	249 MPa as heat treated
2017	Madeva et al.	Al6061	Al_2O_3 and graphite	Liquid metallurgy	90-100 µm	150VHN	193Mpa
2018	Gowri et al.	Al606	B_4C & SiC	Stir casting	35- 40µm	85 BHN	-
2018	Akshay et al.	Al6061	BN	Friction Stir Processed	-	100±2BHN	148±2 MPa
2018	Kishore et al.	Al6061	TiC	stir casting	-	-	-
2018	Subramanya et al.	AA6061	rutile	stir casting	10 µm	91±3HV	165±2 MPa
2018	Ashok et al.	Al606	B_4C	stir casting	8 microns	95HV	149.39 MPa
2018	Gangadharappa et al.	Al6061	Red Mud	stir casting	30-40nm	-	-
2018	Madhukumar and Umashankar	Al6061	Glass Particulate	stir casting	250 microns	93±2HV	182± MPa
2019	Veeresh et al.	Al6061	ZrO_2	stir casting	200 nm	67.8BHV	174.9Mpa

2.10.2. Mechanical Properties Hybrid-Reinforced Aluminum (Al6061) Alloy Matrix Composite.

When two or more than two reinforcements are used in the fabrication metal matrix composite, it is called a hybrid metal matrix composite (Mohammad et al., 2019). The property of the developed material changed due to different properties of the matrix and reinforcements. Metal matrix hybrid composites are the second-generation composite materials that have potential to substitute single reinforced composite by improving properties and have the capacity to satisfying the recent demands of advanced engineering applications (Jaswinder and Amit, 2016; Michael et al., 2015). Various researchers conduct a research work on hybrid metal matrix composites and hybrid reinforced aluminum (Al6061) alloy matrix composite investigated by different authors are discussed as follows.

David et al. (2013) Synthesized and characterized Al6061+Fly Ash+SiC composites by stir casting and compo-casting methods. The AMMC were reinforced with various weight percentages of SiC particulates and a constant weight percentage of Fly Ash. The microstructure and mechanical properties of the fabricated AMCs were examined. The mechanical properties like hardness and tensile strength were improved with the increase in weight percentage of SiC particulates with constant weight percentage of Fly Ash in the aluminum matrix. The maximum hardness and ultimate tensile strength are 80VHN and 213MPa respectively.

Suresh et al. (2014) investigated the Effect of graphite addition on mechanical behavior of Al6061+TiB_2 Hybrid composite. The Al6061 reinforced hybrid composites, containing 2wt% Graphite particle size of 20-25mm and 0, 10, and 20wt% of TiB_2 particle size 1-5mm were prepared by the stir casting process. Subsequently mechanical Behaviors such as hardness, tensile strength using acoustic emission and fatigue behaviors were investigated. The composite of composition Al6061–20% TiB_2 with 2% graphite shows the greatest improvement in mechanical behavior. The peak value of hardness is 91.4HV at a composition of 20% TiB_2 with 2% graphite.

Viney et al. (2014) evaluated mechanical properties and effect of sliding velocity on wear properties of Al 6061+Mg 4%+Fly ash and Al6061+Mg 4%+Graphite 4%+Fly ash Hybrid

Metal matrix composite synthesized by stir casting process. The composition of reinforcement wear taken as follow, first case AL6061, 4%MG chosen as a base metal and varying composition of Fly ash i.e. 10%, 15% and 20% was taken as reinforcement in second case AL6061, 4%MG, and 4%Graphite was taken as base material and varying composition of Fly ash i.e. 10%, 15% and20% as reinforcement. It was found that tensile strength increase with addition of fly ash. Similarly when graphite was added then a decrease in tensile and hardness was observed. The composite with 4%Mg, 15%Fly ash found to be maximum tensile 124MPa whereas composite of 4%Mg, 20%Fly ash was found to be of maximum hardness with a value of 71.3HV.

Partheeban et al. (2015) studied the mechanical behavior of Al6061 alloy, Al6061+10TiB_2 composite and Al6061+10TiB_2+1Gr and Al6061+10TiB_2+2Gr hybrid composite prepared using a powder metallurgy method. The Al and TiB_2 powder has the particle size of 30-50 mm and 1-10 mm, and the graphite particle size varies from 25-50 mm. The Hardness increased with addition of reinforcements of TiB_2 and Nano-Gr on Al6061 matrix. There was also an improvement in the tensile strength with the addition of TiB_2 and Nano-Gr. The highest hardness value 79.04HV is observed at Al6061+10TiB_2+2Gr hybrid composite and the maximum Ultimate compressive strength value 322Mpa is observed at Al6061+10TiB_2+2Gr hybrid composite.

Johny et al. (2018) Developed and studied the property of Hybrid Aluminium Metal Matrix Composite fabricated by stir casting technique. The metal matrix choice was Aluminium 6061and the reinforcements are Zirconium di oxide (ZrO_2) and Aluminium oxide (Al_2O_3) particles with average size of 55-65 μm. The composite comprises of 90% of aluminium 6061, 5% of ZrO_2 and 5% of Al_2O_3 which was restricted to 10 weight percentage. Tensile strength test specimens were cut as per ASTM-E8 standard, and the readings were tabularized. The tensile value show significant improvement and the highest value UTM is 227.3 MPa. The hardness test was performed using Vickers micro hardness tester and its maximum value is 82.9HV at 200kgf load.

Halil et al. (2019) investigated on wear and mechanical properties of Al6061 (>100 μm Particle size) + SiC (>8μm Particle size) + B_4C (>10 μm Particle size) hybrid composites produced with powder metallurgy. It presents the new approach into optimize the mechanical properties of hybrid composites (Al-SiC-B_4C) produced with powder extrusion process. The extruded samples were subjected to T6 heat treatment. After the composite materials produced, the terms of density, microstructure, hardness, transverse rupture strength, tensile strength, and wear resistance are examined. The highest hardness 73±2HB occurred in 12% B_4C reinforced composites. The highest tensile strength 405±2MPa occurred in 12%SiC particle reinforced composite material.

Satheesh and Pugazhvadivu (2019) investigated on physical and mechanical properties of Al6061+Silicon Carbide (SiC) (mesh size 220) +Coconut shell ash (CSA) (40–80 μm size) hybrid composites fabricated by stir casting. Al6061-SiC composite were prepared by adding 10 wt% of SiC into Al6061 melt. The result of experimentation shows, the density of Al6061-SiC-10% CSA hybrid composite is 6.58%, which is lower than Al6061-SiC composite. The hardness and tensile strength of Al6061- SiC-8% CSA hybrid composite increased by 46% and 47.31% respectively. The maximum hardness and tensile strength are 100±2VHN and 200Mpa respectively occurred at Al6061+SiC-8%+CSA hybrid composite increased.

Madeva et al. (2018) Synthesized and characterize microstructural, mechanical behaviors of Al6061, Al6061+ 9wt.%SiC particles of size 90-125microns and Al6061+9wt% graphite particles of size 90-125 microns composites fabricated by liquid metallurgy. The density, Hardness, ultimate tensile strength, yield strength and percentage elongation of both SiC and Graphite composites were evaluated. The microstructural investigation shows, the particle distribution was uniform in these composites. The densities and hardness of Al6061 has increased after the addition of 9 wt% SiC. The result also revealed, Al6061+9 wt. % SiC composites shown 25.32% improvement in ultimate tensile strength compared to Al6061 matrix system. The maximum value of hardness and ultimate tensile strength are 150±2VHN observed at 9 wt. % SiC and 193±2MPa observed at 9 wt. % graphite.

Subramani et al. (2019) studied the characteristics of A6061/ (Glass Fiber + AL_2O_3 + SiC + B_4C) reinforced hybrid composite prepared through Stir Casting. The average size of the reinforcement particles is 25µm. A6061 and its reinforcement particles like aluminium oxide/glass fibers/SiC/B_4C (4% and 5%) with and without glass fiber composite were produced. Subsequently, Microstructural and mechanical testes such as micro hardness test, wear and tensile tests were done. The maximum ultimate tensile strength (125MPa) observed at samples with glass fibers + 5% of other reinforcements and hardness (49.7BHN) observed at samples without glass fibers + 5% of other reinforcements.

Table 2.4. Summary of Hybrid-reinforced aluminum (Al6061) matrix composite.

Year	authors	Matrix	reinforcement	Fabrication method	Reinforcement size	Hardness (Maximum)	UTS (Maximum)
2013	David et al.	Al6061	Fly Ash + SiC	stir casting and compo-casting	-	80VHN	213MPa
2014	Suresh et al.	Al6061	graphite+TiB_2	stir casting	graphite =20-25mm TiB_2=1-5 mm	91.4HV	-
2014	Viney et al.	Al6061	Mg+Graphite + Fly ash	stir casting	Fly ash =100μm	71.3HV	124MPa
2015	Partheeban et al.	Al6061	graphite+TiB_2	powder metallurgy	Al6061=30-50 mm TiB_2=1-10mm Graphite=25-50mm.	79.04HV	322Mpa
2018	Johny et al.	Al6061	ZrO_2+ Al_2O_3	stir casting	55-65 μm	82.9HV	227.3MPa.
2019	Halil et al.	Al6061	SiC+ B_4C	powder metallurgy	Al6061>100 μm SiC>8 μm B_4C >10 μm	73±2HB	405±2MPa
2019	Satheesh and Pugazhvadivu	Al6061	SiC+Coconut shell ash (CSA)	stir casting	SiC=220 mesh CSA=40-80μm	100±2VHN	200Mpa
2019	Madeva et al.	Al6061	Al_3O_2, graphite	liquid metallurgy	90-125 microns	150±2VHN	193±2MPa
2019	Subramani et al.	A6061	Glass Fiber + Al_2O_3 + SiC + B_4C	stir casting	-	49.7BHN	125MPa

2.10.3. Tribological Properties of Aluminum Alloy (Al6061) Matrix Composites

Mukesh and Ashiwani (2019) studied Sliding wear performance of graphite reinforced AA6061 alloy composites for rotor drum/disk application via high vacuum casting technique. The solid lubricant which is graphite was used to reinforce AA6061 alloy by varying Weight percentage from 0–10 wt%. The following parameters were used on pin on dick apparatus: Applied load (15–55 N), sliding speed (0.5–2.5 m/s) and sliding distance (200–1000 m). The specific wear rate increases with normal load (15–55 N). 7.5 Wt% 6061/Gr alloy composite shows superior wear resistance. Due to the presence of graphite particle the adhesive mechanism wear diminished and abrasive wear mechanism dominated.

Aatthisugan et al. (2017) performed a test on wear behaviour of AZ91D magnesium matrix hybrid composite reinforced with boron carbide (B_4C) and graphite produced via stir casting. Dry sliding wear tests were performed by using pin-on-disc as per ASTM G99 standard. The counter disc material was EN31 steel. All of the tests were performed on various applied loads of 5, 10, 20 and 50 N with sliding speeds of 1 m/s. it is observed that there is an increase in coefficient of friction and wear loss with increasing normal load for both AZ91D and AZ91D composites in the load range of 5-50 N. It was found that with an increase in the B_4C content, the wear resistance increased. Abrasion and delamination are the dominant wear mechanisms.

Dou et al, (2014) investigated on friction and wear behaviors of B_4C/6061Al composite fabricated by stir casting method. Study were performed by considering the effect of sliding time, applied load, sliding velocity and heat treatment. The results show that, when the sliding time, applied load and sliding velocity reach critical values (namely 120 min, 30 N and 240 RPM, respectively), the mass loss and friction coefficient (COF) increase significantly. Severe delamination wear is the main wear mechanism after sliding for 120 min and under an applied load of 30 N.

Halil et al. (2019) also perform tribological test on Al6061/SiC/B_4C hybrid composites produced with powder metallurgy. The wear tests were carried out using a pin-on-disk wear-testing device according to ASTM G132-96. The wear tests were performed at distances of 100, 200, and 300 m, at a speed of 1.2 m/s and with imposed loads of 5, 10, and 15 N. The volume loss increased with the increase in applied load and wear distance in all samples. Weight loss decreased with the increase in weight percent of B_4C in the HMMCs. The minimum volume loss was found to be 0.07 mm3 from the 12%B_4Chybrid composite for a 5N load and a 100m sliding distance. Abrasion, deformation, and delamination were main wear mechanisms.

Umanath et al. (2013) analyzed the dry sliding wear behaviour of Al6061/SiC/Al_2O_3 hybrid metal matrix composites synthesized by Stir casting process. The test specimens are prepared and tested as per ASTM standard. Among the four main factors, the volume fraction and counterface hardness have negative contribution and the other two main factors (Applied load and Rotational speed) gives positive contribution, which implies that each individual factor increase the wear of the hybrid composites. The results indicated that the wear resistance of the 15% hybrid composite is better than that of the 5% composite. The fracture surface of composites shows the ductile tear ridges and cracked SiC and Al_2O_3 particles indicating both ductile and brittle fracture mechanism.

Mohammad et al. (2019**)** studied the wear behavior of Al matrix composites reinforced with SiC and MoS_2 synthesized by press and sintering. Wear rate and friction of coefficient SiC+MoS_2 composites were evaluated. As the result of pin on disc wear test according to ASTM G99-95a standard shows, the lowest wear rate and friction of coefficient were attained for Al6061+10SiC+2MoS_2 hybrid composite. According to the scanning electron microscope observations, the predominant wear mechanism was abrasion mostly when MoS_2 particles were incorporated in the pure aluminum. A. Mild delamination was identified as the main wear mechanism for Al/SiC and Al/SiC/MoS2 composites.

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2.11. Literature Summary

The literature review clearly shows that a number of researches have been carried out on the fabrication and characterization of aluminum matrix composites. Various fabrication methods (like liquid state and solid state processing technique) and the effect of processing conditions have been widely used. AMMCs are reinforced with varied particulate ceramic reinforcements and the influence of weight composition reinforcement on the physical, mechanical and tribological behavior of has been studied. Ceramic particles were widely employed as reinforcements in the production of aluminum matrix composites. From the literature, it is obvious that the mechanical and tribological properties of aluminum alloy (Al6061) matrix are significantly improved by the addition of different particulate reinforcements.

2.12. Literature Gap

The previous researchers developed and studied the characteristics of different types of composites. The future manufacturing technology shows an interest on production of cost effective, light weight and good performance products using infinite (unlimited) resources. Single-reinforced aluminum alloy (Al6061) matrix composites and hybrid-reinforced aluminum alloy (Al6061) matrix composite were manufactured and studied to improve performance of Aluminum alloy (Al6061) by different combination of various reinforcements. But still the researchers did not combine the third hardest ceramic material (B_4C) and the fourth hardest ceramic material (SiC) with wall known solid lubricant MoS_2 in hybrid form to increase the mechanical and tribological performance of Aluminum (Al6061) alloy. Among different researchers, Halil et al. (2019) were the only one who develops composite material from Al6061 matrix and SiC+B_4C reinforcements using powder metallurgy fabrication method.

Thus, in the present work, Al6061 was used as a matrix material and SiC+B_4C+MoS_2 were used as reinforcements. The hybrid composite was developed and investigated by combining those reinforcements in the form of none reinforced, double reinforced and triple reinforced at a specific weight composition of each.

CHAPTER THREE

MATERIALS AND METHODS

The detail of matrix and reinforcements used for the fabrication of hybrid aluminum alloy (Al6061) matrix composite and fabrication requirements are presented in this section. Besides, the equipment used, fabrication method adopted and fabrication procedures, sample preparation, and experimental procedure of characterizing the properties of fabricated composites are also discussed in this chapter. Further, the steps follow during mechanical tests, tribological tests, and microstructure observation of the developed metal matrix composite (MMCs) also illustrated.

3.1. Matrix and Reinforcements

The materials used in this work for the development of hybrid Aluminium alloy (Al6061) ware Aluminium alloy (Al6061) as a base material and silicon carbide (SiC), boron carbide (B_4C), and molybdenum disulfide (MoS_2) as reinforcement material and the amount required in kg for each of the material are given in Table 3.1.

Table 3.1. The materials required in kg to develop hybrid Al6061 matrix composite.

No.	Item	Quantity
1.	Aluminum (Al6061)	3646gr
2.	Silicon carbide/SiC/	248.44gr
3.	Boron carbide /B_4C/	195.02gr
4.	Molybdenum di sulfide /MoS_2/	261gr

3.1.1. Matrix

Matrix is one component of composite materials, which used to bind the reinforcements together by the benefit of its cohesive and adhesive properties, to transfer load to and between reinforcements, and to protect the reinforcements from environments such as humidity and some other chemical attack. As discussed in the previous chapters, On the base of matrix material used, composites are categorized to, Polymer Matrix Composites (PMCs), Ceramic Matrix Composites (CMCs) and Metal matrix composites(MMCs). MMCs are the most extensively utilized composites in the industrial sectors because of its essential properties over

PMCs and CMCs. In this work Aluminium alloy (Al6061) is selected as matrix material to fabricate hybrid metal matrix composite (HMMC).

3.1.1.1. Aluminium Alloy (Al6061) Matrix

As mentioned in chapter one in introduction section, different matrix materials, such as Aluminum, Titanium, Magnesium, and other metals are used in the production of MMCs. Among those metals, Aluminum is one of the most favorite matrix materials because of its light in weight, good heat and electrical conductivity, and high corrosion resistance.

Many Aluminum alloys series (e.g. 2xxx, 3xxx, 4xxx, 5xxx, 6xxx and 7xxx) are used industrially to produce different components. Different series of Aluminum alloys comprise of different alloying elements. For example Magnesium (Mg) and Silicon (Si) are major alloying elements in 6xxx series of aluminium alloys.

Six series aluminium alloys have excellent properties such as grater machinability, weldability and formability to form complex structures. Mg-Si aluminium alloys have also light in weight, good castability properties, and grater corrosion resistant. In this work, Al6061 alloys are chosen as a matrix material because of it excellent properties and broadly used in automotive components and architectural materials includes pistons, rotor disks, cylinder liners and decorative parts, and rivets etc. alloying elements, Mg and Si, make 6xxx series of aluminium alloys heat treatable and castable. The detail chemical composition of this alloy is given in Table 3.3. Al6061 aluminum plate and rods are of the most multipurpose heat-treatable alloys. Al6061 alloy is also popular for its medium to high strength requirements, good toughness and excellent corrosion resistance (Davis, 2001).

Because it is much more dispersing glue in MMCs, the matrix alloy should be chosen only after giving careful consideration to its chemical compatibility with the reinforcement, to its ability to wet the reinforcement, and to its own characteristics properties and processing behavior. Due to this property and availability, Al6061 is used as the working matrix material for the production of hybrid metal matrix composite.

Aluminium alloy (Al6061) scraps which used as a matrix material in the production of hybrid composites are get from *life steel Aluminum Work Company, Addis Abeba*. Figure 3.1. Shows aluminum scrap used for production of hybrid matrix composite.

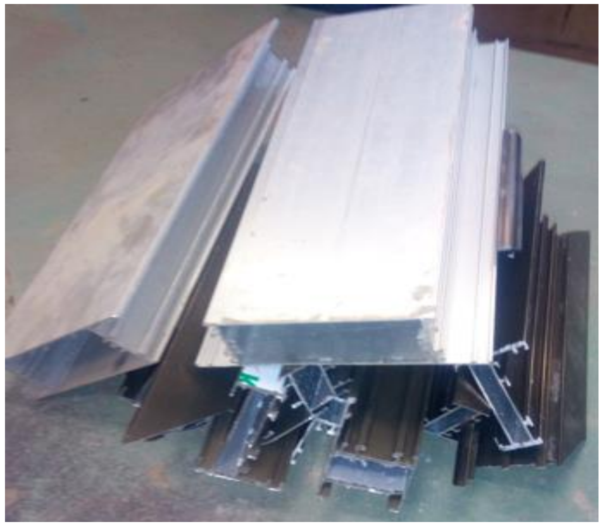


Figure 3.1. Aluminium alloy (Al6061) scrap from life steel aluminum work.

