Synthesis and Investigation of Mechanical and Tribological Property of Al7075 based Composite Reinforced with ZrO_2/Ti-6Al-4V/MoS_2

Nardos Ketsela Harka

A Thesis Submitted to Department of Mechanical Engineering,

College of Mechanical, Chemical, and Materials Engineering

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

Office of Graduate Studies

Adama Science and Technology University

June, 2025

Adama, Ethiopia

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DECLARATION

I hereby declare that this Master Thesis entitled ‘‘**Synthesis and Investigation of Mechanical and Tribological Property of Al7075 based Composite Reinforced with ZrO_2/Ti-6Al-4V /MoS_2**’’ is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Nardos Ketsela Harka

Name of Student	Signature	Date

RECOMMENDATION

We, the advisors of this thesis, hereby certify that we have read the final version of the thesis entitled ‘‘**Synthesis and Investigation of Mechanical and Tribological Property of Al7075 based Composite Reinforced with ZrO_2/Ti-6Al-4V/MoS_2”** Prepared under our guidance by Nardos Ketsela Harka. submitted in partial fulfillment of the requirements for the degree of Mater’s of Science in Manufacturing Engineering. Therefore, we recommend the submission of the final revised version of the thesis to the department following the applicable procedures.

Dr. Habtamu Beri	____________________	____________________
Major Advisor	Signature	Date

APPROVAL SHEET

I, the advisors of the thesis entitled ‘‘**Synthesis and Investigation of Mechanical and Tribological Property of Al7075 based Composite Reinforced with ZrO_2/Ti-6Al-4V/MoS_2”** and developed by **Nardos Ketsela Harka** hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

___________________	___________________	___________________
Major Advisor/Supervisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by **Nardos Ketsela** have read and evaluated the thesis entitled ‘‘**Synthesis and Investigation of Mechanical and Tribological Property of Al7075 based Composite Reinforced with ZrO_2/Ti-6Al-4V /MoS_2”** and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in **Manufacturing Engineering.**

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Finally, approval and acceptance of the thesis is contingent upon the submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

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LIST OF ACRONYMS

Al7075	Aluminum Alloy
AMMCs	Aluminum Metal Matrix Composites
ASTM	American Society for Testing and Materials
ANOVA	Analysis of variance
DOE	Design of experiment
MMC	Metal Matrix Composite
MoS2	Molybdenum disulfide
OM	Optical Microscopy
PoD	Pin on Disc
SEM	Scanning Electron Microscopy
Ti-6Al-4V	Titaniun grade-5
UTM	Universal Testing Machine
VHT	Vickers Hardness Test
wt.%	Weight percentage
XRD	X-Ray diffraction analysis
ZrO_2	Zirconium Dioxide
µm	Micro meter
ρ	Density

ABSTRACT

Aluminum matrix composite (AMMC) materials are now critical engineering materials for aerospace and automotive sectors due to their light weight and their comparative strength-to-weight ratio and better mechanical properties. Al7075 alloy has been increasingly used among them, especially in aerospace materials like aircraft wings, where strength, resistance to wear resistance to stress and failure in the structure are desirable. Nevertheless, poor wear behavior and reduced interfacial bonding between reinforcements and the matrix present challenges. This study approach is aimed to fabricate Al7075 matrix composite materials reinforced with ZrO2, Ti-6Al-4V, and MoS2 by a liquid metallurgy route through stir casting. All the compositions included 2 wt.% MoS_2 as a solid lubricant and for enhancing wettability between reinforcements and molten matrix. Five batches were synthesized at various weight fractions percentage of ZrO_2 and TC4 while keeping MoS_2 invariant. Synthesis was conducted at a stirring rate of 500 rpm, stirring time of 30 min, and 700°C of pouring temperature. Phase and microstructural analysis were carried out using XRD, OM, and SEM while Archimedes' law was used for density and porosity measurement. Mechanical and tribological properties including hardness, compressive strength, wear rate, and coefficient of friction were experimentally evaluated. The enhancement of hardness and compressive strength on the addition of reinforcement was confirmed by the results, and Sample 4 (Al7075 + 5% ZrO_2 + 1.5% TC4 + 2% MoS_2) showed maximum compressive strength (591 MPa) and enhanced hardness (200.7 HV). The reinforcements displayed a uniform dispersion and good interfacial bonding in the micrographs of SEM, although minimal wetting issues with ZrO_2. XRD identified the maintenance of the α-Al phase with supplementary peaks due to ZrO_2 and Ti-6Al-4V based compounds. Wear tests demonstrated that Sample 5, despite realizing a maximum COF value (0.43), exhibiting a minimum wear rate (5.04 µm), and showing a synergy between friction and wear resistance. This research study is expected to help manufacturing sectors in aerospace and researchers specialized in this field of interest.

Keywords: Aluminum Matrix Composite, Stir Casting, hybrid composite, ZrO_2, Ti-6Al-4V, MoS_2, mechanical properties, wear resistance

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Composite materials are engineered systems combining multiple materials to create light-weight, high-performance structures, with their structural integrity analyzed through advanced multi-scale and multi-physics modeling for applications in large-scale engineering designs (Soutis & Moreira, 2020;Chen et al., 2021; Simões, 2024). Composite materials blend properties from their individual components, tailored to meet specific geometric, structural, mechanical, chemical, or aesthetic needs for applications in construction, automotive, aerospace, naval, and biomedical fields (Beaumont, 2020;Egbo, 2021;Oliveira et al., 2025). Composites are used extensively in various parts of aircraft, including airframes, engine parts, and landing gear, with the Boeing 787 using extensive amounts of composite materials to reduce weight and enhance fuel efficiency(Parveez et al., 2022;Rafi, 2024;Ramakrishnan, 2024). Metal matrix composites (MMCs) are vital materials across various industries due to their exceptional properties, including high strength-to-weight ratios and corrosion resistance (Zhou et al., 2024;Sarmah & Gupta, 2024). aluminum, magnesium, and copper are among the most widely used metals in metal matrix composites (MMCs) (Vardhan et al., 2023). Composite materials are improving today's engineering with nature-inspired hybrid designs by combining distinctive elements, increasing their robustness and lifespan, and their durability is tracked by smart technology (Ince et al., 2023; Mengesha, 2025).

1.1.1 Aluminum metal matrix composites

Aluminum metal matrix composites (AMMCs) perform across industries, including aerospace for lightweight strength, in automotive for vehicle performance enhancement and durability, in marine for its ability to endure rigorous corrosion, in sport goods for improved safety and play, industrial machinery for high wear resistance and strength, and electronics for efficient heat dissipation (Fanani et al., 2021;Dubey, 2021;Wu & Zhang, 2024).

Al-7075 is a high-strength aluminum alloy known for its exceptional mechanical properties, including a high ultimate tensile strength and good resistance to corrosion and fatigue. The addition of reinforcements can greatly enhance Al-7075, despite its remarkable qualities. To improve the composite material's overall performance, reinforcements like fibers or nanoparticles are added (Khalid et al., 2023;R. Kumar, Sharma, et al., 2024).

The most frequently used reinforcements in Al 7075 metal matrix composites (MMCs) include Silicon Carbide (SiC), Alumina (Al2O3), Boron Carbide (B4C), Titanium Carbide (TiC), and Titanium Dioxide (TiO2). These materials are chosen for their hardness and strength, which significantly enhance the properties of the base alloy. In AMCs, the reinforcements are incorporated by either the solid or liquid metallurgy route (Shen et al., 2014;Sattar et al., 2025).

1.1.2 Manufacturing methods of Aluminum metal matrix composites

For strengthening, aluminum is blended with reinforcement to form Aluminum Metal Matrix Composites (AMMCs) (B. Singh et al., 2023). The squeeze infiltration method is employed to cast molten metal into a mold. Although spray deposition is expensive and unstable, it sprays droplets for a fine structure. The Physical Vapour Deposition (PVD) coats precisely, but it's a slow process. The In-Situ Method uses a chemical reaction for even blending of reinforcements. The diffusion bonding produces novel designs by joining of layers. Though AMMCs have great potential, issues relating to cost and recycling are still aspects that require attention (Senthil et al., 2020;Adesoji Adediran et al., 2022;Akhil et al., 2023). Al7075 metal matrix composites (MMCs) are mostly made via liquid metallurgy processes, of which stir casting is the most common. This method allows for the incorporation of various reinforcements, enhancing the mechanical properties of the aluminum matrix (Chellam et al., 2022;N. Kumar et al., 2023;Seshappa et al., 2024).

Stir casting is a simple, cost-effective method for producing particle-reinforced MMCs. widely adopted liquid metallurgy technique, fabricates Al metal matrix composites by blending particulate reinforcements into molten aluminum, followed by solidification in a mold. The process begins by heating Al above its melting point, then gradually introducing Reinforcements usually include ceramic powders that are mixed evenly using mechanical stirring, even though challenges come from poor wettability and settling of particle due to differences in density. Stirrer speed becomes important during the mixing of reinforcement particles with molten aluminum. Faster stirring develops a vortex that distributes particles uniformly for optimal bonding with the metal. High-speed or ultrasonic stirrers assist in achieving this uniform mix(Adat et al., 2015;K. Zhang et al., 2020;Mussatto et al., 2021;Sankhla & Patel, 2022;Y.

Wang & Monetta, 2023). Stirring time is critical; too short causes uneven clumping, but too long distorts the stirrer blade. The right time provides even distribution. A steady pour at a sufficiently high temperature, along with the correct particle size and mold configuration, prevents gas bubbles and ensures a high-quality casting (Kumar Sharma et al., 2020).

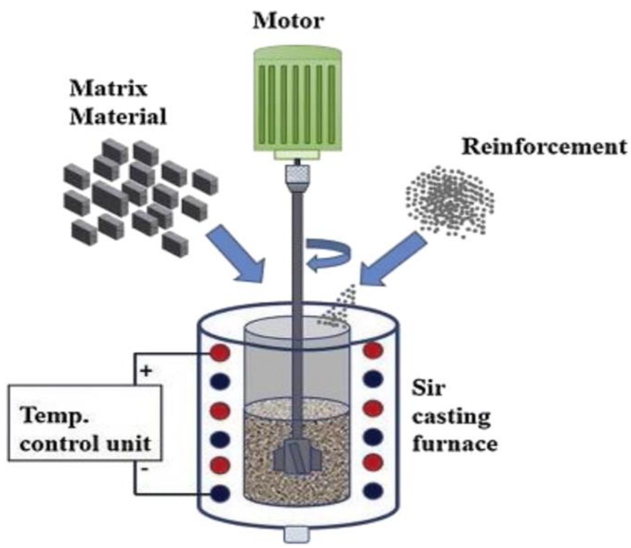


Figure 1-1 A schematic diagram of a stir casting setup (Akinwamide et al., 2020).

1.1.3 Application areas of Aluminum metal matrix composites

Aluminum metal matrix composites (AMMCs) are highly valued across various sectors, including aerospace, automotive, military, and thermal management, due to their remarkable blend of strength and lightness, excellent resistance to corrosion and wear, and outstanding thermal and electrical conductivity. Their lightweight properties help reduce fuel consumption and emissions in transportation, making them ideal for use in brake discs, car pistons, and aircraft components (Yolcular Karaoglu et al., 2021;S. K. Sharma, Gajević, et al., 2024). Beyond aerospace and automotive, AMMCs are utilized in numerous industrial fields because of their impressive durability, impact resistance, and ability to withstand temperature fluctuations. These attributes make them suitable for diverse applications, such as specialized machinery and structural components. Furthermore, AMMCs hold significant potential in the medical field, where strong yet lightweight materials are essential for healthcare equipment and devices (Srivyas & Charoo, 2018;Thakur et al., 2021; Rameshkumar et al., 2025)

1.2 Problem Statement

Contemporary engineering applications necessitate materials that are stronger, lighter, and less expensive, and conventional engineering materials are being replaced by composite materials, particularly metal matrix composites (MMCs), widely used in many industrial applications, including automotive and aerospace applications. Especially, the wings of an airplane are subjected to high wear and corrosion rates. Aluminum alloy is one of the most versatile and highly demanded engineering materials for various applications, including aerospace, automotive, and several others. It is highly valued for its high strength-to-weight ratio, corrosion resistance, and machinability, which makes it a popular choice for structural use in the aerospace industry. One approach to improve the performance of Al7075 can be strengthened is through reinforcement by using the combination of metallic and ceramic particles to form metal matrix composites (MMCs). Zirconium dioxide (ZrO_2) is one such chemical compound, which is extremely hard, heat-resistant, and chemically inert and is best suited to be employed to reinforce aluminum composite toughness and stability (Al Zubaidi et al., 2023). Ti-6Al-4V provides higher toughness and metallurgical compatibility, while molybdenum disulfide (MoS_2) is used as a solid lubricant (Dolev et al., 2021). In spite of the advantages that these reinforcements can bring, one of the major challenges is to ensure uniform dispersion and good interfacial bonding, particularly when using liquid-phase processes such as stir casting. Agglomeration, porosity, and low bond strengths can all be problems that undermine the hoped-for gains in mechanical and tribological properties. Therefore, this study aims to investigate the fabrication and characterization of Al7075-based hybrid composites using ZrO_2, Ti–6Al–4V, and MoS_2 reinforcements is necessary to overcome existing material limitations and meet the demands of high-stress aerospace applications.

1.3 Objectives of the study

1.3.1 General Objective

- The general objective of this research is to experimentally investigate the mechanical and tribological behavior of Aluminum 7075 alloy reinforced with ZrO_2, Ti-6Al-4V and MoS_2 particles through stir casting process.