Table 3.2. Typical composition of Aluminium Al6061 alloy

Element	Al	Mg	Zn	Cu	Si	Mn	Sn	Fe	Cr
Composition (%)	balance	0.8%	0.16%	0.34%	0.70%	0.14%	0.1%	0.33%	0.07%

Table 3.3. Properties Aluminium Al6061 alloy

Property	Value
Density	2.72 g/cm^3
Melting point	605 °C
Modulus of elasticity	68.9GPa
Tensile strength (σ_t)	124-290MPa
Elongation (ε) at break	12-25
Poisson's ratio (ν)	0.33

3.1.2. Reinforcements

The reinforcement phase is stronger than the matrix phase, and that is why it is called Reinforcement. Thus, Reinforcements provides stiffness, strength, thermal stability, and other structural properties in the composites. The reinforcing phase (Reinforcement) is generally considered to possess the following characteristics; Low density, Good mechanical and chemical compatibility, Good thermal stability, High Young's modulus, High compression, and tensile strength, good processability, and Economic efficiency (Haghshenas, 2016).

In the present work Silicon Carbide (SiC), Boron carbide (B_4C), and Molybdenum disulfide (MoS_2) are selected as reinforcement materials to develop hybrid Aluminum Al6061 alloy matrix composite and the properties of each of those reinforcements are discussed as follows. All those reinforcements are imported from HUARUI GROUP LIMITED, Guangzhou center Chengdu china through FedEx.

3.1.1.1. Silicon Carbide (SiC)

Silicon carbide is nonoxide ceramic material made from silicon and carbon atoms. SiC is the fourth hardest material after diamond, boron carbide and cubic boron nitride (Zeynep et al., 2017) and it is rarely found in natural as mineral, but it has been manufactured industrially in powder form.

Silicon carbide is chosen as a reinforcement material because it has exclusive properties such as high hardness and high toughness, thermal and chemical stability, high melting point (2730°C (4946 °F)), oxidation resistance, high erosion resistance, etc.

It is widely used in high hardness and high thermal resistance applications, such as automotive brakes, cylinders, car clutches, valves and bullet proof vests, semiconductor electronics etc. (Srinivasan et al., 2017). Silicon carbide also applicable in abrasive cutters, grinding wheels, cutting tools and nuclear reactors due to high temperature resistance, high thermal conductivity and low nuclear activation.

As different schoolers suggest that, one way of improving mechanical and tribological properties of monolithic aluminum Al6061 alloy is by introducing Silicon Carbide (SiC) in the alloy as reinforcements (Lorenzo, 2008). In this investigation 50-150µm size SiC particles were used. Table 3.5 shows the properties of SiC.

Table 3.4. Properties of Silicon Carbide

Property	Value
formula	SiC
Color	Black
Density	3.21 $g.cm^{-3}$
Melting point	2730°C
Purity	97 %
Form	Powder
Particle size	50-150mesh
Hardness	2800 Kg/mm^2
Young's Modulus	410GPa

3.1.1.2 Boron Carbide (B_4C)

Boron carbide (B_4C) is a non-oxide ceramic having a melting point of 2490 °C (4514 °F), outstanding hardness, low density, relatively good mechanical properties, high resistance to chemical agents, and Good nuclear properties. In fact, boron carbide is the third hardest known industrial material next to diamond and cubic boron nitride. The stoichiometric density measured for B_4C is 2.52 g/cm^3 (Lorenzo, 2008). Due to such vary important properties boron carbide is selected as reinforcement material in the fabrication of aluminium alloy based hybrid metal matrix composite (HMMC). The properties of B_4C are given in table 3.6. In this investigation 50-150µm mesh size boron carbide particles were used.

Table 3.5. Typical properties of boron carbide

Property	Value
Formula	B_4C
Color	Black
Density	2.52 $g.cm^{-3}$
Melting point	2763°C
Purity	96%
Form	Powder
Particle size	50-150mesh
Hardness (Knoop 100 g)	2900-3580 $kg.mm^{-2}$
Young's Modulus	450-470GPa

3.1.1.3 Molybdenum Disulfide (MoS_2)

Molybdenum disulfide (moly) is an inorganic compound made from molybdenum and sulfur atom. The Chemical formula for this compound is MoS_2. It is a silvery black solid that occurs as the mineral Molybdenite, which is the principal ore for molybdenum. MoS_2 is relatively unreactive. It does not affected by dilute acids and oxygen. In appearance and feel, molybdenum disulfide is similar to graphite. It is widely used as a dry or solid lubricant because of its low coefficient of friction and layered structure, in which a plane of molybdenum atoms is sandwiched by planes of sulfide ions.

A limited research work has been reported on AMMCs reinforced with MoS_2. MoS_2 is a strong and heathy material having outstanding chemical and thermal stability, high hardness (HV=30HV), high melting point (1185^{o}c) and a density of 5.06g/cm^3 and it is used for manufacturing bulletproof vests, armour tank etc. Hence, MoS_2 reinforced aluminium matrix composite has gained more attraction with low cost (Subba and Ramanaiah, 2017). Table 3.7 shows the typical properties of MoS2.

Table 3.6. Typical properties molybdenum disulfide

Property	Value
formula	MoS_2
Color	black
Density	5.06g.cm^{-3}
size	2.5µm
Melting point	1185°C
Purity	98.8%
Form	Powder

3.2. Equipment's Used to Fabricate and Prepare Composite Sample

Table 3.8 shows equipment's used to fabricate hybrid aluminum matrix composite and equipment's used to prepare experimental samples.

Table 3.7. Fabrication and sample preparing equipment's

equipment's	Task	Model
Furnace	To melt aluminum alloy	Fuel oil furnace
Stirrer	To distribute reinforcement material uniformly throughout matrix material	Fabricated locally from stainless steal
Hand drill	To give rotational motion to stirrer after the stirrer is attached to hand drill	
Lathe machine	To prepare specimen for mechanical tests	Pinocho, SP/250
Chemical etchant	To prepare specimen for micro structural characterization	Keller's etchant

3.1.1. Furnace

It is a device used to heat and melt metals, metal alloys, metal ores, and other materials for further processing. The furnace uses either electrical or fuel energy as a source of heat. Thus Aluminum Al6061 alloy is melted inside the crucible using a furnace at a temperature of 700^{o}C. To construct furnaces, the following items are used: Body Frame (Plate and Angles), Refractory Bricks, Ceramic Blankets, Crucible, Heating Coil, Thermocouple, Temperature controller, Voltmeter, Ammeter, Transformer (Step down), etc.

3.1.2. Stirrer and Hand Drill

In the stir casting process, mechanical stirring is used to distribute reinforcements throughout the matrix material. So, a Stirrer containing stirrer rod and stirrer blades is required to produce a vortex in the crucible. The stirrer is mostly mounted to the electric motor but in this work, the stirrer was derived by hand drilling device as shown in Figure 3.5. The diameter of the stirrer rod is determined according to the hand drill. In this type of mechanical stirring system, a vortex is produced when the stirrer is mounted to the hand drill and this hand drill gives rotational motion to the stirrer.

3.1.3. Lathe Machine

It is a device that rotates a workpiece about an axis of rotation to perform a number of operations such as turning, treading, facing, knurling, drilling etc. after the composite is fabricated, it is then prepare to the desired shape and size according to ASTM standard to undergo experimentation. Thus the sample is prepared by machining on lathe.

3.1.4. Chemical Etchant

Optical microscope was used to examine and analysis the microstructural distribution of reinforcements in the composite specimens. Keller's etchant was used to etch the polished specimens for getting the clear view.

3.3. Testing Equipment's

Table 3.9 shows the main equipment's which were used for testing the properties of the developed hybrid aluminum matrix composite.

Table 3.8. Testing equipment's

equipment's	Test name	Model
Digital balance	To measure mass of materials	Tecnotest –TL 201/A
Universal test machine(UTM)	Tensile strength test	WP 310 HYDROLIC UTM-Gunt Hamburg
Vickers hardness tester	Hardness test	HVS-50
Optical microscope	Microstructure test	Huvitz HR-300 series
Scanning electron microscope (SEM)	Wear mechanism examination	JEOL
Micro Pin-on-disk Tribometer	Wear and friction test	TR-20-MICRO

1. Digital balance

Digital balance is used to measure the mass of an object. In this work digital balance was used to measure the mass of reinforcement and matrix according to specification; the mass of the hybrid composite for actual density measurement and mass hybrid composite before wear and after wear for tribological property study.

2. Universal testing machine (UTM)

A universal testing machine (UTM), also called a universal tester or materials testing machine is utilized to test the tensile strength, compressive strength of materials and other. Former name of tensile testing machine was a Tensometer. The name "universal" indicates that the machine can do/perform many standard tests such as compression test, tensile test, peel test, bending test, etc. on different components, materials, and structures.

3. Hardness testing machine

Hardness has a number of definitions according to different sectors.

- As per, metal industry, hardness is resistance to permanent deformation.
- As per, metallurgist, it is resistance to penetration.
- As per lubrication engineer, it is resistance to wear.
- As per design engineer, it is a measure of flow stress.
- As per, mineralogist, it is resistance to scratching, and
- As per, machinist, it is resistance to machining.

Generally Hardness can be defined as the resistance of a material to permanent deformation such as indentation, deformation, wear, abrasion, scratching etc.

Hardness testing can be categories into two: Macro-hardness test and Micro-hardness test. Hardness test called Macro-hardness test when applied loads on the indenter are more than 1 kg and In Micro-hardness test, loads applied are less than or equals to1 kg. Materials being tested by Micro-hardness test are very thin.

There are three Types of Macro-Hardness Test (Loads > 1 kg) those are Rockwell hardness test (consists of a diamond cone or hardened steel ball indenter), Brinel hardness test (consists of 10 mm diameter hardened steel or carbide ball) and Vickers hardness test (consists of a diamond indenter, the shape of indenter is a right pyramid with a square base and an angle of 136^o between opposite faces). Type of Micro Hardness Testers (load <1 kg), those are Knop diamond and Vickers diamond pyramid.

4. Optical microscope (OM)

Optical microscope also called as light microscope due to it uses light during examining a typical sample. Optical or Light microscope is the crucial means in engineering and science to examine the microstructure of materials. Light microscopy has been broadly used by metallurgists to examine materials such as metals, ceramics and polymers (Yang, 2008). In this study OM was used to investigate the distribution of reinforcement on base matrix.

5. Scanning electron microscope (SEM)

The scanning electron microscope (SEM) is the most widely used type of electron microscope.

It examines microscopic structure by scanning the surface of materials (Yang, 2008). In this investigation SEM was used to study the morphology of the worn surface of hybrid materials.

6. Pin on Disk Test

Wear (such as wear rates and wear resistance) and Friction test of materials is normally performed using numerous types of tribometer, but pin-on-disk test is one of the most common types of wear and friction characterization tool. The popularity of the pin-on-disk test is due to its simplicity and abundance of the tribological contacts. The wear and friction tests are performed on pin-on-disk apparatus under ASTM G99 standard. Schematically, the pin-on-disk test is shown in the Figure 3.2.

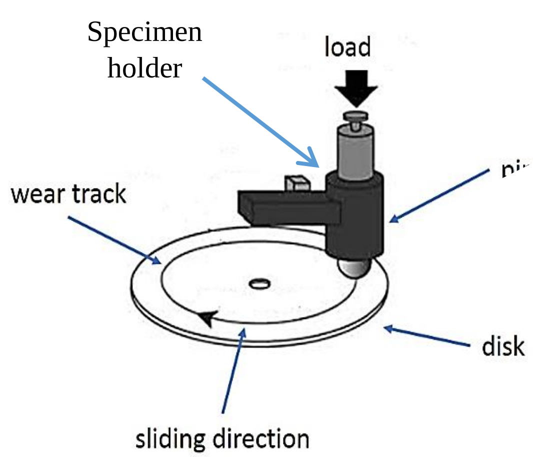


Figure 3.2. Schematic diagram of a pin on disc wear test machine.

3.4. Methods

To accomplish this work the following methodologies were utilized.

3.4.1. Matrix and Reinforcements Selection

In the development of composite materials, it is mandatory to decide the weight percentage of reinforcements in each specimen reasonably before the fabrication started. In this work, the wt% composition of reinforcements are taken from literature and the following four reasons are put into consideration during deciding the wt% composition of reinforcements in each specimen.

- To avoid clustering of reinforcements and reduce the amount of porosity in the composite fabricated by stir casting method, the total maximum weight composition of reinforcements in each specimen should be less than 30% based on the investigation of Ramanathan et al. (2019).
- Experimental investigation of Subba and Ramanaiah, (2017) and others shows that, as the percentage of MoS_2 is greater than 4%, the mechanical properties such as tensile strength and hardness of composite decreases and the maximum values of mechanical properties were obtained at 4% of MoS_2. Accordingly, in this work, 4% of MoS_2 is added in each trial except the first trial.
- According to Halil et al., (2019), to investigate the effect of reinforcement on the properties of Al6061 alloy by making the Wt% of Al6061 constant. So, the weight percentage addition of B_4C and SiC together is 12%. The usage of aluminum alloy is considered to be constant (84%) to investigate the influence of reinforcements on the properties of aluminum alloy exactly.
- One specimen is prepared without reinforcements for comparison purposes.

Based on the above consideration, non-reinforced (Al6061 alloy), double reinforced (Al6061 + SiC + MoS2 and Al6061 + B_4C + MoS_2), and triple reinforced (Al6061 + B_4C + SiC + MoS_2) composite materials are fabricated by stir casting methods, and the detailed weight compositions are presented in Table 3.10.

Table 3.9. Weight composition of reinforcements

Specimen designation	Al6061	B_4C	SiC	MoS_2
None reinforced				
S1	100%	0%	0%	0%
Doubled reinforced				
S2	84%	12%	0%	4%
S3	84%	0%	12%	4%
Tripled reinforced				
S4	84%	3%	9%	4%
S5	84%	9%	3%	4%
S6	84%	6%	6%	4%

3.4.3. Estimating Mass of Matrix and Reinforcements Required For Each Specimens

For the sake of simplification, the specimen for tensile test, hardness test and wear test ware fabricated at once for the given composition of each specimens.

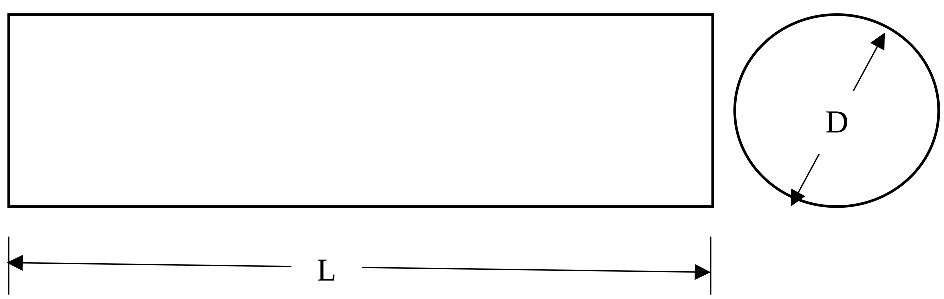


Figure3.3. 2D of cylindrical specimen

A Cylindrical specimen were recommended for metal matrix composite with a size of length (L) and diameter (D) as shown in Figure 3.14 . The size and shape of pattern depends on the types of tests conducted, such as;

- The size of tensile test specimen total length
- The size of wear test specimen
- The size of Hardness and microstructural test specimen
- The amount of material remove by machining (machining allowance)
- Shrinkage allowance

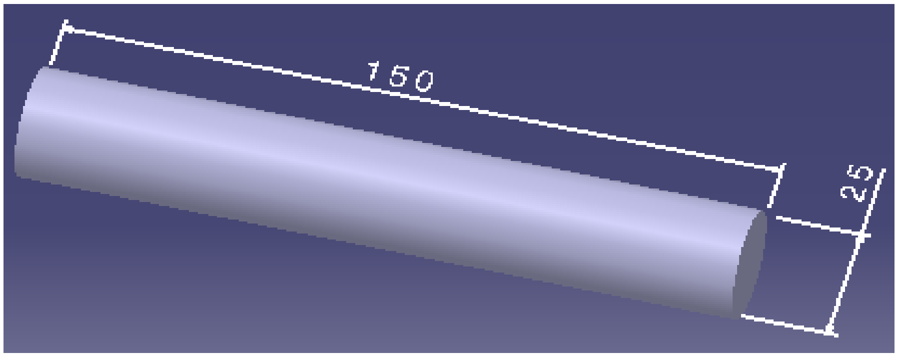


Figure 3.4. 3D Catia drawing of cylindrical specimen.

Length, L=150 mm Diameter, D= 25 mm

The volume of cylindrical specimen/mold can be calculated as follows,

$$V= \Pi x D^2 x L/4 \qquad \text{Eq. (3.1)}$$

Where V= volume of specimen in cm^3

L= length in cm, L=150mm=15cm

D= diameter in cm, D=25mm=2.5cm

$V= \Pi \text{ x } (2.5cm)^2 \text{ x } (15cm)/4$ $\underline{V= 74\ cm^3}$

So, the volume of material required to produce two specimens.

$$V=2x74cm^3$$

$$V=148\ cm^3$$

Since the mold is sand mold, considering sprue, runner, riser and other is obligatory. Thus, the estimated volumes for those are 110 cm^3.

So, the total volume require to fabricate the specimen is 258cm^3.

$$V_{total} =258cm^3$$

The required amount of matrix (Al6061) and the reinforcements (SiC, B_4C and MoS_2) in each specimen are estimated as follow in kilogram based on the weight composition set in Table 3.10.

The density of matrix (Al6061) and the reinforcements (SiC, B_4C and MoS_2) are:

Density of Aluminum alloy (Al6061), $\rho_{Al6061} =2.72\ gr/cm^3$

Density of Silicon carbide (SiC), ρ_{SiC} =3.21 gr/cm^3

Density of Boron carbide (B_4C), ρ_{B4C} =2.52 gr/cm^3

Density of Molybdenum disulfide (MoS_2), ρ_{MoS2} =5.06 gr/cm^3

The weight of matrix (Al6061) and the reinforcements (SiC, B_4C and MoS_2) in each specimen for the given compositions are estimated as follows.

$$m_{x} = V_{total} \times \rho_x \times y \qquad \text{Eq. (3.2)}$$

Where x= matrix/reinforcement

y = weight % of matrix/reinforcement x

- ✓ Total Weight of Aluminum alloy (Al6061), m_{Al6061}= 3646gr
- ✓ Total Weight of Silicon carbide (SiC), m_{SiC} = 248.44gr
- ✓ Total Weight of Boron carbide (B_4C), m_{B4C} = 195.02gr
- ✓ Weight of Molybdenum disulfide (MoS_2), m_{MoS2} =261gr

3.4.4. Stirrer and Stirrer Setup Fabrication

In MMC, fabricated using the Stir casting method, a mechanical stirrer is required to form a vortex for the necessity of the uniform distribution of reinforcement particles into the molten matrix material. Therefore, proper selection of a suitable blade angle, diameter, and number is crucial to obtain a good level of mixing. In this work, for the fabrication of a simple stirrer setup; 40x40 and 30x30 HRS, 3mm thick sheet metal, 15mm diameter staleness steal circular rod, 3mm thick staleness steal, and hand drill machine with 600RPM is used. Before the fabrication of the stirrer setup; the dimension of the furnace and the dimension of the crucible were measured properly and the stirrer setup fabricated accordingly. Table 3.11 shows the dimensions of each part and usage of each part of the stirrer setup.