1.3.2 Specific Objectives

1. To develop Aluminum based Reinforced Metal Matrix Composites composite at varied weight percentage of reinforcement via stir casting method.
2. To measure theoretical and actual density and also porosity of developed composite
3. To study phase, uniformity of grains and micro structural analysis of developed samples with characterization techniques (SEM, XRD and OM).
4. To investigate physical property (density, porosity), mechanical properties (hardness and compressive strength) of developed samples.
5. To investigate the wear resistance of developed samples at specified load, speed and sliding distances.

1.4 Significance of the Study

Al7075-based composites are increasingly recognized in the aerospace and automotive industries due to their greater strength-to-weight ratio and corrosion resistance. However, certain limitations, such as lower wear resistance and thermal instability, restrict their extensive application. In this work, a novel hybrid metal matrix composite system is introduced by incorporating ZrO_2, Ti-6Al-4V, and MoS_2 to enhance its mechanical and tribological behavior via a low-cost stir casting route. The study advances the development of hybrid metal matrix composites and acts as a foundational reference for future study, making it academically significant. Practically, it promotes material innovation for local and international industries that require lightweight and strong materials for high-stress applications. It is also beneficial to future researchers by offering information that can inform material selection, design enhancement, and cost-effective production processes.

1.5 Scope of the Study

The present research study mainly focuses on the detailed development and characterizations of the mechanical and tribological properties of Al7075-based metal matrix composites reinforced with ZrO2, Ti-6Al-4V and MoS_2 particle. Besides that, study examines Al7075 composite fabrication techniques with variable weight compositions of ZrO_2, Ti–6Al–4V and MoS_2 and thereby tries to provide insight into how such variable composition alters base metal properties. It represents the complete characterization, which gives proper description of the exact distribution of the reinforcement particles along with different phases of the material that may evolve in the structure of the composite. The mechanical, tribological, and corrosion test series is done in a very systematic manner to evaluate the overall performance and diversified properties of the composite material containing different reinforcement compositions.

1.6 Organization of the thesis

The research paper contains five chapters, and each chapter's meanings are explained as follows. The introduction chapter is chapter one of the study. It contains a background of Study Statement of Problem, objectives, scope of the research, organization of the report, and limitation of the work The second chapter discussed various works of literature done by various writers that Highlighting study of metal matrix composite material The third chapter is concerned with materials and methods employed to achieve this thesis work. This The section includes Matrix and reinforcement materials, Fabrication Equipment, Testing equipment, Composition preparation for fabrication of composites, process of composition fabrication method, and other such sections. The experimental findings of mechanical, microstructure and tribological properties of specimens of Al7075+ZrO_2+ Ti–6Al–4V +MoS_2 composite have been discussed and discussed in Chapter four finally Chapter five contains conclusion of experimental results and suggestions for Upcoming works

1.7 Limitation of the study

The following is a list of the limitations encountered during sample production for this study: The materials' accessibility and lab organizations' readiness to cooperate. The effectiveness and accessibility of the equipment and facilities utilized to carry out the test and experiment. Additionally, the installation of the equipment for the particular task and the need for experienced labor.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Composite materials comprise a blend of substances combined to attain distinct structural properties that beyond those of the individual materials(Gebrehiwet et al., 2023;Rawat & Saxena, 2019). Composite materials are advanced structures formed by combining different materials, resulting in properties like lightness, durability, and high performance. They are increasingly important in engineering, with applications ranging from airframes to medical implants, continuously expanding their uses through ongoing research (Arif et al., 2017; Yılmaz & Emre, 2024;X. Huang et al., 2023;Khan et al., 2024).

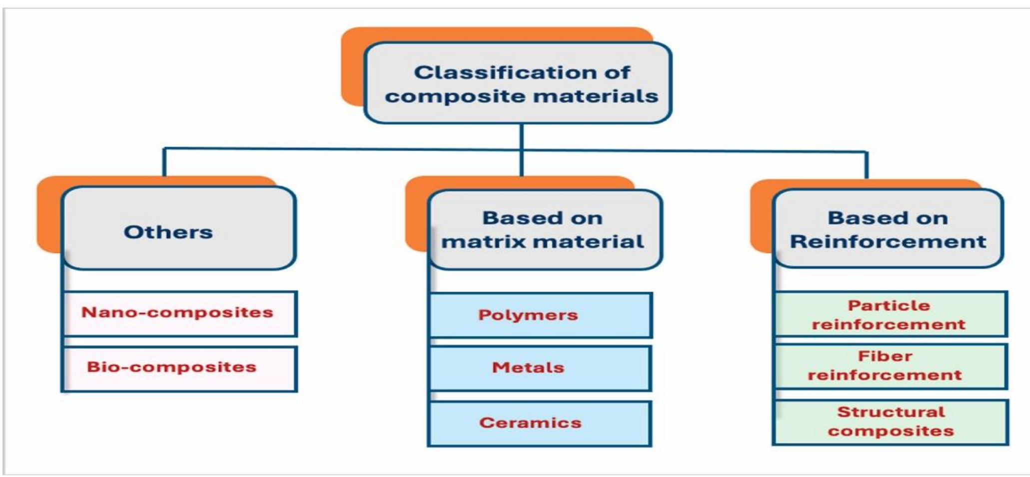


Figure 2-1 Composite material classification (Phiri et al., 2024)

Metal matrix composites (MMCs) are advanced materials combining metals with reinforcing particles. The literature was reviewed to study reinforcement materials, fabrication methods such as stir casting, powder metallurgy, and squeeze casting, process parameters, characterization techniques, and the mechanical and tribological properties of metal matrix composites (Geng & Wu, 2018;Ashebir et al., 2022;Gnanaraj & Prabhu, 2022).

2.2 Metal Matrix Composites

Metal matrix composites (MMCs) are engineered materials consisting of a metallic matrix (e.g., Al, Mg, Ti, Cu) reinforced with a secondary phase such as fibers, particles, or whiskers for achieving enhanced different properties (Sarmah & Gupta, 2024;Baliarsingh et al., 2024).The objective is to increase the metal's strength, stiffness, wear resistance, and thermal stability while maintaining its ductility. In fact, as recent reports reveal, in comparison to unreinforced alloys, MMCs have a lower coefficient of thermal expansion, improved wear and abrasion resistance, lower density, and an improved strength-to-weight ratio. As (Pooja et al., 2025; Alem et al., 2025;S. K. Sharma, Saxena, et al., 2024) showed, MMCs "provide superior tensile strength, stiffness, wear resistance, yield strength, thermal stability, and low density," thereby rendering them promising to be used in electronic, automotive, and aerospace applications. The proper use of reinforcement and processing allows such light metals to exhibit much greater Young's moduli and tensile strength in comparison with the parent metal (Srivastava et al., 2018;Kishawy & Hosseini, 2019;Rohatgi et al., 2013) . Research conducted by (Sarmah & Gupta, 2024b) has also indicated that MMCs find application in critical areas owing to their improved strength-to-weight ratio while being resistant to corrosion and wear.