Table 3.10. Stirrer and stirrer setup parts and usage

No.	Part	Dimension	Material	Usage
1.	leg	750mm height, 40x40 HRS	Steal	Support all parts of stirrer setup and allow adjustable hand drill holder to move up and down
2.	pin support hand drill holder	300mm height by 1000 length, 30x30 HRS	Steal	It can be moved up and down. So used to adjust the stirrer in the required position and used to hold the hand drill machine.
3.	Hand drill support	100mm height and 30mm diameter hole	Steal	This support welded on the adjustable hand drill holder. Used to support and make erect upright hand drill on position.
4.	Stirrer rod and stirrer impeller	15mm diameter and 500mm height rod and 3mm thick and 50mm length and 40mm width welded at 30^o	Staleness steal	Machine one end of the rod to 10mm to fit with hand drill grip size. The stirrer blade is welded at an angel of 30^o. Thus, this stirrer used to make vortex inside the crucible to distribute the reinforcement uniformly.
5.	Heat protector	3mm thick by 50mm length by 50 mm width	Steal	Since the hand drill is made up of low heat resistance material, it required heat protector. In this setup steal sheet metal is used. Thus heat protector used to minimize the heat effect from the furnace on the hand drill machine
6.	Hand drill machine	10 mm grip size		Give rotational motion to the stirrer

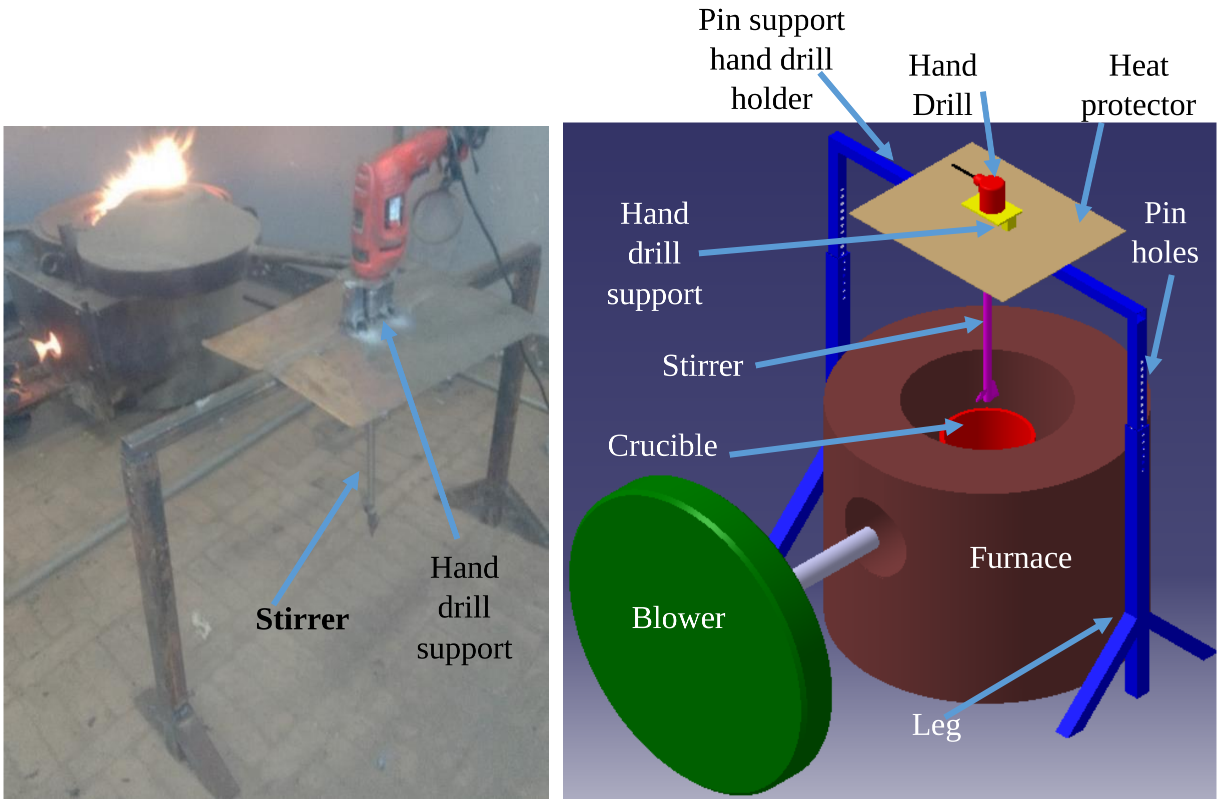


Figure3.5 Stirrer setup driven by hand drill machine

3.4.5. Pattern and Mold Preparation

Sand casting is the most widely used casting process in the manufacturing sector due to its various advantages over other manufacturing processes. Sand casting is resistant to elevated temperature, almost all metal can be cast using a sand-cast, sand casting is used for casting components ranging from very small to extremely large size, etc. (Ramana Rao,1996). Because of such and other advantages, the sand casting was used in this work to fabricate hybrid composites. Among different stapes in sand casting, mold preparation is the one which takes time and has been done with extreme care and skill.

The size of mold required to fabricate the composite depends on the size of specimens used for various tests. All specimens for various testes were fabricated at once using one mold. Thus, the size of molds to be prepared is 25mm in diameter and 150mm in length, as shown in figure 3.6. The size of the specimen is determined by the ASTM standard and some other considerations. The estimation of the mass of the matrix and reinforcements required for each specimen were discussed in the following sections and subsections. The procedures followed during preparing a sand mold, for the fabrication of hybrid aluminum matrix composites is discussed as follows with a photographic illustration.

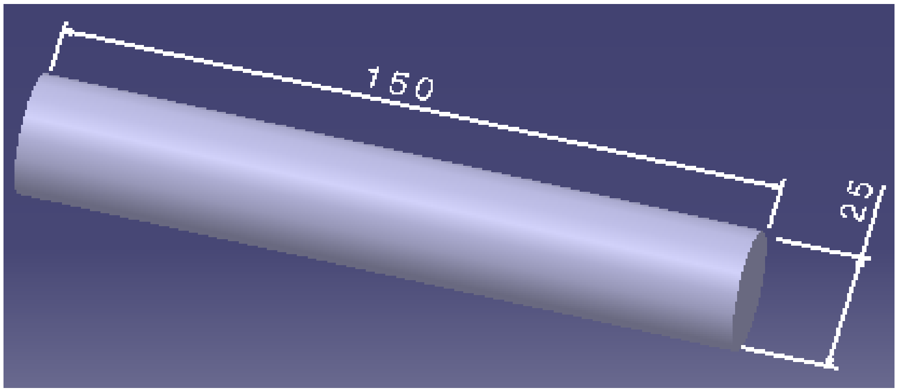


Figure 3.6. 3D CATIA V5 drawing of cast specimen dimension in Millimeter (mm)

Sand Mold preparation processes:

- A cylindrical Pattern is made from wooden material based on the size of specimens (25mm in diameter and 150mm in length) and divides the pattern equally into drag pattern and cap pattern. The wooden pattern was prepared using a lathe machine by turning and facing operation. The external surface of the pattern was smoothed using sandpaper. Figure 3.7 shows the pattern that was used in the fabrication of hybrid composite.

Figure 3.7. Cylindrical wooden pattern

- Sand preparation such as Sieving, Moisturize using water and mixing the sand.
- Molding of drag, which is the lower part of the molding box. This is done by Place half the pattern on the molding board (inside the molding box called drag) and add the mixed sands in the box over the pattern. Then manually compact the sand to have the required shape of the pattern. After the compaction is complete, level off the excess sand with the striker bar. Finally, turn the drag upside down.
- Molding of the cap, which is the upper part of the molding box. molding of the cap is accomplished by placing it over the molded drag and make the proper alignment. Put half of the pattern exactly on the other half of the pattern placed on the drug and put sprue and riser pins also. Similarly, compact the cap with molding sand.
- Separate the two boxes and withdraw the pattern, sprue pin, and riser pin carefully. Preparing gating systems (sprue, riser, veins, runner, etc.) as shown in figure 3.8.

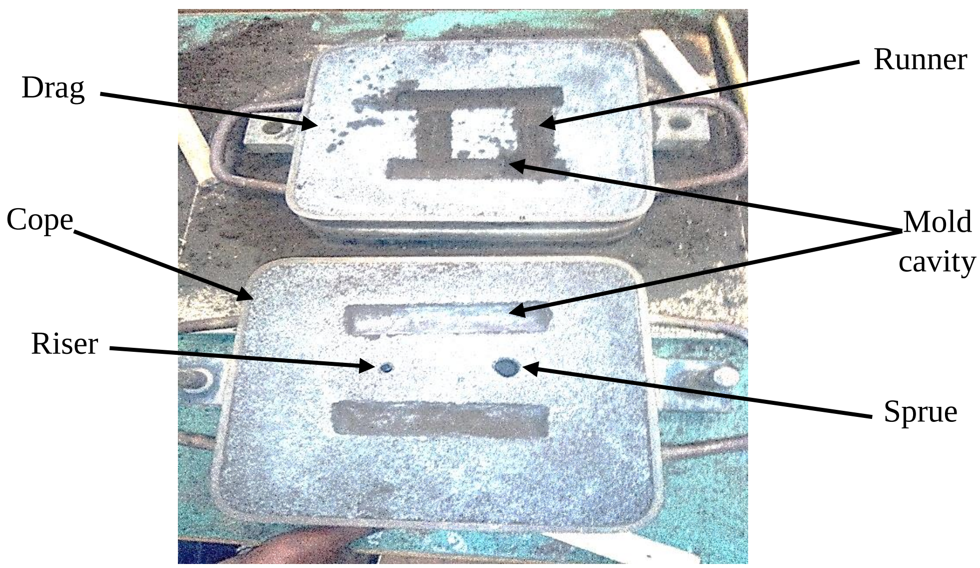


Figure 3.8. Sand casting mold

- Finaly, Re-assambel the cap and the drag box after the mold periparation is done, then puring of molten aluminum alloy well mixed with renforcment in to the mold was continued.

3.4.6. Composite Fabrication

Casting is the most frequently used production method in MMCs, as it is low cost and appropriate for mass production of machine components. The fabrication of a hybrid aluminum metal matrix composite reinforced with SiC, B_4C, and MoS_2, was performed using the stir casting method. The Stir casting method, (also called the liquid state method) is mainly used for the production of a particulate type of composite materials, in which ceramics reinforcements are mixed with a molten metal matrix employing mechanical stirring. The liquid composite material is then, cast by conventional casting techniques and may also be processed by conventional metal forming technologies like forging, extrusion, and other (Ramanathan, 2019).

The Aluminum alloy matrix is placed in a crucible of the furnace and allowed to melt. After the aluminum matrix melted successfully, the preheated reinforcements are added into the molten aluminum and mechanically stir at a rotational speed of 600rpm for 5minute. The mixture of molten aluminum and Reinforcement then allowed to solidifying inside the mold. Hybrid aluminum metal matrix composite was fabricated in such away.

Steps involved in the fabrication of composite materials are:

- Measure the required amount of aluminum matrix and reinforcements by mass for each specimen according to the specifications given in Table 3.10.
- Put Aluminum alloy in a graphite crucible and allow the fuel fire inside the furnace to melt the alloy. Once, the furnace is started, kept it for some minutes to confirm the molten state of aluminum alloy.
- Preheat the reinforcements to remove moisture content and to increase its wettability.
- Then, the corresponding preheated reinforcements were added into the molten aluminum at two stapes and stir mechanically at a rotational speed of 600rpm for 3minute to distribute the reinforcements uniformly.
- After stirring is performed, the slag was removed from the mixture of molten aluminum. The molten state of a mixture was then allowed to flow in the prepared sand mold and solidification takes place inside the mold.
- Finally, withdraw the composite from the mold after solidification, as shown in Figure 3.9. A. below and produced specimen based on ASTM standards for various tests.

Figure 3.10. Shows the steps involved during manufacturing of hybrid aluminum matrix composite in form of flow chart.

Figure 3.9. Solidified cast hybrid composite specimen (A) before runner, riser and sprue is cut out (B) after runner, riser and sprue is cut out

Measure the required amount of aluminum (Al6061) for each specimen

Measure the required amount of reinforcements for each specimen

Put aluminum (Al6061) in to crucible and melt

Per-heating reinforcements side by side

Add the reinforcement in to the molten aluminium by stage and perform stirring

A mixture of matrix and reinforcement then added in to prepared mold

Finally, withdraw the hybrid composite specimen affect solidification.

Figure 3.10. Flow chart of stapes involved in fabrication hybrid composite.

3.4.7. Specimen Preparation

After successfully fabricate the composite material using stir casting method, the composite was then prepared for a specimen of a mechanical test, physical, microstructural characterization, and tribological test. For physical, mechanical, and tribological tests, the specimen is prepared to the required shape and size according to ASTM standard by machining on a lathe. Chemical enchant was also used to prepare a specimen for microstructural characterization of the composite.

- Machining and cutting

The surfaces of fabricated composite were very rough and have unwonted parts on it. To reduce surface roughness, to avoid unwanted parts, and to come up to the required shape and size as per ASTM standard machining on lathe and cutting using abrasive cutter was done. Figure 3.11 shows the machining of a composite specimen on a lathe machine.

Figure 3.11 Machining of specimen for various test

- Grinding, Polishing and Etching of specimens

The main object of Grinding and Polishing of specimens is to generate a flat surface; removes cut marks; levels and free from excessive deformation. Some of the steps are; rough grinding, fine grinding, and polishing.

In the first step, cut specimens are ground with sandpaper of grit sizes of 120, 400, 800, 1200, and 2000 grits. After grinding, to removes the artifacts of little stock and make the surface mirror, polishing was performed by adding diamond suspension, as shown in Figure 3.12 A. When doing this, moderate Pressure is needed at the start of each step and then gradually reduce the Pressure to keep the specimen from plastic deformations. A two-wheel system, motor control, 50 to 500 rpm, RB 204 Metpol-II Model polishing machine was used.

Finally etching using Keller's chemical etchant was done. Etching is the process of making microstructural features through selective chemical attack to present the grains and grain boundaries clearly. For Aluminium and aluminum alloy Keller's chemical etchant is recommended. Figure 3.12 B shows etching of hybrid composite.

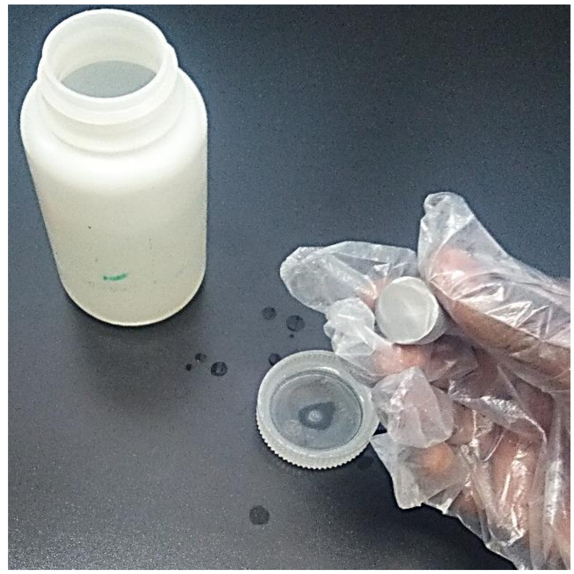


Figure3.12 A. Polishing   B. Etching

3.4.8. Experimentation analysis

Experimental investigations were conducted on physical properties (such as density and porosity) and mechanical properties (like tensile strength, and hardness). Moreover, microstructural and tribological properties (such as wear loss and coefficient of friction), were also performed. During experimentation, the most valuable results for each test were collected and those results were analyzed and discussed. Finally, critical conclusions were drawn according to the discussed and analyzed result. In the present work, the following experiments were performed, and their experimental procedures were discussed in detail as follows.

3.4.8.1. Density and Porosity Measurement

Density and porosity are the physical property of the material. Theoretically, the density of the material generally can be defined as mass over unit volume.

The theoretic density (ρ_{th}) of hybrid aluminum matrix composite was calculated using the rule of mixtures as shown in Eq. (3.3) (Rajesh et al., 2018). Consider, the produced Hybrid aluminum matrix composite is the mixture of aluminum alloy (Al6061), boron carbide (B_4C), silicon carbide (SiC) and Molybdenum disulfide (MoS_2).

$$\frac{1}{\rho thx} = \frac{wt\%\ Al6061}{\rho Al6061} + \frac{wt\%\ B4C}{\rho B4C} + \frac{wt\%\ SiC}{\rho SiC} + \frac{wt\%\ MoS2}{\rho MoS2} \qquad \text{Eq. (3.3)}$$

Where: ρ_{thx}= theoretic density of composite specimen x= 1,2,……9 ; wt% Al6061= mass percent of aluminum alloy in the composite specimen; wt% B_4C= mass percent of boron carbide in the composite specimen; wt% SiC = mass percent of silicon carbide in the composite specimen; wt%MoS_2= mass percent of Molybdenum disulfide in the composite specimen; ρ_{Al6061}= density of aluminum alloy; ρ_{B4C} = density of boron carbide; ρ_{SiC} = density of silicon carbide and ρ_{MoS2}= Molybdenum disulfide

Experimentally, the Density hybrid aluminum matrix composite can be formulated as follows: the actual density of composite can calculated using Archimedes principle. The cylindrical specimen was weighted in air (m_{air}) and weighted again in distilled water (m_{water}). The actual/experimental density (ρ_a) was calculated according to Eq. (3.4) (Wang et al., 2004).

$$\rho a = \frac{mair}{mair - mwater}\, \rho_{water} \qquad \text{Eq. (3.4)}$$

Where: ρ_a = actual/ experimental density; m_{air} = mass of composite in air and m_{water} = mass of composite in distilled water and ρ_{water} = density of distilled water at 25^{o}C = 997.044 kg/m^3.

The porosity of each hybrid composite material can be determined based on Eq. (3.5) (Aatthisugan, 2017).

$$P = 1 - (\rho a/\rho_{th}) \qquad \text{Eq. (3.5)}$$

Where P = the porosity of composite material, ρa = the actual density of composite material and ρth = the theoretic density of composite material.

3.4.8.2. Microstructural Test

The metallurgical aspect of fabricated hybrid aluminum matrix composites was examined by optical microscope (model Huvitz HR-300 series). In the present investigation, 20x, 50x, and 100x magnifications were used to identify the morphology and distribution of reinforcement particles in the Al6061 matrix. The general Procedures followed during specimen preparation for metallographic investigation are:

- Cut the specimen to 20mm diameter and 10mm height as indicated in Figure 3.14.
- Grinding, the specimens were ground with sandpapers of 220, 400, 800, 1200, and 2000 grits, respectively.
- Polishing, polishing was performed using diamond suspension on a two-wheel system RB 204 Metpol-II Model polishing machine.
- Standard etching, Etching the specimens using Keller's chemical etchants.
- Finally, a microstructure investigation was Conduct using optical microscope.

To observe the detailed microstructure/ grains boundaries/ of the aluminum matrix composite and study the distribution of reinforcements throughout the aluminum matrix Keller's etchant was used. Table 3.12 shows the content of Keller's etchant.

Table 3.11. Keller's etchant for aluminium alloys (Senthil and Maheswaran, 2019)

Keller's Etchant	**Concentration(ml.)**	**Conditions**
Distilled water	190	10-30 second immersion (Use fresh)
Nitric acid	5	
Hydrochloric acid	3	
Hydrofluoric acid	2	

3.4.8.3. Tensile Test

Tensile strength of a material is the ability of a material to resist loads which applied in the longitudinal direction of specimen in out ward direction. Tensile specimens are prepared from casted cylindrical rods of hybrid aluminum matrix composite. The report of Callister (2007) and Mohan et al., (2014) indicates that, ASTM standards E-8 and E-8M are standard test methods for tensile testing of metallic materials. A standard tensile specimen is shown in Figure 3.14 with a circular cross section was used. Tensile specimens of circular cross-section with a standard diameter of 8mm. according to ASTM E-8, the gauge length should be at least four times its diameter for ASTM E-8. Thus, 50 mm (2.0 in.) of gauge length was used. The end section diameter and length of 12mm and 20mm respectively was used as shown in the figure 3.13. To prepare the tensile test specimen, Pinocho, SP/250 model Lathe machine was used.

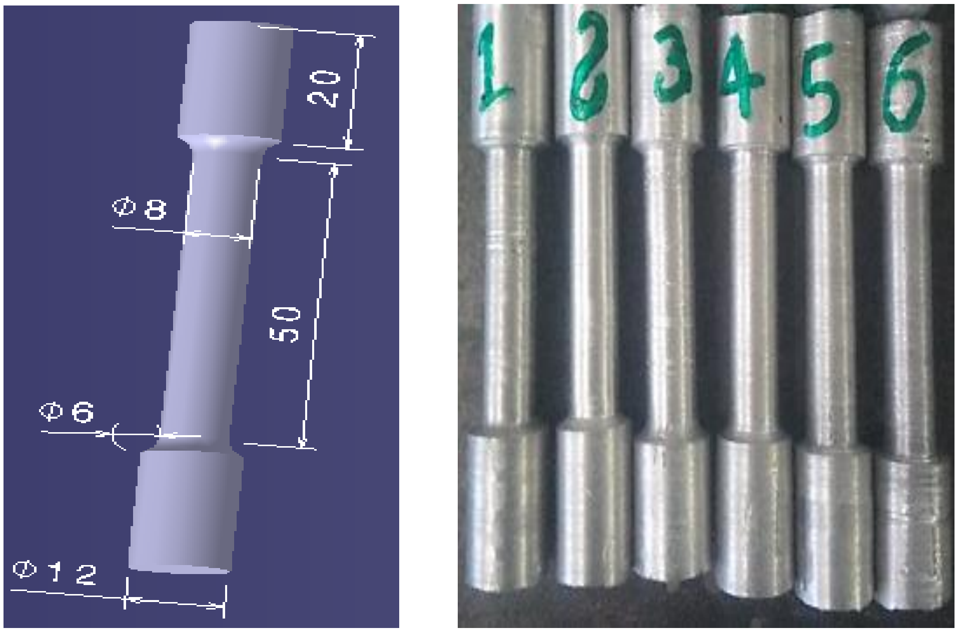
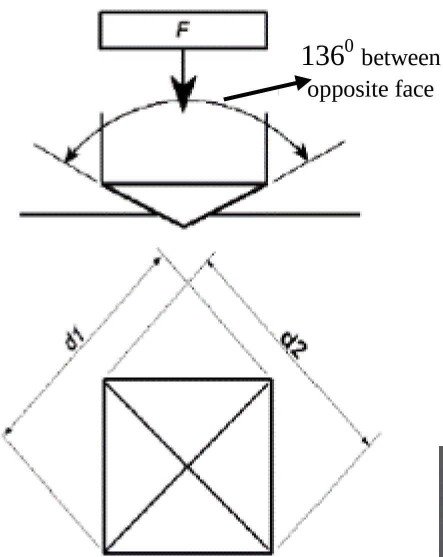


Figure 3.13 ASTM E-8 standard tensile specimen with circular cross-section

3.4.8.4. Hardness Test

In the present work, Vickers hardness tester machine was used to measure the hardness value of hybrid Aluminum alloy (Al6061) matrix composite fabricated via stir casting technique. Vickers hardness tester consists of a diamond indenter; the shape of indenter is a right pyramid with a square base with angle of 136^{o} between opposite faces. This hardness tests conducted on cast aluminum alloy (Al6061) and aluminum alloy (Al6061) hybrid composites containing different weight percentage of reinforcement particles. Before hardness test is measured, the surface of the material is grind and polished. During tasting 10kgf was used with duration of 10sec. Figure 3.14 shows the specimens used for hardness test with a measurement of 20mm diameter and 10mm height.



$$HV= \frac{2F\sin\frac{136^2}{2}}{d^2} = 1.854\frac{F}{d^2} \qquad \text{eq.3.3}$$

Where F= load in kgf

d=mean of two diagonals, d1 and d2 in mm

HV= Vickers hardness

Figure 3.14 Microstructural and hardness test specimen 20 mm diameters with 10 mm height

3.4.8.5. Wear and friction test

The term wear can be defined as the gradual loss of mass from the surface of a solid body due to mechanical causes (Mang et al., 2011). The dry sliding wear tests were conducted on computerized TR-20-MICRO model micro pin-on-disc Tribometer, based on ASTM G99 standard under room temperature. Micro pin-on-disc Tribometer apparatus, as shown in the Figure 3.15, mainly have pin (specimen), disk, load and pin holder. The disk material used for in this investigation was EN-31 hardened steel disk. During the test, three different load was used (10N, 30N and 50N in step of 20N). Constant wear track diameter (80mm), test duration (5min), rotation of disk (200rpm) sliding distance (251.2m) was used.

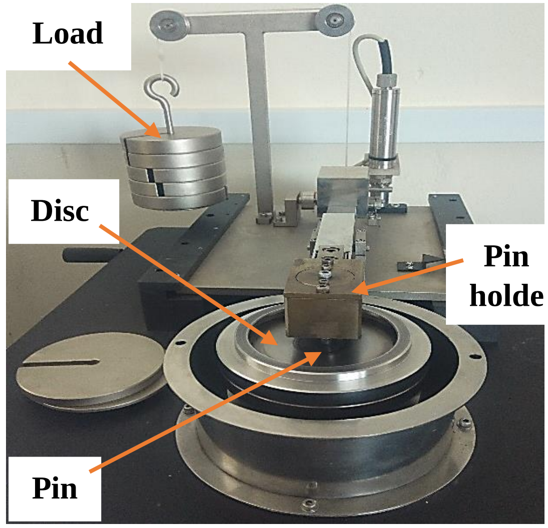


Figure3.15. Micro pin on disk tribometer during testing

For tribological property study, the developed composite specimen was first prepared as per ASTM G-99 standard to a dimension of 6mm diameter and 12mm height as shown in the Figure 3.16. Then, the specimen was smoothly polished with fine sand paper, fixed to specimen holder properly and pressed against rotating disk under the specific parameters set on computer. During the test, coefficient of friction and wear loss wear continuously recorded. The result of coefficient of friction vs time graph was taken from the computer that was integrated with the wear test device. To compute the wear loss, electronic weighing machine with accuracy of ± 0.0001g was used.

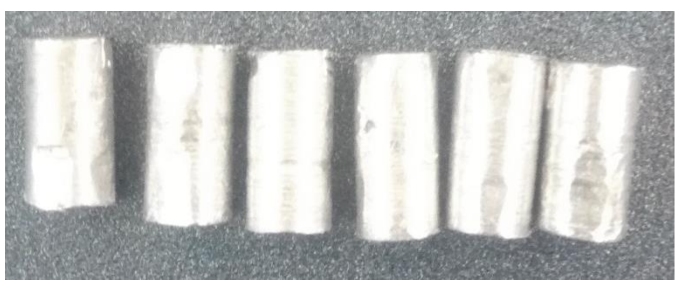


Figure 3.16. Specimens for wear test

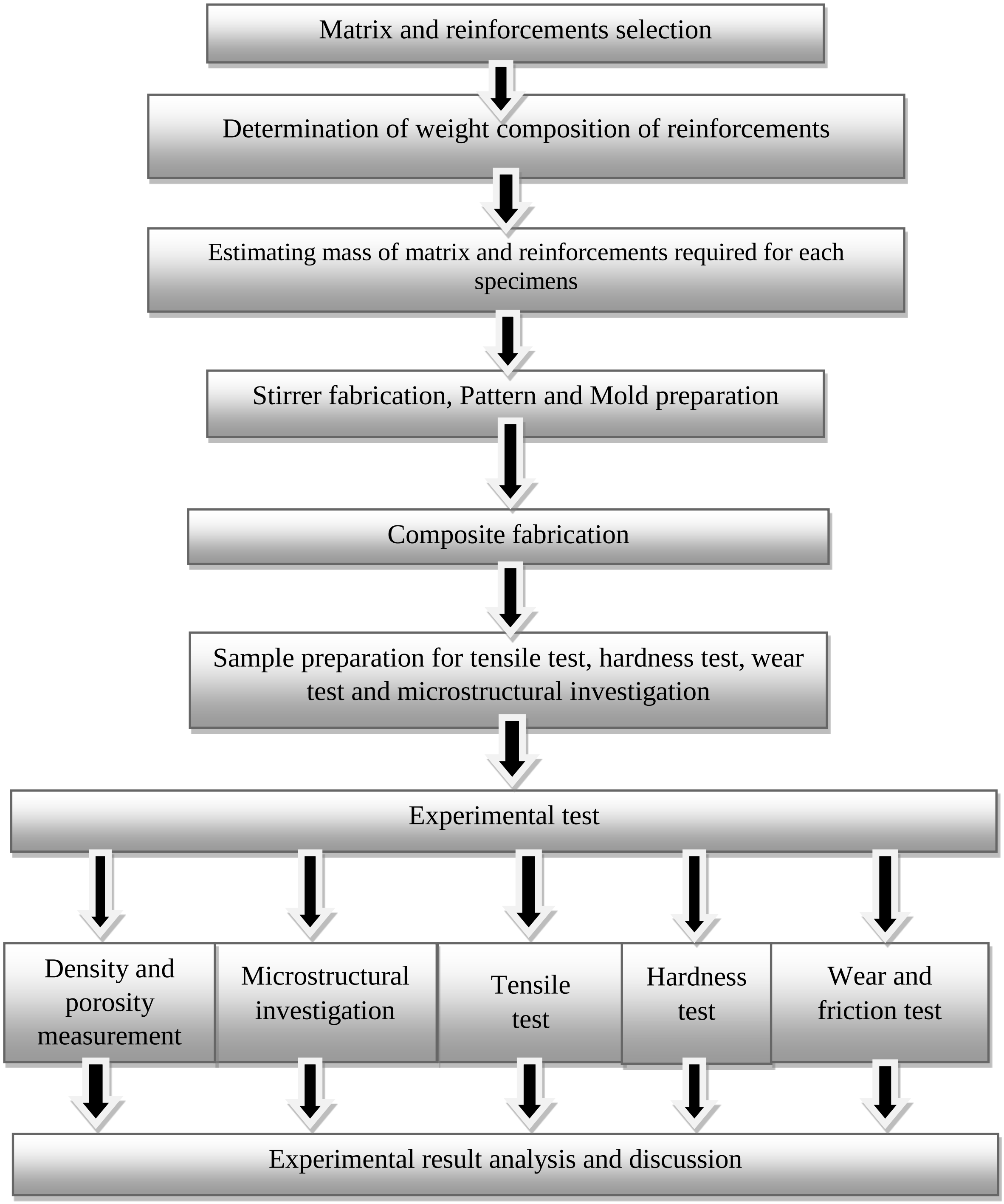


Figure 3.17. General Procedure used in this research work to fabricate and characterize hybrid aluminum matrix composites.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Density and Porosity

Density and porosity are the physical property of the material. Theoretically, the density of the material generally can be defined as mass over unit volume. The theoretical density of the developed hybrid composite is calculated using the rule of the mixture as shown in Eq. (3.3) and the actual density is measured using Archimedes principle as shown in Eq. (3.4). The porosity of each hybrid composite material can be determined based on Eq. (3.5).

Figure 4.1 shows the variation of density of hybrid composite specimen as mentioned in Table 4.1. Due to the presents of voids and segregation of heavy particles towards the bottom, the theoretical density of hybrid composite is more than the experimental density. The investigation shows that, the density of hybrid composite is slightly higher than that of the density of non-reinforced specimen. An increase in density is due to, an increase in SiC and the presents of 4% MoS_2 reinforcements. The density of hybrid composites decrease with increase in weight composition of B_4C, while, increases with increase in weight percentage of SiC.

Table 4.1. Density and porosity of hybrid Al6061 matrix composite

Designation	$Al6061/B_4C/SiC/MoS_2$ composite	Theoretical density (gr/cm^3)	Actual density (gr/cm^3)	Porosity (%)
S1	Al6061	2.72	2.680	1.4
S2	$Al6061/12\%B_4C/4\%\ MoS_2$	2.74	2.698	1.5
S3	Al6061/12% SiC /4% MoS2	2.81	2.716	3.4
S4	$Al6061/3\%B_4C/9\%SiC/4\%MoS_2$	2.80	2.710	3.2
S5	$Al6061/9\%B_4C/3\%SiC/4\%MoS_2$	2.76	2.702	2.1
S6	$Al6061/6\%B_4C/6\%SiC/4\%MoS_2$	2.77	2.689	2.9

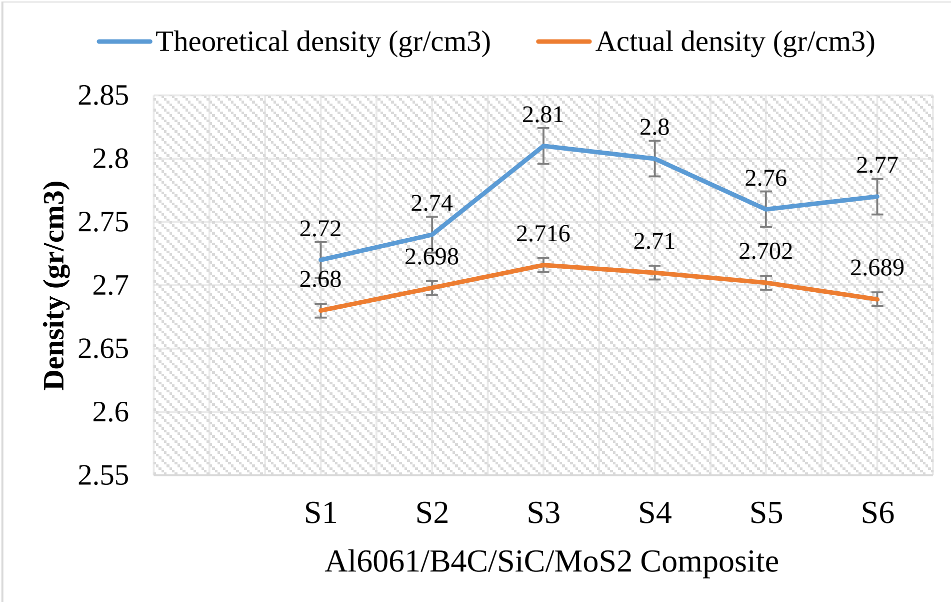


Figure 4.1Actual and theoretical density of hybrid aluminium alloy composite

Gowri et al. (2018) have reported that porosity levels within the range of 2-4% are acceptable levels in cast composites. From Figure 4.2 as listed in Table 4.1, the porosity level of the developed hybrid composite is in the range of 1.4-3.4%, which is acceptable according to the report. This indicates that the stir casting technique is highly efficient to fabricate hybrid aluminum alloy composites.

The use of a degassing agent is responsible for the low porosity level & minimal casting defects in the composites produced. As the percentage of SiC is increased the porosity level increased and High porosity is observed at 12%SiC4%MoS2. From the observation, it can be understood that an increase in porosity level is due to the relatively high density of SiC and MoS_2 and the moisture content of sand mold. As the density increase, segregation of reinforcements towards the bottom of the crucible occurs. Beyond that, according to the report of Bharath et al. (2014) the porosity level of the composite rises as a result of gas bubbles during stirring; gas inoculation during reinforcement addition; hydrogen soluble capability of aluminum; and the pouring high from the crucible to the mold.

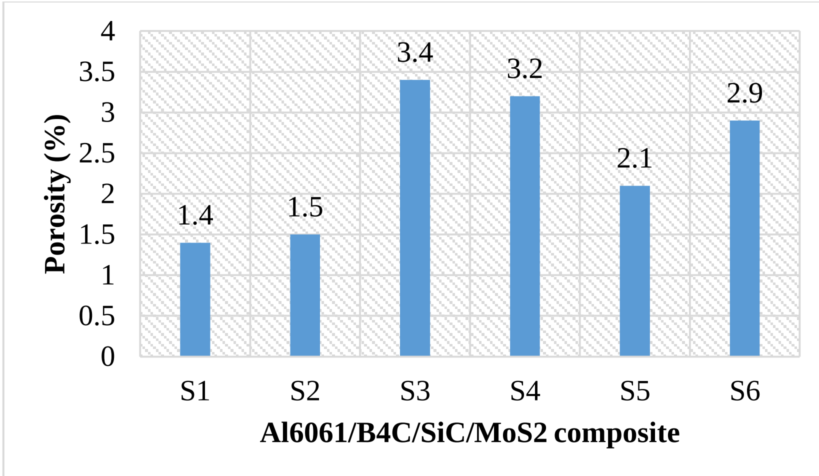


Figure 4.2 Porosity (%) level of developed composite

4.2. Tensile Test

Circular cross-section, the dog bone type, tensile test specimens were used with a gage length (G), specimen diameter (D), fillet radius (r) of 50mm, 8mm, 6mm respectively as shown in Figure 3.15. The tests were executed on a computerized WP 310 HYDROLIC Gunt Hamburg model universal testing machine (UTM) as shown in Figure 4.3 (A). Plastically deformed tensile test specimens are shown in Figure 4.3 (B). The tensile specimen undergoes brittle fracture. This test is carried out at a constant crosshead speed of 3mm/min with a maximum 50kN capacity of UTM. The readings of test result give force against elongation and stress against percentage elongation.

Figure 4.3 (A) Tensile test set up on UTM (B) plastically deformed tensile test specimens.

Table 4.2 shows the list of ultimate tensile strength and percentage elongation result of hybrid Al6061/B_4C/SiC/MoS2 composite testes under 50KN load capacity UTM. The test results reveal the comparison between non-reinforced specimens (as cast Al6061 alloy), double reinforced composite specimens (Al6061+SiC+MoS_2 and Al6061+B_4C+MoS_2), and triple reinforced composite specimens (Al6061+B_4C+SiC+MoS_2).

Table 4.2. Tensile strength of the developed hybrid metal matrix composites

Designation	Al6061/B_4C/SiC/MoS_2 composite	Ultimate tensile strength UTS (MPa)	Elongation E (%)
S1	Al6061	76.66	11.90
S2	Al6061/12%B_4C/4% MoS_2	94.01	10.32
S3	Al6061/12% SiC /4% MoS2	80.27	11.43
S4	Al6061/3%B_4C/9%SiC/4%MoS_2	88.08	10.83
S5	Al6061/9%B_4C/3%SiC/4%MoS_2	91.63	10.08
S6	Al6061/6%B_4C/6%SiC/4%MoS_2	88.98	10.82

Figure 4.5 shows the ductile characteristics of each of developed composites. Mechanical characteristics of aluminum alloys can be enhanced by the addition of ceramic powders such as silicon carbide, boron carbide, alumina, titanium carbide, etc. With the addition of such reinforcements to the base matrix, the hardness increases while ductile decreases (Halil et al., 2019). Thus, from figure 4.5, it can understand that the ductility of aluminum alloy (Al6061) decreases with the addition of particulate reinforcements. The lowest percentage elongation was obtained at Al6061/9%B_4C/3%SiC/4%MoS_2, which decreases the ductility of the base matrix by 15.29%.