2.2.1 Reinforcements in Metal Matrix Composite

Metal matrix composites (MMCs) are categorized according to the nature and type of their reinforcements, largely into continuous fibers, short fibers (whiskers), and particulates (Gill et al., 2022;Rathod & Menghani, 2019). Continuous fiber reinforcements give excellent strength and stiffness in the direction of the fiber axis and are used in highly sophisticated aerospace applications to provide improved multidirectional load-carrying (P. Yadav etal.,2021). Short fibers and whiskers offer moderate improvement in properties and are more isotropic in nature than continuous fibers(Doorbar & Kyle-Henney, 2018;Belliveau et al., 2023;Pheysey et al., 2024). Particulate-reinforced metal matrix composites (MMCs) find extensive applications due to the relatively ease of fabrication, affordability, and enhancement in hardness, wear resistance, and dimensional stability (Cai & Jin, 2018;M. Wang et al., 2024). Silicon carbide (SiC), alumina (Al_2O_3), boron carbide (B_4C), and zirconia (ZrO_2) are some of the ceramic particulate reinforcements used (Neuman et al., 2017). Metallic reinforcements such as tungsten, molybdenum, and titanium alloys are being developed for applications needing toughness and thermal stability (Abdullah et al., 2024). Besides, the incorporation of nanoscale reinforcements like graphene, carbon nanotubes (CNTs), and nano silica has been identified as possessing great potential to enhance the strength, stiffness, and wear characteristics of aluminum-based metal matrix composites (MMCs) (Baig et al., 2018;Dr. K. Fazlur Rahman & Praveen B.M, 2024)

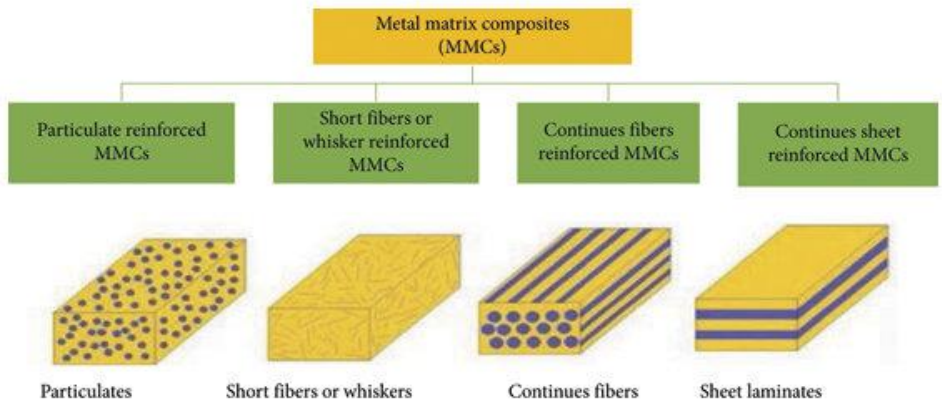


Figure 2-2 Classification of Metal Matrix Composite (Simsir et al., 2020)

2.3 Aluminum Metal Matrix Composite

When lightweight, high stiffness and moderate strength are required properties, aluminum metal matrix composites are a class of materials that have successfully met the majority of the exact specifications. AMMCs have a significant amount of potential for the creation of composites with the required qualities for specific applications due to their versatility in primary processing and range of reinforcement materials (Nturanabo et al., 2020;Krishnan, 2022).Because of their exceptional heat conductivity and low weight, aluminum alloys are a popular technical application used in a variety of industries, including the automotive, aerospace, and mineral processing industries. These composites have enhanced properties for high-temperature applications when reinforced with the inclusion of ceramic particles. When ceramic particles are added for reinforcement, these composites are more suited for applications requiring high temperatures (Thakur et al., 2021). The 6000 series of aluminum alloys is one of the series that can be heated. The alloys Al6060, Al6061, Al6063A, Al6065, Al6081, Al6082, Al6105, Al6162, and Al6951 have all been extensively studied; of these, Al6061 alloy is highly corrosion resistant, has a respectable strength, and finds extensive use in the automotive and construction industries. Aluminum alloys 7075 are preferred in the automotive and aerospace industries due to their superior strength and toughness. Generally aluminum alloys and MMCs are extensive usage due to their increased strength, stiffness, wear resistance, fracture toughness (L. et al., 2012;Saikrupa et al., 2021;Alawady, 2024). The primary disadvantages of aluminum matrix metal matrix composites (AMMCs) include particle dispersion, wettability, and chemical reactions between the reinforcement and the matrix. These parameters significantly affect the mechanical, tribological, and corrosion properties of the produced metal matrix composites. Therefore, in order to create AMMCs that are suited to a certain application, the drawbacks must be addressed by optimizing the process parameters(Suthar & Patel, 2018;V. M. Kumar & Venkatesh, 2019;Sambathkumar et al., 2023)

2.3.1 Reinforcements in Aluminum Metal Matrix Composite

Researchers have extensively studied aluminum metal matrix composites (AMMCs) due to their mechanical and tribological properties when reinforced with various materials. The properties of AMMCs are significantly influenced by the reinforcement material type, size, distribution, and volume fraction. Depending on their characteristics and operational functions, the reinforcement of AMMCs has been generally classified as ceramic reinforcers, metallic reinforcers, solid lubricants, and their hybrid combinations. The following sections analyze each reinforcement type and its effect on the properties of Al7075-based composites.

2.3.1.1 Ceramic reinforced composites

A review of several studies on aluminum matrix composites (AMCs) has been studied in this paper, with a focus on the wear behaviors and mechanical properties of aluminum alloys such as Al7075 when reinforced with materials like fly ash, silicon carbide, and rice husk ash (Yadav et al., 2018;Kamboj, 2017). The researchers have discovered that adding these reinforcements can improve properties like ductility, hardness, and tensile strength, though the effects can vary depending on factors like particle size and weight fraction (Chelladurai et al., 2021), for example, larger fly ash particles can increase ductility, while increasing their weight fraction might decrease it. The studies also emphasize the significance of the manufacturing process, with methods like stir casting being essential to achieving a uniform distribution of reinforcements, which ultimately improves material performance. Overall, the results indicate that the mechanical properties of aluminum composites can be greatly enhanced by careful selection of reinforcement materials and processing techniques, increasing their suitability for a range of engineering applications (P. Kumar et al., 2020;Koria et al., 2023;R. Kumar, Bairwa, et al., 2024;Narendran et al., 2024). Al7075 nanocomposite was synthesized incorporating 40 nm nano zirconium oxide powders (0, 0.8, 1.6, and 2.4) wt% Al 7075 alloy reinforced with the stir-casting process. The influence of ZrO_2 NP loading on mechanical behavior and full characterization was demonstrated. Al performance with ZrO_2 nanocomposite was analyzed using a Vickers hardness tester, and scanning electron microscope, energy-dispersive X-ray, compression test, Lee's disc, and Shore D equipment to determine hardness, structure, composition, Young's modulus, and thermal conductivity. Hardness (120.3–177) HV, compression strength (624.2–878.6) MPa, yield modulus (38–70 MPa), surface roughness (0.876–0.606) µm, and thermal conductivity (2.0–2.39) W/m² °C enhanced by increasing ZrO_2 NP reinforcement wt%. The results indicate 5 wt% nano-ZrO_2. Al 7075 reinforced composites exhibited better performance than pure Al 7075 alloy. In summary, ZrO_2 reinforcement enhanced the mechanical Al 7075 properties (Gunasekaran et al., 2020;Pul, 2021;J. Zhang et al., 2023;Sudhagar et al., 2024;Abdelhady et al., 2024). Recently, synthesis has been done to improve mechanical properties of B4C- and BN-reinforced Al7075 hybrid composites. Previous works on the mechanical properties have reported the increased hardness, tensile strength, and corrosion resistance of the aluminum alloy due to ceramic reinforcement with boron carbide and boron nitride for automotive and marine application purposes. Stir casting is a widely used technique for the fabrication of these composites because of its simplicity and flexibility. The uniform distribution of reinforcement particles significantly improves the material's mechanical properties; the greater reinforcement content imparts superior hardness and strength (Patil et al., 2020;Ramadoss et al., 2020;Silambarasan B et al., 2023;Çanakçı et al., 2024).

2.3.1.2 Hybrid Reinforced Composites

Recently, a number of investigations reported improvement in mechanical and tribological properties of aluminum alloys by reinforcing with ceramic particles and solid lubricants as hybrid composites (Dubey, 2021). Fabrication of AMCs using friction stir processing to improve wear and corrosion resistance is investigated(Eivani et al., 2021). The mechanical and tribological characteristics of Al 7075 was examined by hybrid composites reinforced with Molybdenum Disulfide, Zirconia and Nickel. Stir casting was used to create the composites, and X-ray diffraction (XRD), energy dispersive spectroscopy (EDS), and scanning electron microscopy (SEM) were used to examine their microstructure(Singh Rathaur et al., 2019;Sabbar et al., 2021). Al 7075's elemental composition was verified to be consistent with the ASM

Handbook. The base material's microhardness was evaluated at 87 HV, and the composites showed notable increases in this value (173 HV, 179 HV, and 206 HV for the first, second, and third variants, respectively). The dry sliding wear test resulted a significant drop-in wear rate of 59.94%, due to the added reinforcements, and no intermetallic compound were produced. The study concluded that adding of these reinforcements improved hardness and wear resistanc (D.K.Sharma et al., 2019;Ranjan&Shanmugasundaram, 2019;Prashanth Reddy & Raju, 2020;V. Sharma et al., 2023). Reinforcing of these composites was done using MoS_2 and CeO_2 with speed and passes acting as key factors. The test results indicated improved distribution of particles, grain refinement, and increase in hardness due to FSP at lower speeds or after multiple passes(Gaurang & Student, 2015). Hybrid composites have improved wear resistance due to the self-lubrication effect of MoS_2 and improved corrosion resistance owing to CeO_2 (Adiga et al., 2022). However, at high processing speeds, poor particle distribution and corrosion take place. (Maji et al., 2021) suggests that the combination of MoS_2 and CeO_2 forms a synergy that enhances the wear and corrosion resistance remarkably, hence making these composites suitable for extreme structural applications. Recent development in composites has proven the addition of ceramic reinforcements like Al_2O_3 and mica, improving the mechanical properties of Al7075(Baradeswaran & Elaya Perumal, 2014). Tests have shown that such hybrid composites outperform the unreinforced aluminum alloys in many respects, such as hardness, wear resistance, and tensile strength (Johnson & Raja, 2020). The stir casting method has been used to ensure uniform dispersion of reinforcement particles, which is highly critical for the optimization of performance. The presence of mica further helps in improving the tribological properties, and when combined with Al2O3, it produces less frictional force and wear rate. These composites could be useful in aerospace and automotive applications (Erappa Rajj et al., 2024;kishore et al., 2021). Hybrid metal matrix composite materials have been of focal importance in material science lately owing to their superior mechanical and wear properties(Pooja et al., 2025). Wear behavior of AA7075 aluminum alloy reinforced with SiC and MoS2 by the stir casting method was discussed by this study, which investigated the wear behavior of SiC weight percentages of 3, 6, and 9% while MoS2 content was held constant at 1%. The results showed that the increase in SiC content significantly improved the hardness and tensile strength of the hybrids; it also indicated that the composite containing 9% SiC and 1% MoS2 was the best among them(Kumaraswamy et al., 2021;Bharathi & Sampath kumar, 2023;Arun et al., 2024; Suresh et al., 2018). On similar lines, wear resistance was improved with the increase in SiC content, while the presence of MoS2 made friction reduction possible, and hence the hybrid composite was suitable for those applications where the requirement was for strength and wear resistance. The result of this research work therefore brings to the for the need for optimization of reinforcement materials in the interest of improving wear properties in aluminum matrix composites for applications (Karthikraja et al., 2023;Balaji et al., 2024;Umanath et al., 2020). Among these metal matrix composites, the ceramic particle-reinforced aluminum-based MMCs with solid lubricants such as alumina (Al2O3) and molybdenum disulfide (MoS2) have exhibited tremendous improvement in mechanical and tribological properties, making them fit for aerospace as well as automotive applications. The work carried out by (Saritha et al., 2018) relates to the mechanical and wear behavior of the Al7075 alloy reinforced with varying wt% of Al2O3 (4, 8, and 12%) and MoS2 (2, 4, and 6%). The stir casting method was used to fabricate the hybrid composites, while testing showed that alumina increased hardness and tensile strength in the base material; MoS_2 provided improved wear resistance with its self-lubricating effect. On the other hand, higher MoS_2 content led to higher porosity, slightly lessening the composite's hardness. All the above findings have established the possible use of Al7075-Al_2O_3-MoS_2 hybrid composites in applications involving high strength and wear resistance. It also shows that balancing reinforcement ratios is necessary in an effort to optimize mechanical performance and minimize porosity(Ramanan et al., 2019;Yehia et al., 2023;Pandey et al., 2024).

2.3.1.3 Solid Lubricant Reinforced Composites

The solid lubricants such as molybdenum disulfide (MoS_2) reinforced in AMC have huge potential for improvement in mechanical and tribological characteristics. The influence of MoS_2 reinforcement on mechanical properties of Al7075 hybrid composite fabricated by a powder metallurgy process has been studied(Rajesh kumar et al., 2020;Ajay Kumar & Mallikarjuna, 2022). The present study details the addition of various weight percents (2%, 4%, 6%, and 8%) of MoS_2 and their influences on hardness, tensile strength, compressive strength, and wear behaviors. With the increase in MoS_2 content, an increase in wear resistance and a decrease in coefficient of friction were observed, attributed to the solid lubricant characteristics of MoS_2. However, the study also recorded that porosity in composites was due to the sulfide gas given off during sintering, hence disturbing the microstructure of the composites(Vazirisereshk et al., 2019;Devaganesh et al., 2020). This study therefore points out the possibility of MoS_2-reinforced Al7075 composites that depict high wear resistance and improvement in the mechanical properties for performance applications (Prabhu Deva et al., 2024).