Figure 4.4 shows the graph of the ultimate tensile strength of hybrid Al6061/B_4C/SiC/MoS_2 composites subjected to the tensile test under a similar environment. Ultimate tensile strength of hybrid Al6061 composites advanced due to the addition of B_4C, SiC, and MoS_2. Non-reinforced cast Al6061 was exhibited the lowest UTS (76.66 MPa). The highest value of UTS was obtained at Al6061/12% B_4C/4% MoS_2 hybrid composite with a value of 94.01MPa. The improvement in UTM is because of the strong interface bonding between the matrix and reinforcements phase, less void and good wettability of reinforcements due to the presence of reactive element called Magnesium in the alloy. The interface bonding transfers the load from the matrix to the reinforcements and leads to an increase in UTS. The lack of pores in hybrid composites was also responsible for the rise in UTS. By the addition of 12% of SiC and 4% of MoS_2, ultimate tensile strength was improved by 22.63%. Generally, the tensile strength of hybrid composites (S2, S3, S4, S5, and S6) is increased by 22.63%, 4.71% 15.84%, 19.66%, and 16.07%, as compared with non-reinforced.

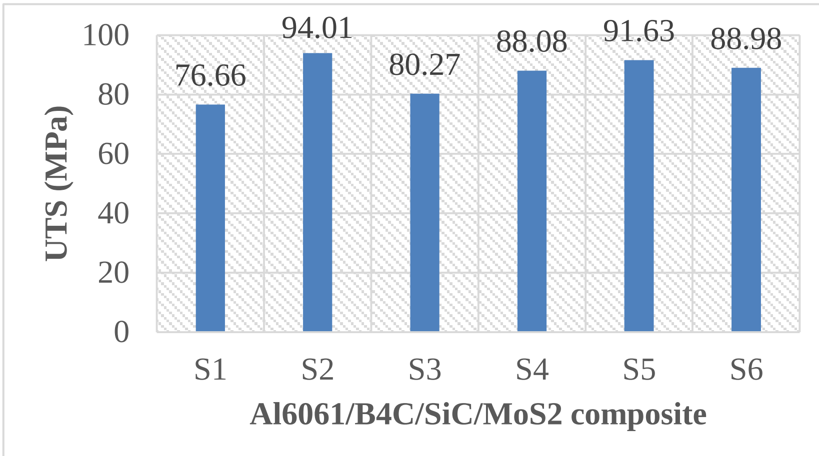


Figure 4.4 Graph of ultimate tensile strength of hybrid Al6061/B4C/SiC/MoS2 composites.

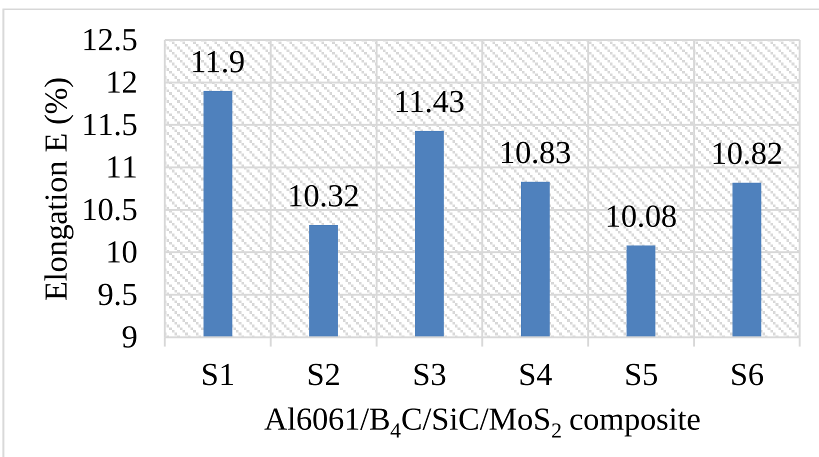


Figure 4.5 Percentage elongation of hybrid Al6061/B4C/SiC/MoS2 composite

4.3. Hardness Test

A hardness test was conducted via Vickers hardness tester machine to know that the hybrid composite is more resistant to scratching or penetration. During tasting 10kg.f load was used with a duration of 10sec. Table 4.3 shows, Vickers hardness test result of each of hybrid aluminum alloy (Al6061) matrix composites. Three trials for each were used and the average value was evaluated. From Figure 4.7, it can be observed that the hardness of the hybrid composite is greater than that of cast alloy (Al6061) without reinforcement.

The result revealed that, as the percentage of boron carbide increased, the hardness of aluminum alloy (Al6061) increases. This improvement is due to the high hardness of boron carbide, uniform distribution of the reinforcement particles, and good wettability of boron carbide with the matrix. The hardness result presented in table 4.3 and compared with the hardness result Ashok Kumar et al. (2018), Rao and Ramanaiah (2017), and Ravi (2015), better and comparable due to hybrid reinforced. Figure 4.6 shows the image of the hardness test result of Al6061/12B_4C/4MoS_2 taken from a computer screen during the test.

The addition of 12% of B_4C and 4% of MoS_2 improves the hardness of aluminum alloy (Al6061) by 28.31% and the addition of 12% of SiC and 4% of MoS_2 increases the hardness of aluminum alloy (Al6061) by 16.90%. Generally, the hardness of hybrid composite (S2, S3, S4, S5, and S6) is increased by 28.31%, 16.90%, 16.94%, 20.06%, and 20.20% as compared with non-reinforced. The order hardness of hybrid composite from highest to lowest is S2 >S6>S5>S4>S3>S1.

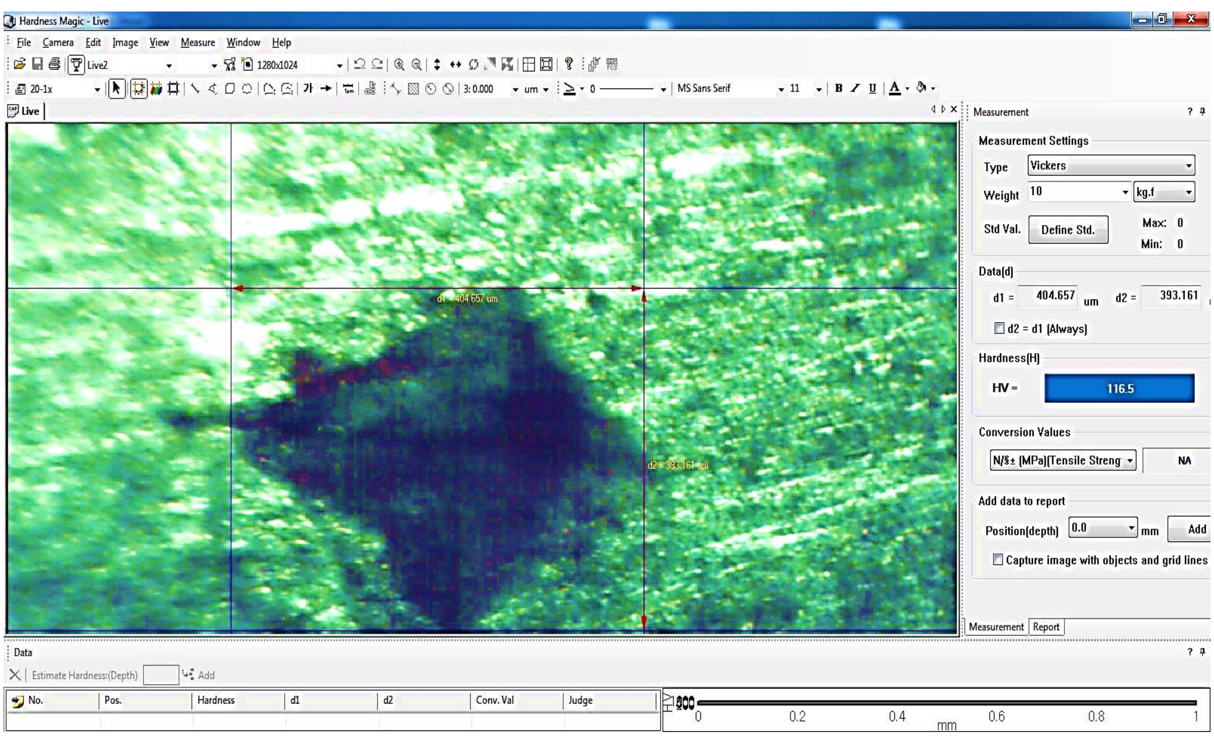


Figure 4.6 Vickers hardness test result of Al6061/12B4C/4 MoS2

Table 4.3. Hardness strength of the developed hybrid metal matrix composites

Designation	$Al6061/B_4C/SiC/MoS_2$ composite	Vickers Hardness (HV)			Average Vickers hardness (HV)
		Test 1	Test 2	Test 3	
S1	Al6061	95.1	89.5	82	88.87
S2	$Al6061/12\%B_4C/4\%MoS_2$	116.5	110.1	115.5	114.03
S3	Al6061/12%SiC /4%MoS2	106.2	100.8	104.7	103.89
S4	$Al6061/3\%B_4C/9\%SiC/4\%MoS_2$	106.5	104.7	100.6	103.93
S5	$Al6061/9\%B_4C/3\%SiC/4\%MoS_2$	114.8	111.9	93.4	106.70
S6	$Al6061/6\%B_4C/6\%SiC/4\%MoS_2$	110.4	106.5	103.6	106.83

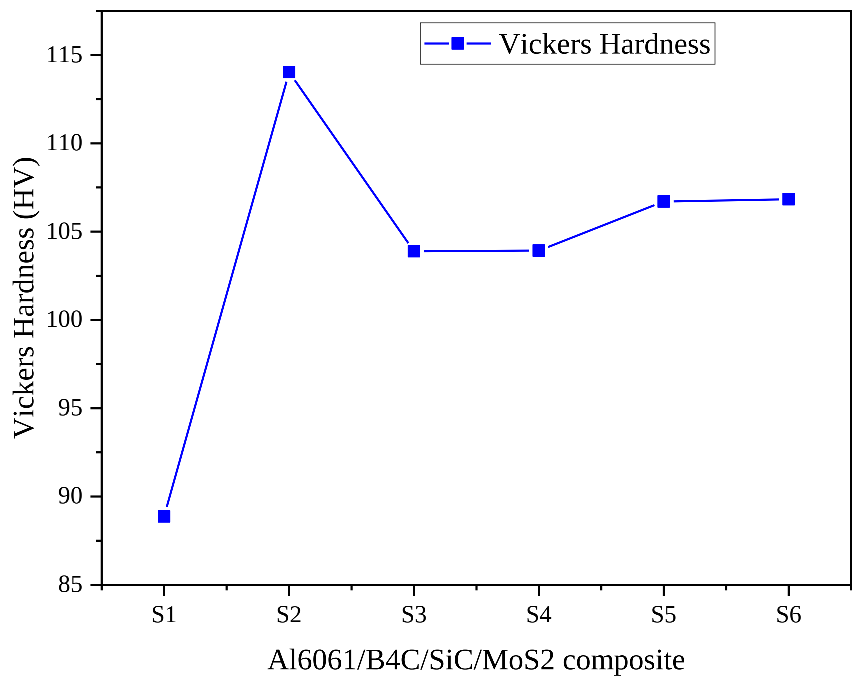


Figure 4.7 The effect of weight percentage of reinforcements on hardness of Al6061

4.4. Wear Test

The wear loss and coefficient of friction of the hybrid aluminum composites were measured using a micro pin-on-disc wear tester (TR-20-MICRO). The tests were conducted as per ASTM G-99 standard under dry sliding conditions at atmospheric temperature. The wear tests were carried out at three different loads of 10N, 30N, and 50N and a constant speed of 200RPM and a sliding distance of 251.2m on specimens of size 6mm diameter and 12mm length. The weight of the specimens before and after the wear tests were measured using a digital weighing machine (technotest TL 201/A) with an accuracy of ±0.0001g.

From the test, wear loss (g) and the coefficient of friction (COF) were determined. Table 4.4 and shows the list of COF with respect to normal load and weight composition. Figure 4.8 A. shows the Variation of COF Vs load. From the graph, it can be observed that as the load increases from 10N to 50N in the step of 20N, the coefficient of friction increases. This increment is due to, as the normal load increases the contact area between the surface of the specimen and the disk increases. As the contact area increases between the surfaces of sliding objects, the friction force rises. As a result the coefficient of friction increases.

The Variation of coefficient of friction COF with weight composition is also indicated in Figure 4.8.B. from the experimental record, it can be observed that unreinforced (Al6061 cast) has high coefficient of friction (COF) relative to hybrid reinforced composite. The decrement in coefficient of friction (COF) is attributed to the presence of solid lubricant molybdenum disulfide (MoS_2) which forms thin lubricating films or coating over the surface during sliding. The formed thin film prevents subsurface contact between sliding surfaces. Consequently, the friction coefficient was minimized.

The lowest COF friction (0.25 at 10N load) was observed for double reinforced specimen Al6061/12B_4C/4MoS_2. As the report of Halil et al. (2019), the presence of B_4C has also an effect on the friction coefficient due to it forms a boron oxide (B_2O_3) layer at the contact zone. When B_4C particles are pulled out from the composite and react with the environment due to some temperature rise, it creates the B_2O_3 oxide layer.

Table 4.4 Coefficient of friction Vs Load result

Load	Al6061/B_4C/SiC/MoS_2 composite					
	S1	S2	S3	S4	S5	S6
	COF					
10N	0.41	0.25	0.40	0.32	0.30	0.33
30N	0.47	0.29	0.43	0.36	0.34	0.37
50N	0.49	0.33	0.45	0.41	0.39	0.43

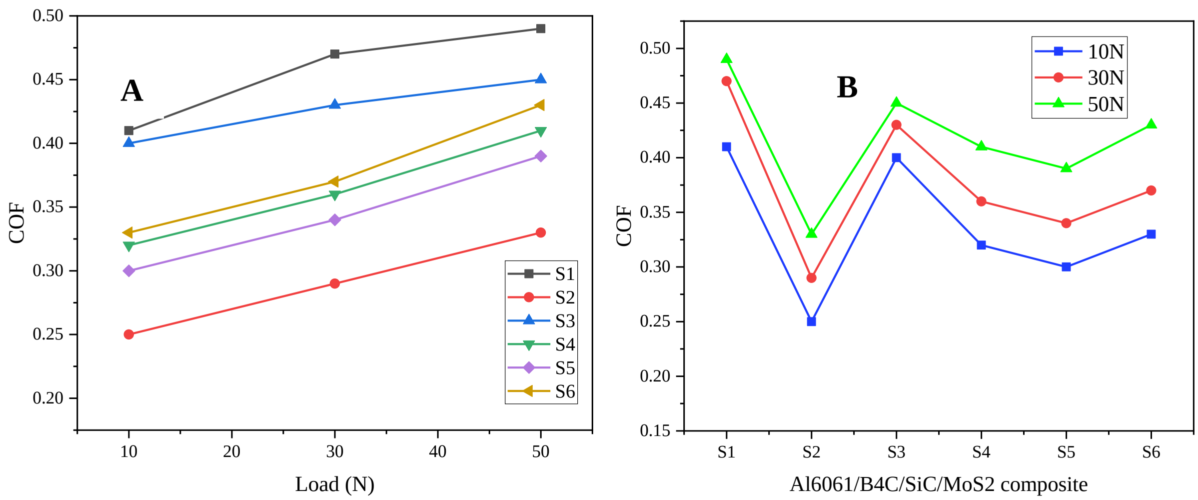
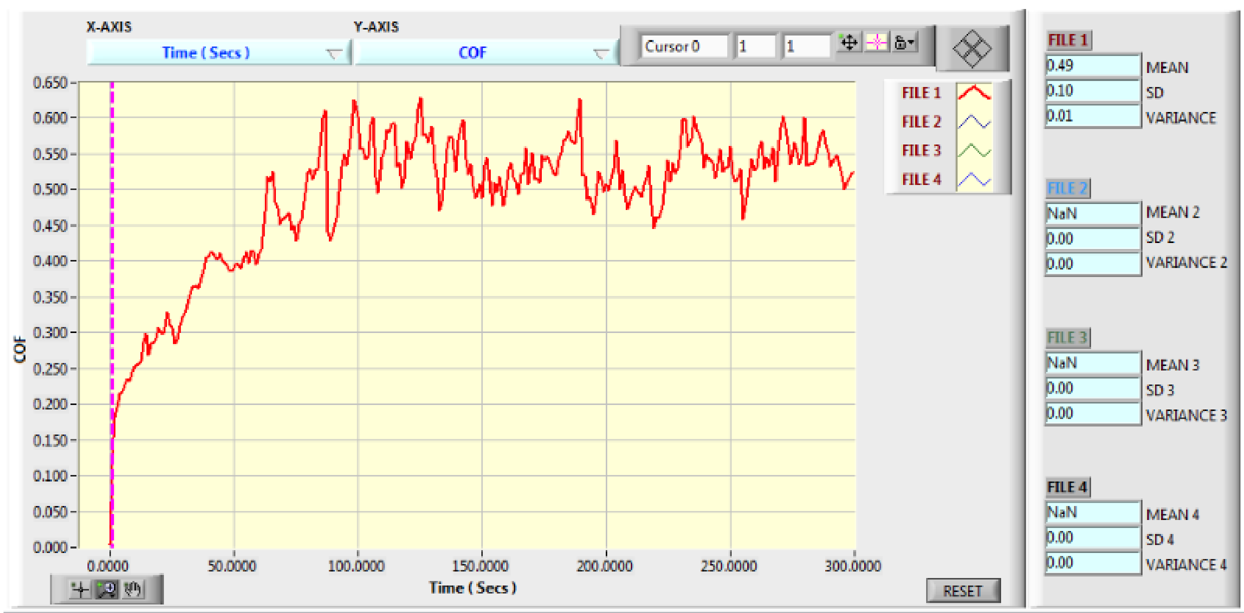
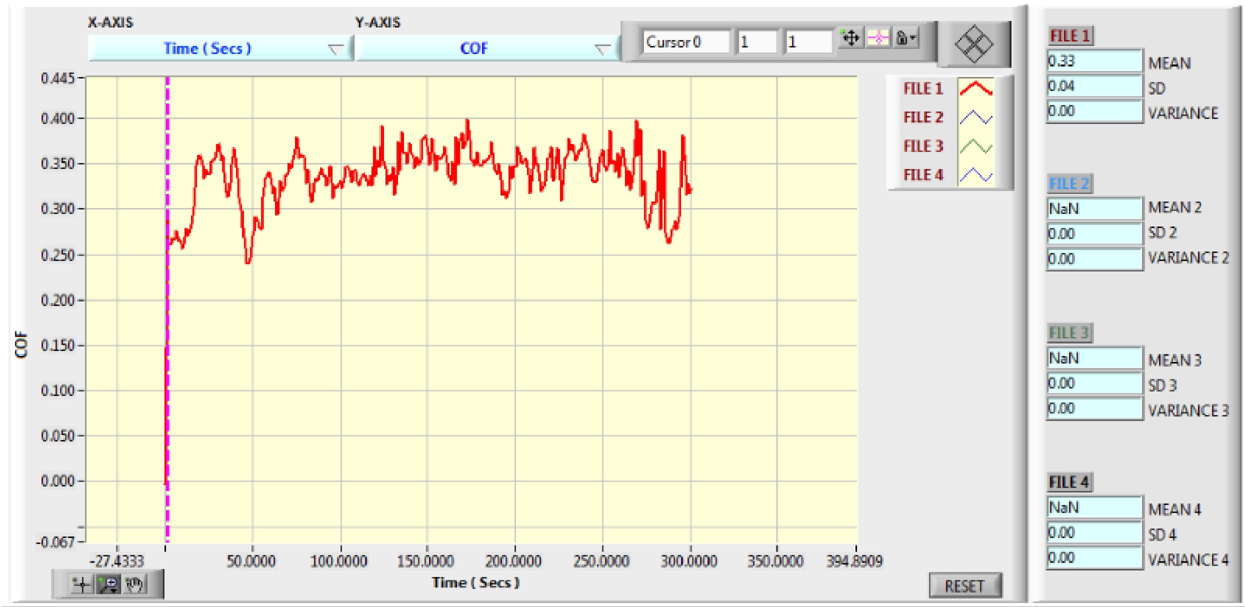


Figure 4.8 A. Variation of COF with load. B. Variation of COF with weight composition.