2.3.1.4 Metallic Reinforced Composites

(Nath OP & Arul, 2020) investigated the effects of the addition of various percentages (1, 5, 10, and 15%) of NiCp as reinforcement in Al7075 alloy on hardness and wear resistance. This paper presents the results obtained by stir casting and subsequent T6 heat treatment, showing that the addition of NiCp increased the micro-hardness and enhanced the wear resistance of the alloy. For example, the hardness and wear resistance of Al7075 alloy with the addition of 15% NiCp have been improved by 146% and 93%, respectively, compared to the base alloy. The improvement in wear resistance is due to the formation of the intermetallic compounds Al3Ni, which was confirmed by FE SEM and XRD analysis. The study also pointed out that the wear rate increases with an increase in load and decreases with an increase in sliding velocity due to the formation of a protective oxide layer (D. M. Shinde et al., 2020;Ashebir et al., 2022).

2.3.2 Fabrication Techniques and Associated Challenges in Hybrid AMMCs

Many fabrication techniques, including centrifugal casting and squeeze casting, have been conducted and compared with stir casting, which has turned out to be effective in achieving uniform distribution within the matrix (Bhowmik, Kumar, et al., 2024). (Raghuvaran et al., 2021) was done based on previous studies by changing the weight percentage of SiC in Al7075 and exploring its mechanical properties, which included tensile strength, hardness, and wear resistance. From this, results have agreed with the literature review those mechanical properties improved with SiC reinforcement up to 6% and declined thereafter. (Rao, 2021) reviews the work on the application of nano-sized SiC particles for the reinforcement of Al7075 alloy. The study explained that ultrasonic cavitation during the stir casting process enhanced the dispersion of SiC particles, enabling it to attain improved mechanical properties and wear resistance (Idrisi & Mourad, 2019). Addition of 2.0 wt.% SiC resulted in an improvement in yield strength by 94.52% along with enhanced in wear resistance by 79.8%, compared to the base alloy. Detailed strengthening mechanisms, including thermal mismatch, Orowan strengthening, and grain refinement, were considered in an attempt to explain such improvements (X. J. Wang et al., 2014;Maddaiah et al., 2024). Fabrication of AMCs using friction stir processing to improve wear and corrosion resistance is investigated. Reinforcing of these composites was done using MoS2 and CeO2 with speed and passes acting as key factors (D. K. Sharma et al., 2019). The test results indicated improved distribution of particles, grain refinement, and increase in hardness due to FSP at lower speeds or after multiple passes. Hybrid composites have improved wear resistance due to the self-lubrication effect of MoS2 and improved corrosion resistance owing to CeO2 (L. Zhang et al., 2025). However, at high processing speeds, poor particle distribution and corrosion take place. The literature suggests that the combination of MoS2 and CeO2 forms a synergy that enhances the wear and corrosion resistance remarkably, hence making these composites suitable for extreme structural applications (Maji et al., 2021). (Gajakosh et al., 2021) outlines the role of reinforcement with TiO_2 and Gr on mechanical properties of Al7075 alloy. In the present work, the fabrication and enhancement of the composites were carried out by stir-casting followed by hot-rolling at 450°C to a thickness reduction of 90%. Microstructural examination showed that the introduction of both TiO_2 and Gr particles induced uniform dispersion and improved the bonding among grains in the hot-rolled samples, thus enhancing their hardness and tensile properties. Due to hot rolling, the structural defects and grain size were significantly refined, which resulted in superior mechanical properties, such as better ultimate tensile strength and microhardness, compared with the as-cast composites for hot-rolled samples. This study concludes that reinforcement with TiO_2 and Gr has significantly improved the strength and wear resistance of Al7075 for aerospace and automotive applications(Jamaati et al., 2011;Iyengar et al., 2021;S. Sharma et al., 2024). Integration of diverse materials is required for the fabrication of light weight structures from metal alloys, polymers, or composites, which will reduce CO2 emissions in transportation (Jang et al., 2023). Differences in properties hinder the assembly of these materials in multi-material structures. The primary issue in the stir casting process is the uniform distribution of reinforcing particles. Considering its flexibility, affordability, and suitability for mass production, stir casting is a good technique for composite fabrication and the industrial fabrication of AMCs and HAMCs (Rangrej et al., 2021). The distribution of reinforcing particles in the finished composite controls the expected characteristics of AMCs and HAMCs. However, the parameters of the stirring process control the dispersion of reinforcements (Ali, 2020). For the constantly expanding businesses and research, determining the best way to choose stirring parameters and their impact on particle distribution remains a difficulty (Sahu & Sahu, 2018). Two challenges in the stir casting process of producing hybrid AMMC are homogeneous particle dispersion and tool wear during machining. Efforts are focused on using high-quality materials, like PCD tools, and optimizing cutting settings to increase the mechanical and surface quality of composites (Syed et al., 2022). The final composite's mechanical qualities may be seriously affected if porosity forms. In the stir casting process, porosity must be managed since it might result from incomplete mixing or gas entrapment. Researchers are experimenting with temperature and stirring rate changes as well as other methods to decrease porosity (S. S. Shinde & Barve, 2024).

2.3.3 Mechanical and Tribological Properties of Al7075-Based Composites

The mechanical and tribological behaviors of reinforced aluminum metal matrix composites have been performed by various researchers, especially on strengthening, wear resistance, and durability of the composites. Considerable attempts have been carried out in order to reinforce mechanical performances under diversified conditions by adding particles such as MoS2 in Al-based composites (Hossein-Zadeh et al., 2019). Application of Al6061 and Al 7075 aluminum alloys in the manufacture of composites due to their excellent mechanical characteristics, such as strength and resistance to corrosion in aerospace and automotive industries. The addition of reinforcements like SiC to aluminum alloys improves tensile strength, hardness, and wear resistance up to an optimum percentage of reinforcement beyond which these properties may fall (G. B. V. Kumar et al., 2010;Raghuvaran et al., 2021).

2.3.3.1 Effect of Reinforcement Combinations on Mechanical and Tribological Properties

Several works were performed to improve the mechanical and tribological properties of AMCs by the addition of different reinforcements, such as B4C, MoS2, and MWCNT. Reinforcements in AMCs enhance mechanical properties such as hardness and tensile strength, and improve tribological properties including wear resistance (R. Kumar & Mondal, 2024). The combined addition of B4C and MoS2 is found to improve the wear resistance and friction coefficient of AMC significantly, hence suitable for high-stress applications in aerospace and automotive components (Raja et al., 2021). (Abdul et al., 2023) fabricated self-lubricating hybrid composite Al7075 reinforced with MoS2 and ZrB2 via stir casting. In that work, they showed that the addition of ZrB2 enhanced the hardness and strength of Al7075, while MoS2 increased the ductility as expected from its soft, self-lubricating characteristic. Grain refinement was improved in hybrid composite, the distribution of particles was more uniform, and dislocation density was higher, hence an ideal candidate for high-performance applications in aerospace and automotive industries(S. K. Sharma, Gajević, et al., 2024). Hybrid composites produced by Al7075 alloy reinforced with SiC, red mud, and MoS2 are discussed. It investigates the effects of varied composition on mechanical properties, wear behavior, and microstructure. The study results show that 2.5 wt% each of red mud and SiC added to 10 wt% MoS2 delivers the maximum hardness and tensile strength. MoS2 with its self-lubricating properties improves the wear resistance (Gurmaita et al., 2024). On the other hand, the impact strength decreases with increasing MoS2 content, which reflects a classic hardness-ductility trade-off. From the study, it was found that appropriate reinforcement combinations improve mechanical and wear properties for possible use in automotive and aerospace applications (Xiao et al., 2017). (Siva Surya & Prasanthi, n.d.) presents the tribological behavior of Al7075/SiC composites produced by powder metallurgy. Emphasis was given to the effects brought about by variation in weight percentage of SiC (10, 15, and 20 wt%) on the wear loss and coefficient of friction for different loading conditions. Based on the Taguchi design and ANOVA analysis, the study concluded that the composites with 15% SiC exhibit optimum tribological properties, including minimum wear loss and friction. The wear mechanisms developed were predominantly those of abrasion and delamination, which were found to be dependent on SiC content and sliding conditions. The correlation of multiple parameters, valuable data has been obtained for those industrial sectors like automotive and aerospace where wear resistance and strength are inalienable features (Mahdavi & Akhlaghi, 2011;Bhowmik, Sen, et al., 2024). Various studies have reported a significant improvement in mechanical and tribological characteristics after the addition of reinforcement materials like SiC and MoS2 to the hybrid metal matrix composite material (Kuppusamy et al., 2024). (Maruthi Varun & Raman Goud, 2019) studied the mechanical characteristics of Al7075 composites containing different weight percentages of SiC, while maintaining a constant weight percentage of MoS2. They reported that the increase in weight percentage for SiC led to improved tensile strength and hardness. Their findings also reveal how hybrid composites can replace traditional material use in very technical applications, such as in automotive and aerospace engineering. (Jayakumar et al., 2023) Processing of AMMCs prepared by Al7075 alloy reinforced with different weight percentages of titanium carbide particulates. The composites, fabricated by a stir-casting method, are investigated for their microstructural and mechanical properties with reinforcement levels from 0% to 6% by weight. It establishes that the properties of hardness, tensile strength, and density are enhanced with the uniform dispersion of TiC particles, though at the expense of reduced ductility. Microstructural examination by SEM and XRD techniques confirms the homogeneous distribution of TiC and its effect on grain refinement. The conclusion of the study states that TiC-reinforced AMMCs have exhibited very good mechanical performance, besides catering to the increasing demands of the aerospace and automotive industries where properties of strength-to-weight ratio and wear resistance play a dominant role (Kadam & Shinde, 2020;Krishna Prasad et al., 2022;Abiodun Balogun et al., 2022). The work carried out by (Saritha et al., 2018) relates to the mechanical and wear behavior of the Al7075 alloy reinforced with varying wt% of Al2O3 (4, 8, and 12%) and MoS2 (2, 4, and 6%). The stir casting method was used to fabricate the hybrid composites, while testing showed that alumina increased hardness and tensile strength in the base material; MoS_2 provided improved wear resistance with its self-lubricating effect. On the other hand, higher MoS_2 content led to higher porosity, slightly lessening the composite's hardness. All the above findings have established the possible use of Al7075-Al_2O_3-MoS_2 hybrid composites in applications involving high strength and wear resistance. It also shows that balancing reinforcement ratios is necessary in an effort to optimize mechanical performance and minimize porosity (Sambathkumar et al., 2021;Ravikumar et al., 2022;Lovevanshi et al., 2024).

2.3.3.2 Environmental Degradation and Durability of Al7075-Based Composites

(Niverty & Chawla, 2021) The study primarily examined the corrosion and corrosion-fatigue behavior of a dissimilar alloy joint of Ti-6Al-4V and AA 7075-T651 in a seawater environment. X-ray computed tomography at an advanced level is utilized to examine the behavior of the materials under exposure to 3.5 weight percent NaCl solution. To gain a greater understanding of the worst-case scenario of corrosion damage in this alloy pairing, the researchers monitored the progression of corrosion over time and identified certain microstructural features that contribute to the initiation of cracking. The work is important for advancing the durability and reliability of material utilized for maritime use in the aerospace environment (Baragetti, 2014;Baragetti & Arcieri, 2018). Aluminum alloys are being utilized commonly in engineering disciplines owing to their high strength at low density (Altaş et al., 2024). However, their poor resistance to corrosion and wear has largely limited their application in marine hardware. This study successfully improved the corrosion and wear resistance of a conventional 7075 Al alloy by coating with a high-performance Ti-6Al-4V titanium alloy via in-house annular laser cladding facilities. Microstructural examinations verified that the defect-free Ti–6Al–4V coating is metallurgically bonded to the 7075 Al alloy substrate together with higher bonding strength (Li et al., 2024a). The electrochemical test results showed that compared to hot-forged 7075 Al The Ti–6Al–4V coating has better corrosion resistance because of the alloy and hot-forged double-phase Ti–6Al–4V bulk alloy. its net-basket α-single-phase microstructure. The results of the wear testing also indicated that the coefficient of friction and the wear volume of Ti–6Al–4V coating is far less than that of 7075 aluminum alloy. This kind of improvement in wear resistance is closely linked to the Ti–6Al–4V coating's high hardness and good fatigue-wear resistance. Thus, this work can be used as a guide to enhance Aluminum alloys' corrosion and wear resistance through depositing Titanium alloy coatings by means of the annular laser cladding process, which will further broaden the application range of Aluminum alloys for marine hardware. (Sun et al., 2023)(Liu et al., 2024) explores such use of hydrothermal carbons derived from cellulose as an environmentally friendly reinforcement for Al7075 alloy. Fabricated by means of powder metallurgy, the present work investigates composites with different HTC contents (0.25, 0.50, and 1.00 wt%). It was found that the addition of HTC led to the enhancement of microstructure, finer grains, along with improved mechanical properties, such as hardness and ultimate compression strength (Simsir et al., 2020). The composites also show better tribological properties due to the self-lubricating effect of HTC. HTCs homogeneously distributed allowed the improvement of corrosion resistance by reducing crack propagation in the matrix. HTCS in this study hold great promise as an economic and eco-friendly carbon source alternative in conventional carbon-based reinforcements for composite materials targeting automotive and aerospace applications (Arsun et al., 2021).