Specimen 1- Al6061 at 50N load

Specimen 2- Al6061/12%B_4C/4%MoS_2 at 50N load



Specimen 2- Al6061/12%B4C/4%MoS2 at 50N load

Figure 4.9 Coefficient of friction Vs time on Micro pin on disc tribometer at 50N load.

Table 4.5 lists experimental results of weight loss (g) with respect to normal load and weight composition (S1, S2, S3, S4, S5, and S6) and Figure 4.10. A. illustrates the variation of wear loss against normal load as a function of composite specimen. As the load increased from 10N to 50N, wear loss rises linearly. This is due to as the load increase, contact area increases; as a result, fatigue force, deformation force increases, and some temperature rises occur. This increment leads to crack forming and propagation, deformation, pool out of reinforcement particles, and forming of wear debris increases. The rise in wear debris also has a negative effect on the wear resistance of the material. The formation of wear debris leads to breakdown of lubricating layers and plowing of composite surface. Due to such a reason, weight loss rises as load increases. At 50N load, the maximum weight loss was 0.0032g for unreinforced specimen and the minimum weight loss was 0.0016g for the double reinforced specimen (Al6061/12%B4C/4%MoS2) as shown in Figure 4.10. B. Thus, at 50N load the wear resistance of aluminum alloy was improved by 68.42% when it was reinforced. The order of wear performance of composite specimen from better to worst was S2 > S5 > S6 > S4 > S3 > S1.

Table 4.5. Wear loss vs Load

Load	$Al6061/B_4C/SiC/MoS_2$ composite					
	S1	S2	S3	S4	S5	S6
	Wear loss					
10N	0.0015	0.0003	0.0013	0.0011	0.0006	0.0007
30N	0.0021	0.0008	0.0018	0.0017	0.0012	0.0015
50N	0.0032	0.0016	0.0029	0.0028	0.0020	0.0023

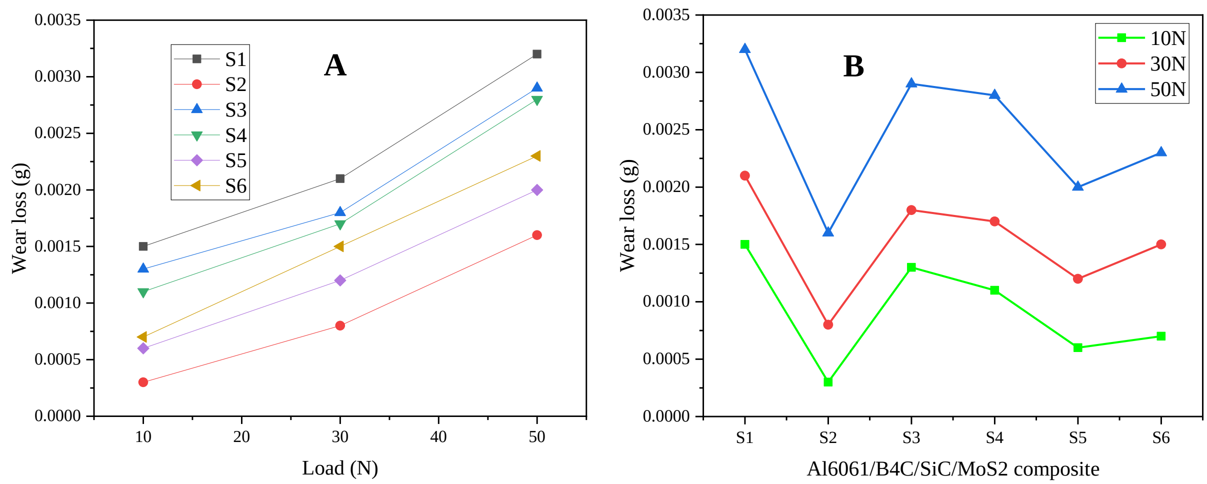


Figure 4.10 A.variation of wear loss with load B. variation of wear loss with weight composition

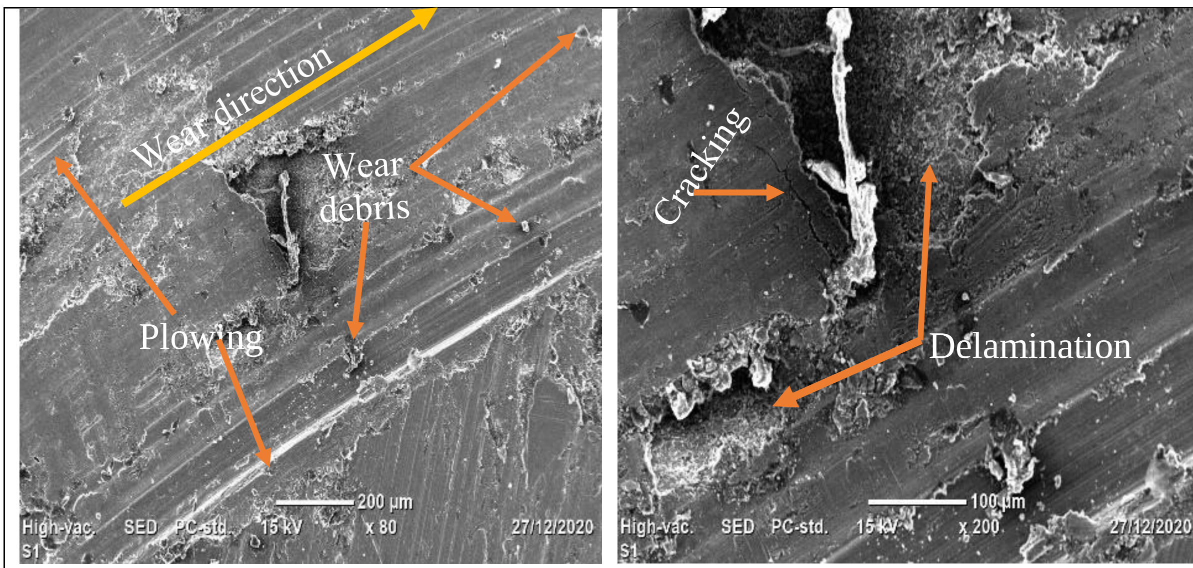
4.5. Wear Mechanism

The wear morphology of S1, S2, S3, S4 and S5 at 50N load was observed under scanning electron microscope (SEM). Figure 4.11 shows the image of worn surface each specimen under different resolution. Due to the presence of solid lubricant MoS_2 thin tribo-layer were formed over the surface, thus coefficient of friction and the rise of temperature reduced during sliding. Thus, the probability of occurrence of tribological reaction and adhesive wear mechanism on HAMMCs were less. Since, abrasion wear happens mostly in tribological systems in which the tribo-elements exhibit broadly different hardness values (Mang et al., (2011)), abrasive wear and surface fatigue wear are the possible wear mechanisms.

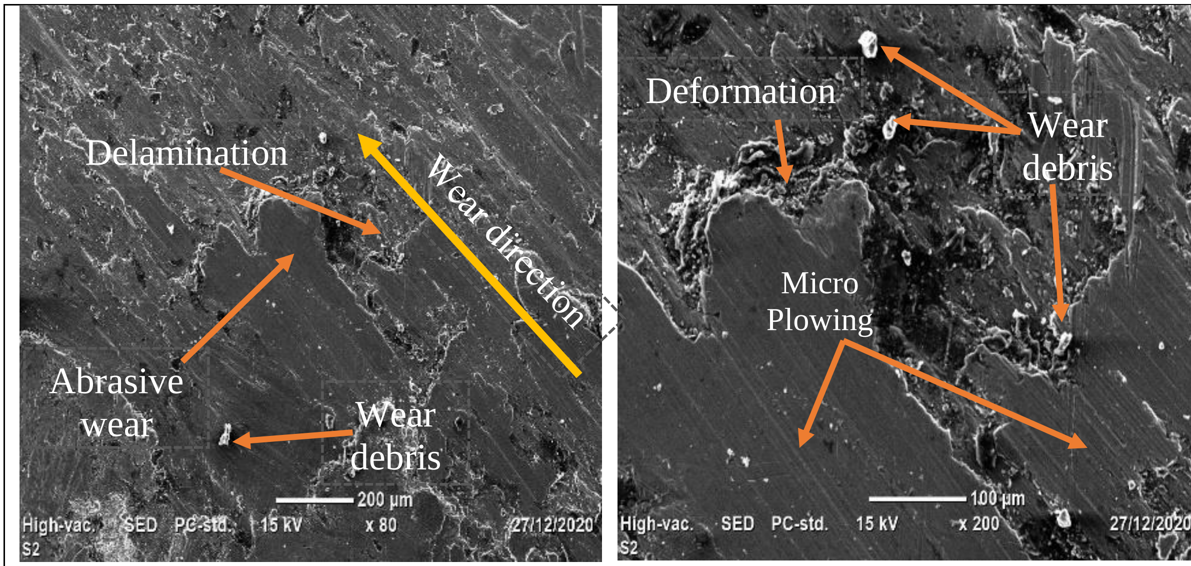
Wear morphology of the worn surface of hybrid composite were investigation under 50μm, 100μm and 200μm resolution with a magnification of 500x, 200x and 80x respactivly. From worn surface analysis under SEM, wear mechanisms such as wear debris, plowing, cracking, deformation wear, pool out and delamination wear were observed. Wear debris and delamination wear were the predominant wear mechanisms of hybrid metal matrix composite.

The wear debris produced during rubbing of two counter surfaces, helps the breakdown or disintegration of this tribo-layer into further wear debris and surface plowing. Thus, this mechanism accelerates abrasive wear. From this, it can be conclude that abrasive and surface fatigue wear are the main wear mechanisms of the fabricated hybrid aluminum matrix composite.

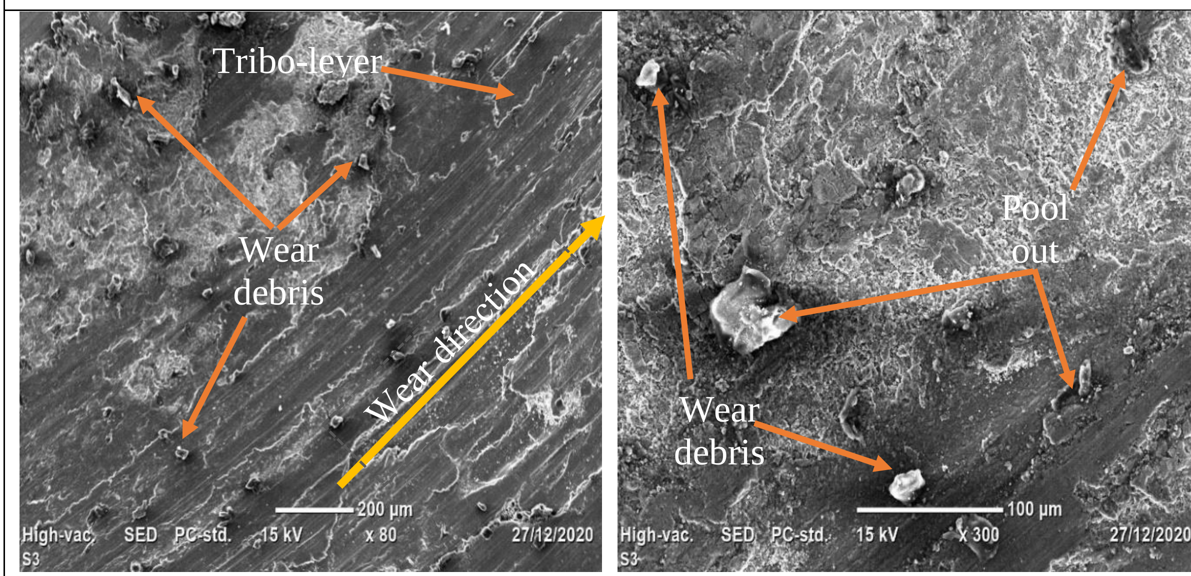
With the addition of reinforcements less wear defects (such less plowing, less delamination and less wear debris) were observed in the direction sliding. This is because of the presence of hard ware resistance particles and solid lubricant reinforcements.



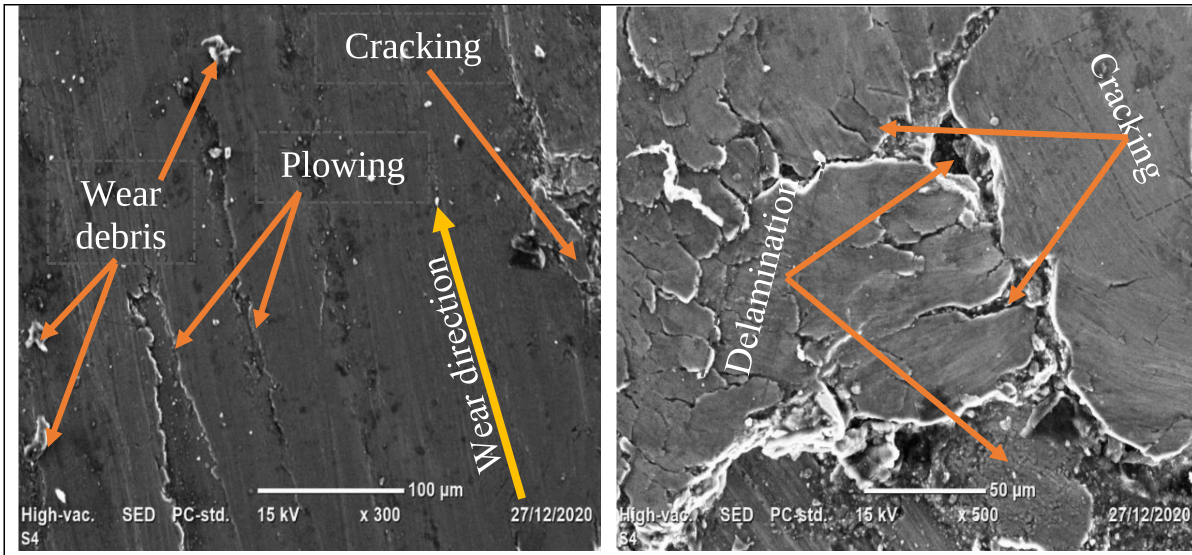
S1 - Al6061



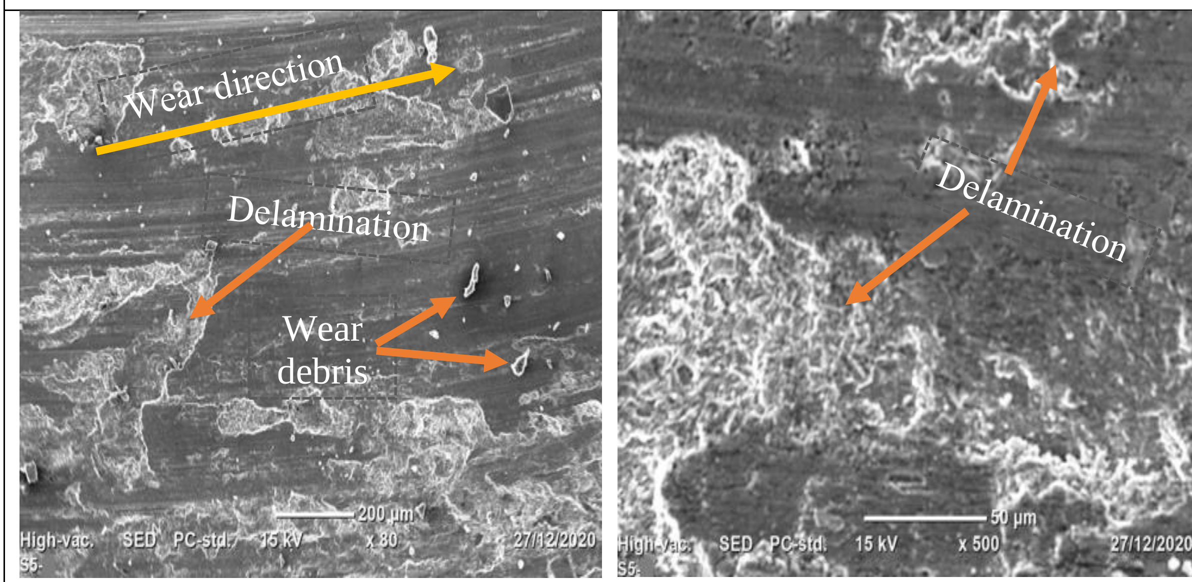
S2 - Al6061/12%B4C/4% MoS2



S3 - Al6061/12% SiC/4%MoS2



S4 - Al6061/3%B4C/9%SiC/4%MoS2



S5 - Al6061/9%B_4C/3%SiC/4%MoS_2

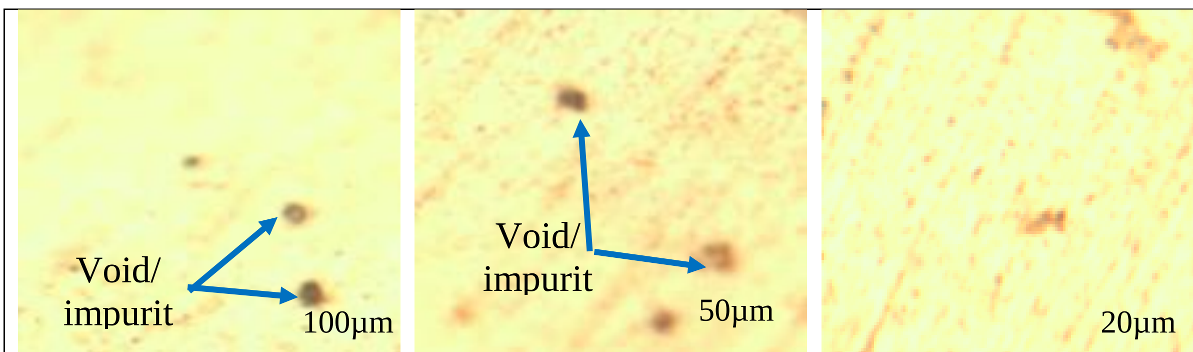
Figure 4.11 SEM image of wear morphology of specimen 1,2,3,4 and 5 at 50N load

4.6. Microstructural observation

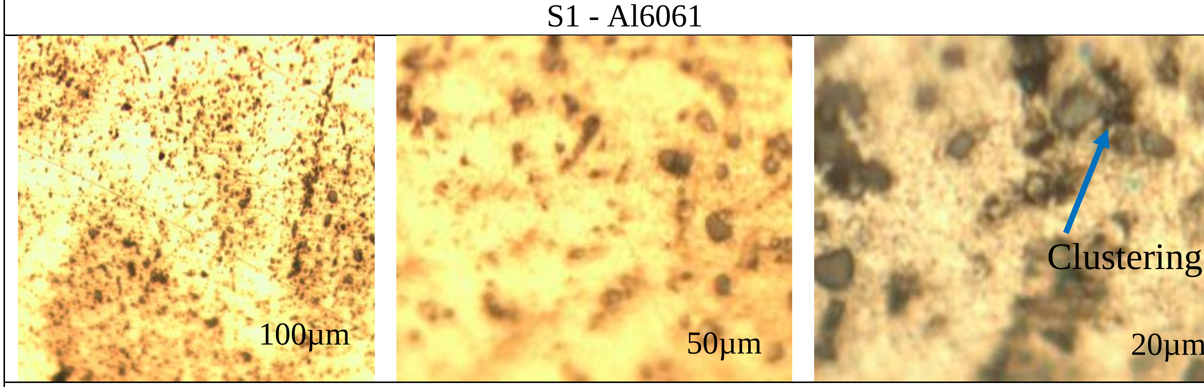
Microstructures of the developed hybrid composites were investigated by optical microscope (model Huvitz HR-300 series). In the present investigation, 20x, 50x and 100x magnifications were used to identify the morphology and distribution of reinforcement particles in the Al6061 matrix.

For the microstructure examination, the caste composite samples were ground using abrasive silicon carbide paper of different grit sizes and polished using diamond suspension on a two-wheel system polishing machine. The specimen was etched using Keller's chemical etchant before observed using optical microscopy.

Figure 4.12 shows the optical microscope images of hybrid aluminum (Al6061) matrix composite at different magnifications. Figure 4.12 S1, S2, S3, S4, S5, and S6 shows the microstructure of non-reinforced (Al6061), Al6061/12%B_4C/4% MoS_2 hybrid composite, Al6061/12% SiC/4% MoS_2 hybrid composite, Al6061/3%B_4C/9%SiC/4%MoS_2 hybrid composite, Al6061/ 9%B_4C/ 3%SiC/ 4%MoS_2 hybrid composite and Al6061/ 6%B_4C/ 6%SiC/ 4%MoS_2 hybrid composite respectively. The image revealed that the particles of the reinforcements were uniformly distributed throughout the base matrix aluminum alloy (Al6061). This behavior can be credited to the effectiveness of vortex action and the use of appropriate procedure of composite fabrication. No crack was observed from the image. Some clustering of reinforcements was observed on specimen S2, S3, and S5. This is mainly due to the usage of a high weight percentage of reinforcements (16% total) and the imperfectness of string mechanisms.



S1 - Al6061



S2 - Al6061/12%B_4C/4% MoS_2

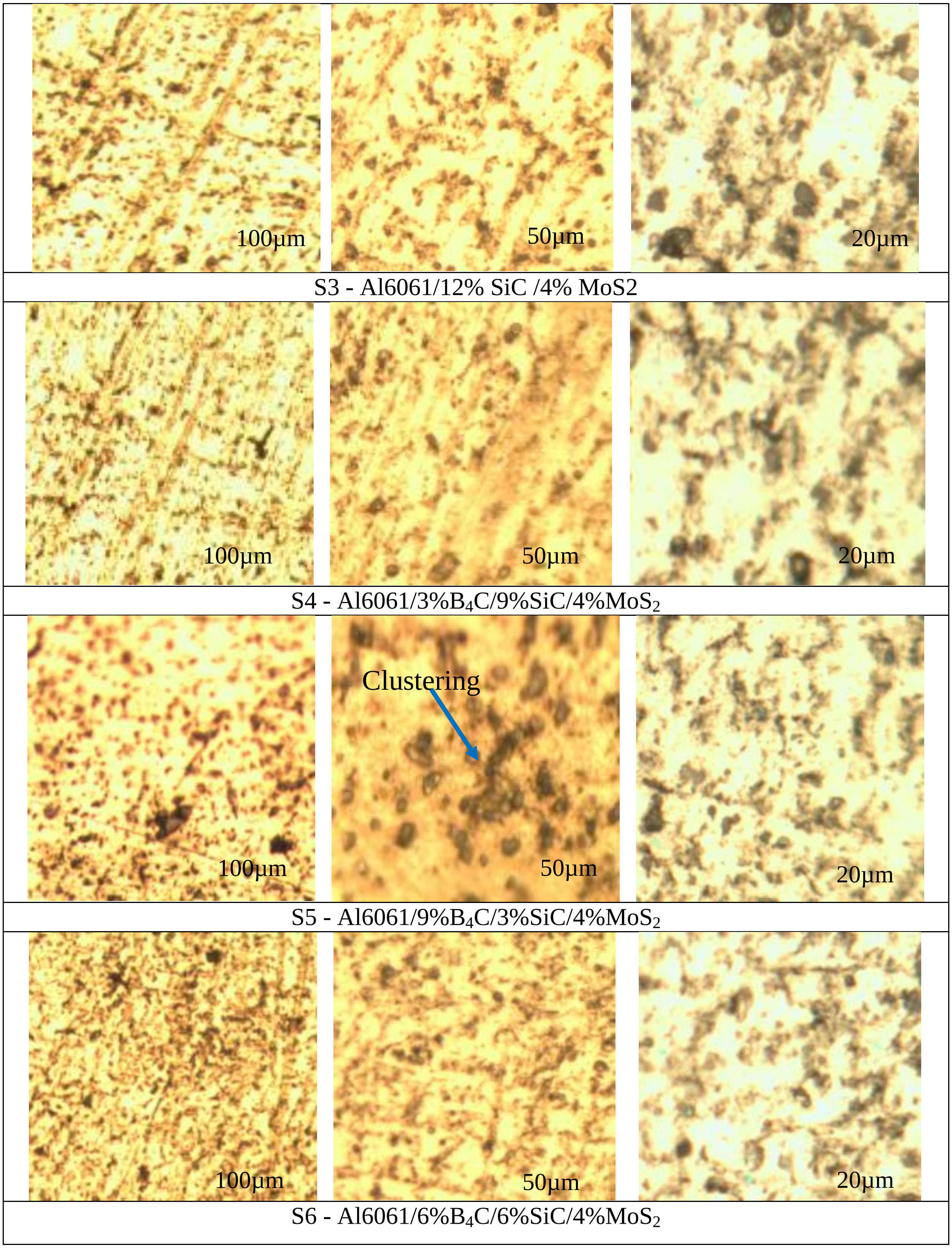


Figure 4.12 Optical microscope image of hybrid composite

5. Conclusion and Recommendation

5.1. Conclusion

In the present work, fabrication of hybrid aluminum alloy (Al6061) metal matrix composite with different weight percentage of B_4C, SiC and constant 4%MoS_2 via stir casting and evaluation of microstructure, density, porosity, tensile strength, hardness, wear loss, coefficient of friction and wear morphology was done. The conclusions are as follows:

- Hybrid Al6061 matrix composites were successfully produced by melt vortex method using two bladed stirrer, two stages mixing and preheating of the reinforcing particles.
- The optical microscope images of the composite revealed that the particles of the reinforcements were uniformly distributed throughout aluminium alloy (Al6061) matrix.
- As compared to cast non-reinforced aluminum alloy (Al6061), the density of doubled and tripled reinforced Al6061 composite increased to some extent due to the density of SiC and MoS_2. The highest density was recorded at Al6061/12SiC/4MoS_2. As the percentage of SiC increased, the porosity level also increased and high porosity was observed at 12%SiC4%MoS_2.
- The hardness of prepared hybrid aluminum matrix composite improved with increase in weight percentage of B_4C and the highest hardness was recorded on Al6061/12B_4C/4MoS_2 composite with average hardness value of 114.03HV. On the other side the lowest hardness value was observed at Al6061 cast without reinforcement, which have average hardness value of 88.87HV. Thus, the hardness of Al6061 was improved by about 28.31%.
- Ultimate tensile strength of the hybrid Al6061 composites advanced by the addition of B_4C, SiC, and MoS_2. By the addition of 12% of SiC and 4% of MoS_2, ultimate tensile strength was improved by 22.63%.
- As the load increases from 10N to 50N in the step of 20N, the coefficient of friction increases. Due to the contact area among the surface of the specimen and the disk increases.
- As the load increased from 10N to 50N, wear loss rises linearly. At 50N load, the maximum weight loss was 0.0032g for unreinforced specimen and the minimum weight loss was 0.0016g for double reinforced specimen (Al6061/12%B_4C/4%MoS_2) at this load.

The order of wear performance of composite specimen from better to worst was S2 > S5 > S6 > S4 > S3 > S1.

- Wear debris and delamination wear are the predominant wear mechanisms of the composites.

5.2 Recommendation

Stir casting is suggested as the most feasible process due to low cost, simplicity and the ability to ensure uniform distribution of reinforcement particle. Since Al6061/B_4C/SiC/MoS_2 composite have shown high improvement towards hardness, tensile strength, wear loss and coefficient of friction than the base material, it can recommended that this composite materials are a good replacement for materials that have higher density which used for automotive bodies, engine block, connecting road, rotor drum/disk etc. Producing hybrid Aluminum alloy (Al6061) reinforced with B_4C, SiC, and MoS_2 in large quantity, with proper stir casting setup and the used for automobile parts; improves strength, durability and reduce the overall weight of the machine. This leads to low consumption of fuel and long life of the machine.

5.3 Future Work

The following works are suggested for future works form different perspectives in the field of Al6061/B_4C/SiC/MoS_2 HMMCs:

- Design of stir casting set up using speed controller motor and temperature control unit with atmosphere control system enables optimization of process parameters and will leads to produce better quality composite.
- Design and use of permanent casting mold leads to fabrication of better quality composite.
- Investigation of the machining characteristics and optimizing the machining parameter for this hybrid composite is an important aspect of machining.
- Further processing this hybrid composite (such as extrusion, forging and heat treating etc.) and studying mechanical, physical and tribological properties is another aspect of research on hybrid composite.
- Investigating of the effect of varying the weight composition molybdenum disulfide on the tribological properties of high strength hybrid composite at 12% of B_4C will be better in the field of tribology.

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APPENDIX

Appendix A: Tables

Table A-.1. Mass of specimens in air and in distilled water for experimental density measurement.

Designation	$Al6061/B_4C/SiC/MoS_2$ composite	Mass of the specimen in air (g)	Mass of the specimen in water (g)
S1	Al6061	14.204	8.92
S2	$Al6061/12\%B_4C/4\%\ MoS_2$	14.089	8082
S3	Al6061/12% SiC /4% MoS2	15.744	9.965
S4	$Al6061/3\%B_4C/9\%SiC/4\%MoS_2$	15.442	9.770
S5	$Al6061/9\%B_4C/3\%SiC/4\%MoS_2$	11.703	7.412
S5	$Al6061/6\%B_4C/6\%SiC/4\%MoS_2$	13.279	8.357

Table A-.2. Mass of specimens before wear test and after wear test at 10N, 30N, and 50N load

Designation	$Al6061/B_4C/SiC/MoS_2$ composite	Before wear test (g)	After wear test (g)		
			10N	30N	50N
S1	Al6061	0.7618	0.7603	0.7582	0.7550
S2	$Al6061/12\%B_4C/4\%\ MoS_2$	0.8183	0.8180	0.8172	0.8156
S3	Al6061/12% SiC /4% MoS2	0.8585	0.8572	0.8554	0.8525
S4	$Al6061/3\%B_4C/9\%SiC/4\%MoS_2$	0.8152	0.8141	0.8124	0.8096
S5	$Al6061/9\%B_4C/3\%SiC/4\%MoS_2$	0.8714	0.8708	0.8696	0.8676
S6	$Al6061/6\%B_4C/6\%SiC/4\%MoS_2$	0.8158	0.8151	0.8136	0.8113

Table A-.3. Output stress-elongation-table for Al6061

Material: Al6061

Free Text:

Initial measurement length: 50mm

Specimen diameter: 8mm

Date: 28.12.2020

No.	S [N/mm²]	E [%]
0	0.00	0.00
1	0.40	0.54
2	4.18	1.69
3	9.55	2.90
4	29.05	4.11
5	33.10	5.36
6	52.42	6.96
7	63.31	8.62
8	76.66	9.15
9	60.71	10.16
10	10.13	11.72
11	2.44	11.90

Table A-.4. Output stress-elongation-table for $Al6061/9SiC/4MoS_2$

Material: Al6061/9SiC/4MoS2

Free Text:

Initial measurement length: 50mm

Specimen diameter: 8mm

Date: 28.12.2020

No.	S [N/mm²]	E [%]
0	0.00	0.00
1	0.90	0.54
2	1.969	1.49
3	6.77	3.90
4	14.93	4.01
5	33.04	5.36
6	47.04	6.06
7	59.56	7.62
8	65.78	8.15
9	71.33	9.16
10	94.01	10.72
11	65.05	11.10
12	8.21	11.43

Appendix B: Figures

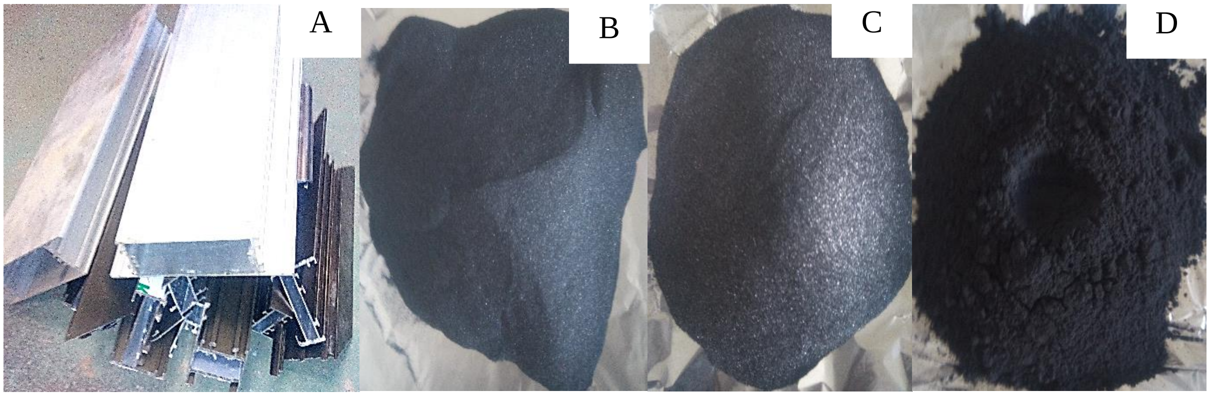


Figure A-.0.1. Image of aluminum matrix and reinforcement powder used (A) Aluminum alloy. (Al6061) scrap from life steal aluminum work. (B) Silicon Carbide (SiC) with particle size of 50 to 120 micron meter. (C) Boron Carbide (B_4C) with particle size of 50 to 120 micron meter. (D) Molybdenum Disulfide (MoS_2) with particle size of 2.5 micron meter.

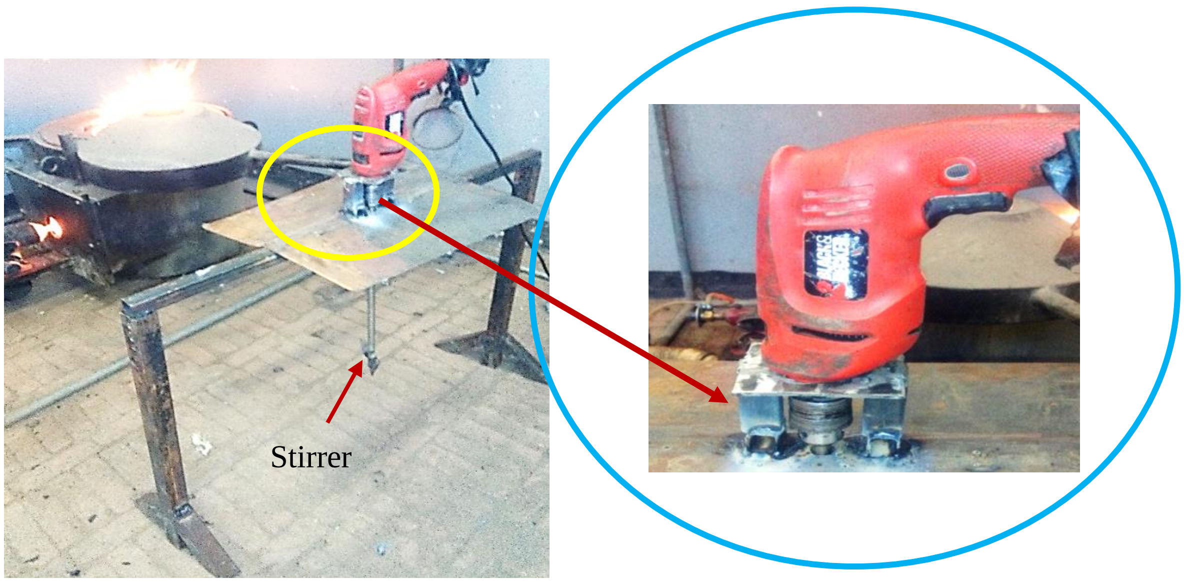


Figure B-.0.2. Stirrer setup using hand drill machine

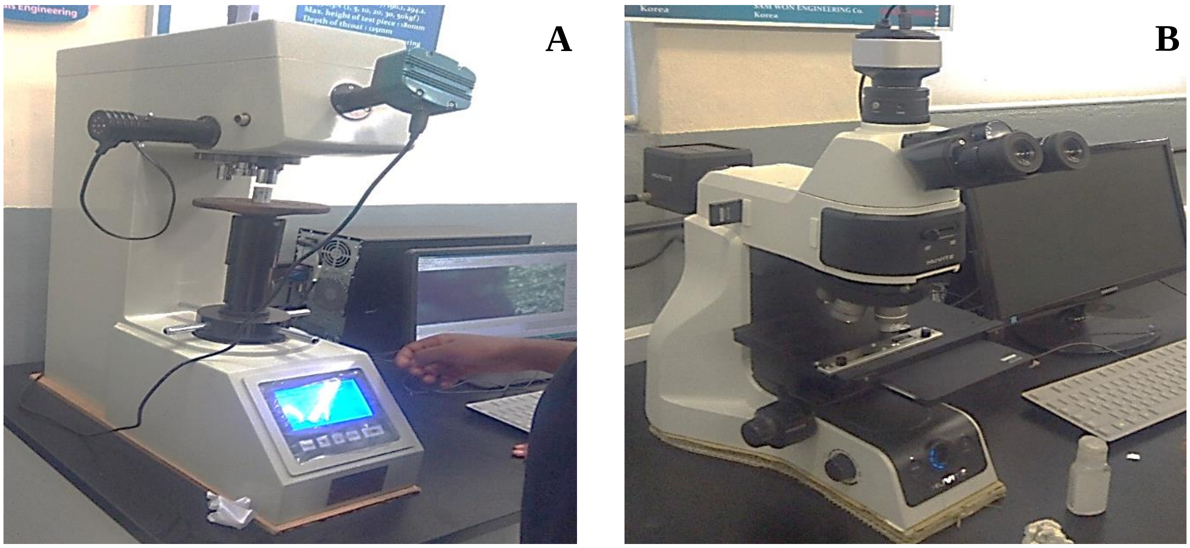


Figure B-.0.3. A. Vickers hardness tester machine B. Optical microscope

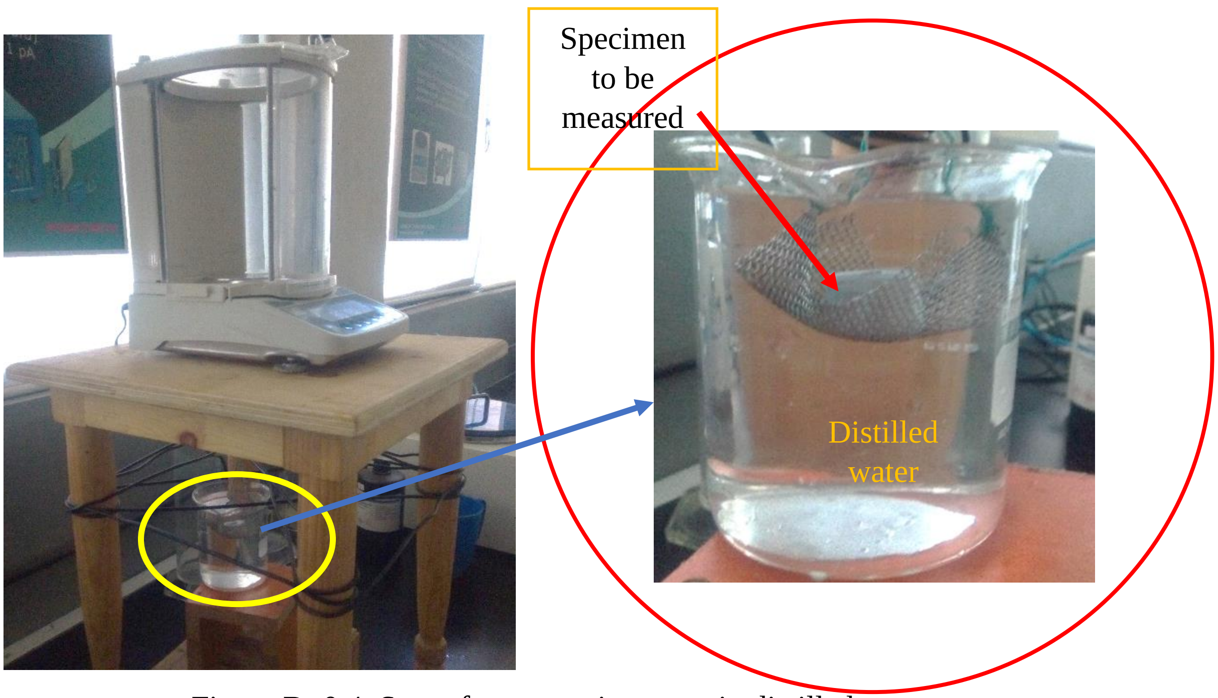
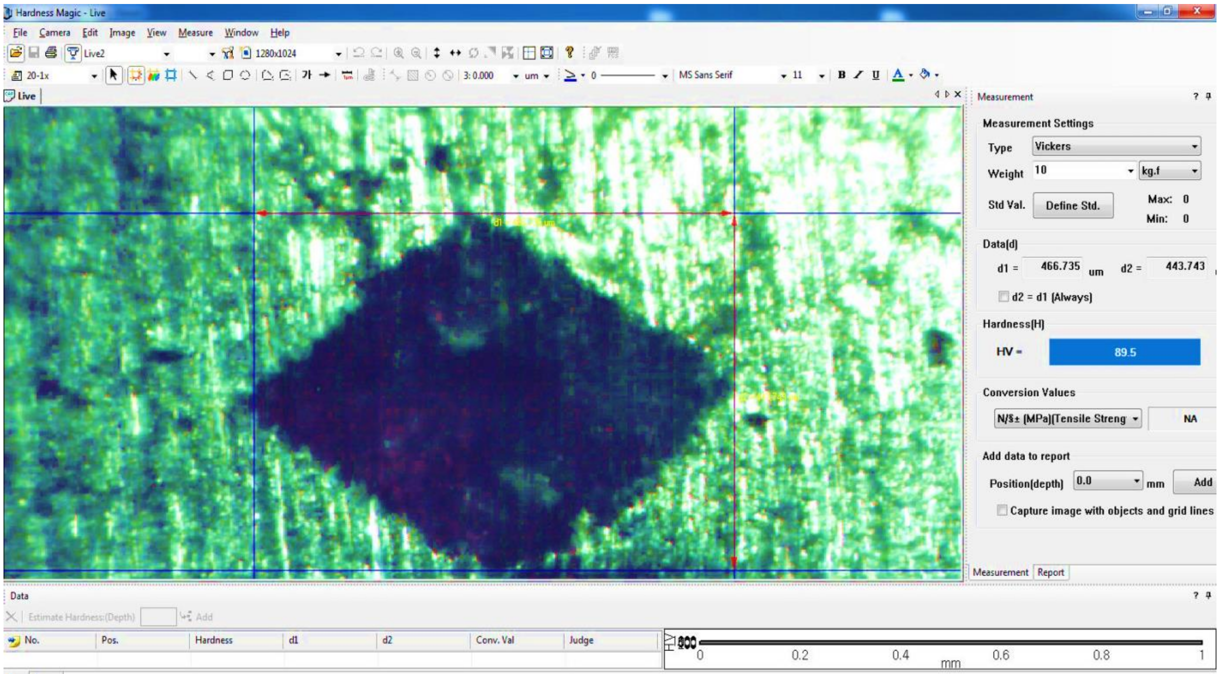
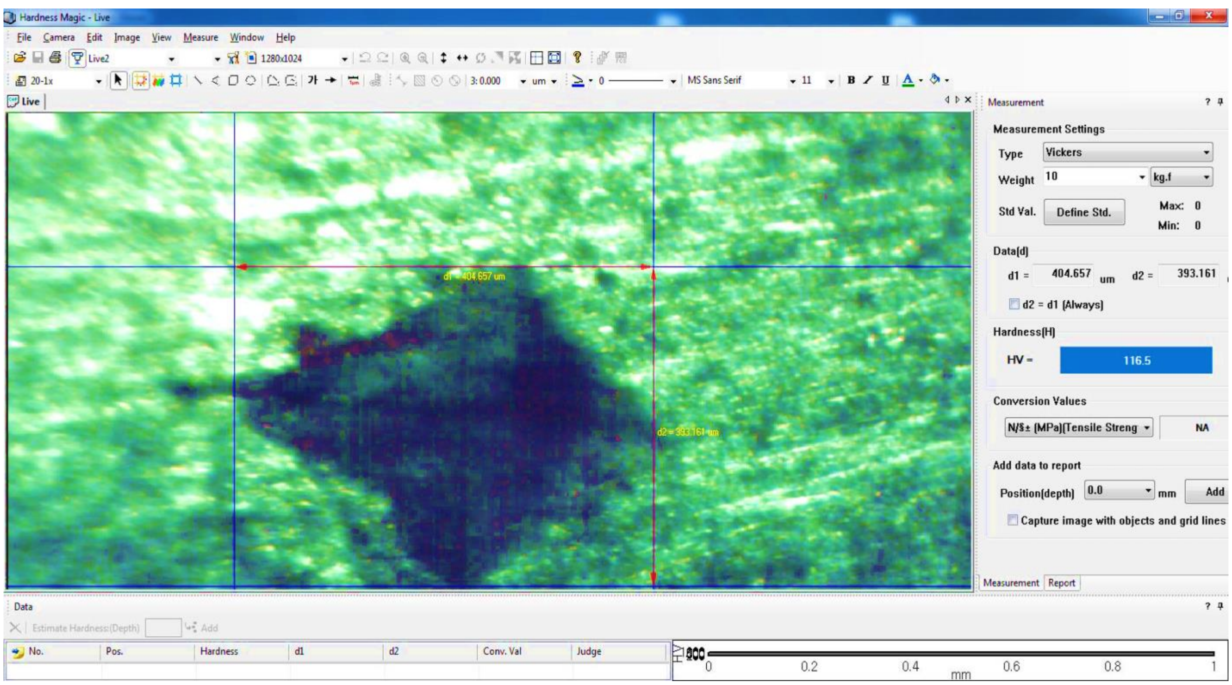


Figure B-.0.4. Setup for measuring mass in distilled water



Specimen 1- Al6061



Specimen 2- $Al6061/12\%B_4C/4\%MoS_2$

Figure B-.0.5. Vickers hardness value for Specimen (1, 2, 3, 4, 5, and 6).

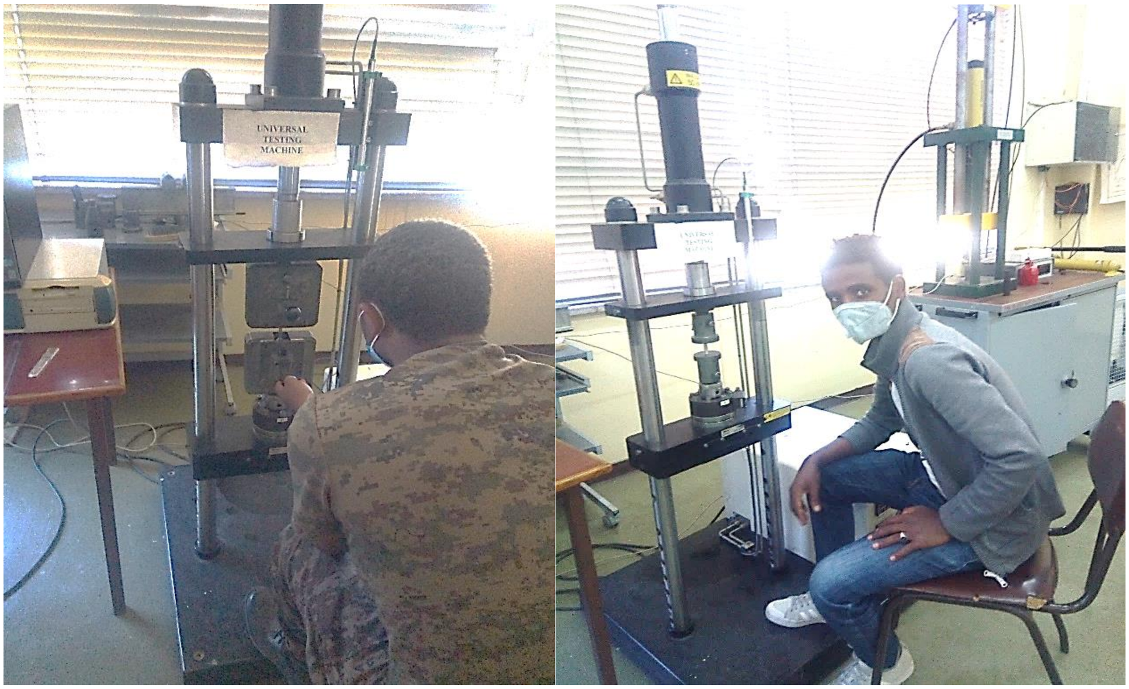


Figure B-.0.6. Universal testing machine (UTM).

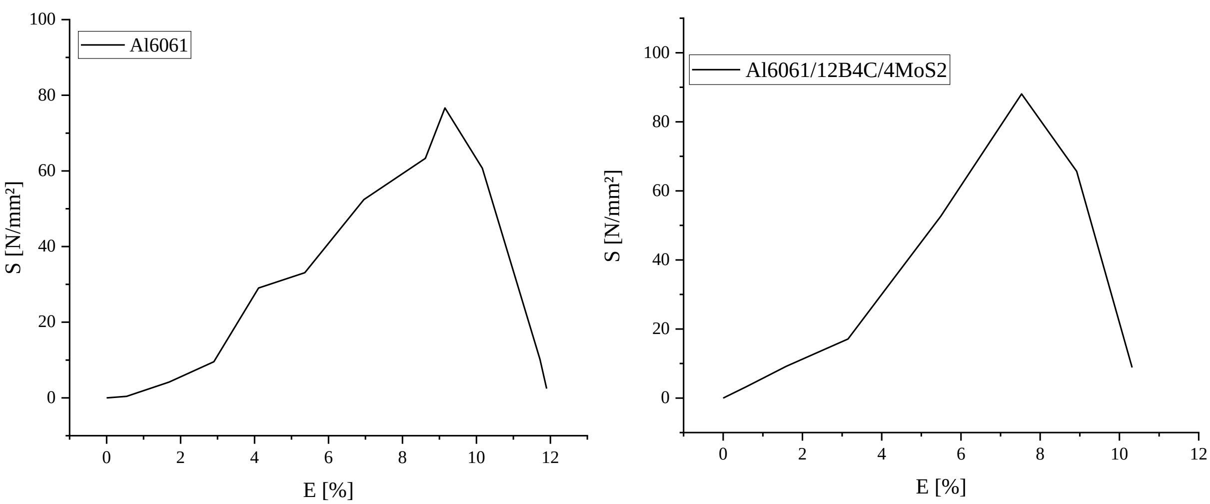
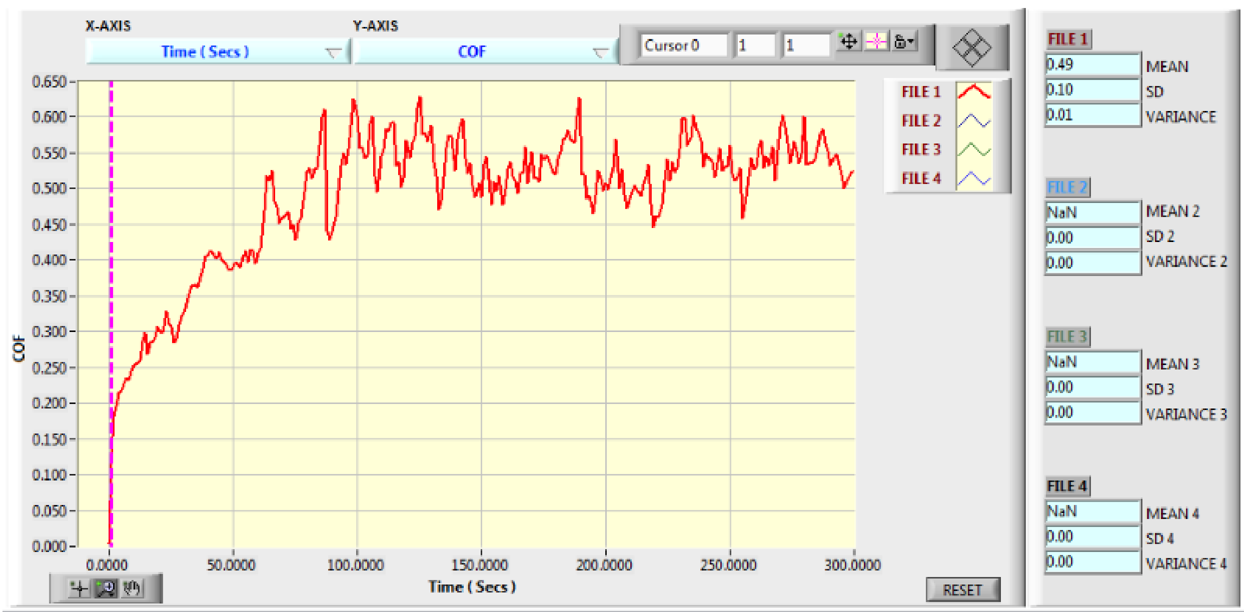
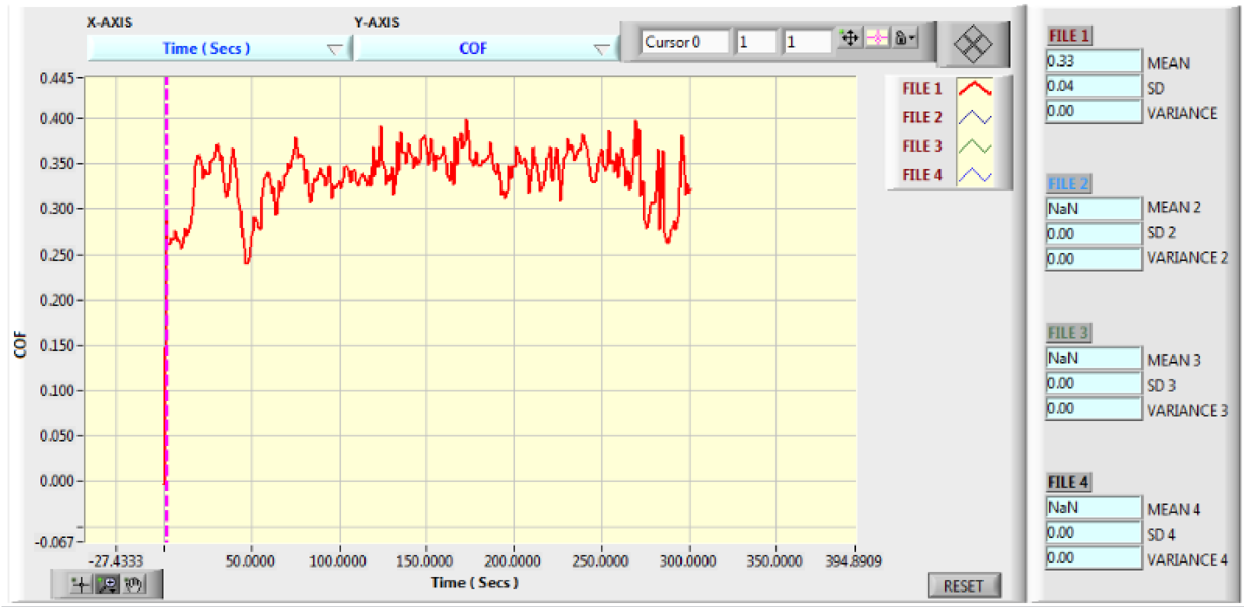


Figure B-.0.7. Stress Vs elongation diagram of S1, and S2.

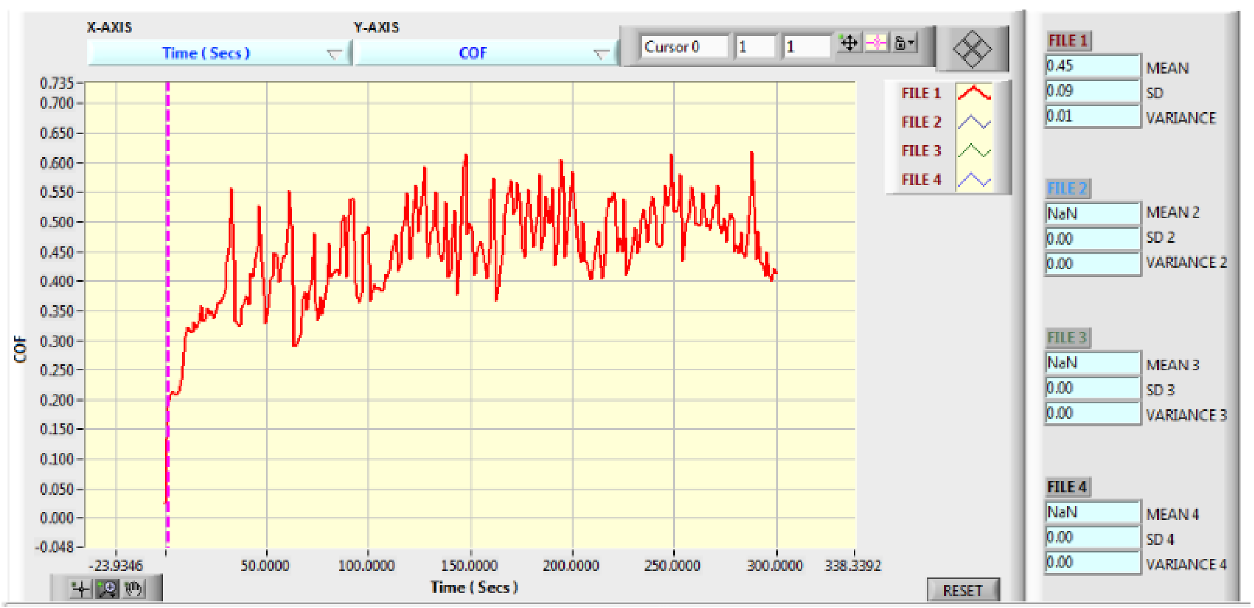
Figure B.0.8. Full image micro pin on disk tribometer use for wear test.



Specimen 1- Al6061 at 50N load



Specimen 2- Al6061/12%B_4C/4%MoS_2 at 50N load



Specimen 3- Al6061/12% SiC/4%MoS_2 at 50N load

Figure B-.0.9. Graph of coefficient of friction Vs time on micro pin on disc tribometer at 50N load.