2.4 Literature summery

Generally, in the literature survey, it has been found by researchers that Aluminum Metal Matrix Composites (AMMCs), specifically those based on Al7075, are widely studied for their strength, light weight, and resistance to wear and corrosion. Different researchers have reinforced Al alloys with various materials to improve their mechanical and tribological performance. Typically, ceramic particles including zirconia (ZrO_2), silicon carbide (SiC), alumina (Al_2O_3) are added into the composition in order to improve hardness and wear resistance. The addition of metallic hard phases to titanium-based alloys, and Ni leads to an increase in toughness and thermal stability, while, solid lubricants such as molybdenum disulfide (MoS_2) act as friction reducing agents and improve the wear characteristics. The recent works are mainly related to composite hybrids with two or more types of reinforcements. This approach has shown improved results, especially when combining rigid ceramics with self-lubricating materials. Stir casting is mostly used for producing these compo-sites because it is simple, cost-effective, and suitable for large-scale production. Despite the vast amount of works covering various reinforcement combinations and their influence on properties such as hardness, tensile strength, and wear resistance, there are still some aspects that are relatively unexplored. For instance, limited work has been reported on the combined effect of ZrO_2, Ti-6Al-4V, and MoS_2 on Al7075 matrices, and In general, it can be concluded that hybrid materials reinforcement of Al7075 can bring about considerable enhancements, as evidenced by available literature; however, there is a need for more investigations, especially for such a specific combination and processing route, as was the case in this study.

2.5 Research Gap

Earlier research has investigated the strengthening of Al7075 with sole ceramic particles (e.g., ZrO_2, SiC, Al_2O_3), metals (e.g., Ti-based alloys), and solid lubricants (e.g., MoS_2) to enhance the hardness and wear resistance. The majority of the works have been on single or binary strengthening phases, and relatively limited research has investigated the combined effect of ZrO_2, Ti-6Al-4V, and MoS_2 in the hybrid composite system. The available literature also lacks sufficient information on the tribology, microstructural homogeneity, and interface adhesion between such hybrid composites processed via stir casting method. This work aims to fill this gap through the fabrication and characterization of Al7075-based hybrid composites reinforced with ZrO_2, Ti-6Al-4V, and MoS_2 with particular focus on the mechanical and tribology properties for applications specific to the aerospace sector, such as the use of aircraft wing structures.

CHAPTER THREE

MATERIALS AND METHODOLOGY

3.1 Introduction

This study employed various materials and apparatus, applying specific techniques and procedural processes to conduct the experimental activity. The matrix and reinforcement materials, and the fabrication technique employed for the synthesis of Al7075 metal matrix composites (MMCs), This chapter provides a comprehensive overview of the sample preparation for mechanical and tribological tests, along with the characterization equipment employed. It also describes the parameters and criteria of the production process employed to ensure valid and reliable outputs.

3.2 Materials

The proposed research proposal work focuses on the fabrication of Al7075-based composites reinforced with ZrO_2, Ti-6Al-4V and MoS_2 particulates for enhanced mechanical properties and tribological behavior. These materials have been used in the present research: a base matrix consisting of Al7075, well-renowned for its very high strength-to-weight ratio, and reinforcements consisting ZrO_2 which is a ceramic reinforcement that would increase the hardness and wear resistance, Ti–6Al–4V also has high strength and corrosion resistance and MoS2, an additive that was added for its excellent solid lubrication characteristics, improving wear resistance in dry sliding applications. Composites will be fabricated by the stir casting method, which allows for proper distribution of the reinforcing particles in the matrix. Again, different weight fractions of ZrO_2, Ti-6Al-4V and MoS2 reinforcements will be considered to study their effects on the overall properties of the composite. During the process of preparation, the key process parameters which include stirring speed, temperature, and particle size will be controlled so as to have reliable dispersion of particles and good bonding between the matrix and reinforcements. Porosity, hardness, and density will be measured in order to characterize the mechanical properties of composites. Tribological characteristics will be measured using tests by wear under different loads, sliding distances, and velocities under a dry environment. Microstructural characterization will be performed by using Optical Microscopy to evaluate the distribution of the particles, X-Ray Diffraction for phase characterization, and Scanning Electron Microscopy to study morphology and wear patterns.

Mechanical and tribological tests will be conducted accordingly with ASTM in order to guarantee the reliability and congruence of test results obtained.

3.2.1 Aluminum Alloy

Al7075 is a type of wrought alloy that has high tensile strength, resistance to corrosion, and good heat treatment. It comprises 90.0% aluminum, 5.6% zinc, 2.5% magnesium, 1.6% copper, and 0.23% chromium. These can vary according to manufacturing processes. Having a density of 2.81 g/cm³ (0.102 lb/in³) it is considered a lightweight metal. It is considered a light metal. Its properties include low density, while the high yield strength is more than 500 MPa, making this alloy one of the strongest aluminum alloys available today, with very good suitability for applications involving high level of stress. This alloy commonly finds its application in the fields of aerospace and automotive where the parts undergo heavy loads and deterioration.

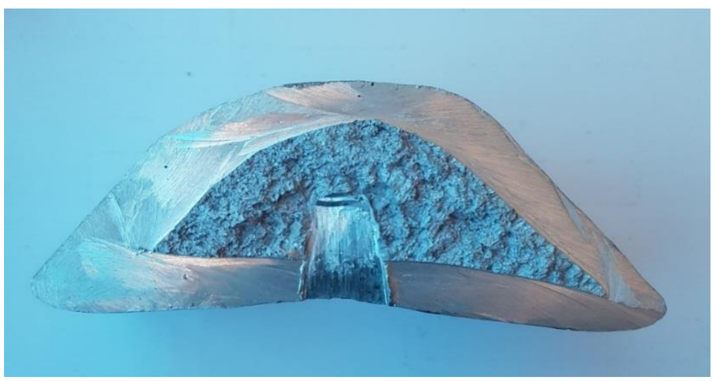


Figure 3-1 Cross-section of cast Al7075 alloy

Table 3.1 Material properties of 7075 aluminum alloy (Shobhit Agarwal & Tarun Saatyaki, 2020)

property	Metric value
Ultimate Tensile Strength	572 MPa
Tensile Yield Strength	503 MPa
Shear Strength	331 MPa
Fatigue Strength	159 MPa
Modulus of Elasticity (GPa)	70-80

Shear Modulus	26.9GPa
Density (g/cc)	2.81
Hardness (HB500)	60

3.2.2 Zirconium Dioxide

Zirconium dioxide (ZrO_2), sometimes known as zirconia. It is a white crystalline oxide of zirconium. Because of its amazing properties, such as high melting point, mechanical strength, ionic conductivity, etc., ZrO_2 is widely used as a kind of structural and functional material. At a very high temperature, around 2370°C, it is converted to the cubic structure. Stabilized forms (e.g., yttria-stabilized zirconia) are used in various applications, including dental ceramics, oxygen sensors, and thermal barrier coatings.

Figure 3-2 Zirconium Dioxide Powder

Table 3.2 Property of Zirconium Dioxide (Callister, 2020)

Property	Value/Description
Chemical formula	ZrO_2
Melting point (°C)	2715
Density g/cm^3	5.68
Hardness (Mohs scale)	8.5
Color	White
Electrical conductivity	Insulator
Thermal conductivity at 100°C(W/m-k)	2.5

3.2.3 Titanium Alloy (Ti-6Al-4V)

Ti-6Al-4V (also known as Grade 5 Titanium Alloy) is the most widely used titanium alloy, which is the best blend of strength, durability, and light weight. It provides high tensile strength, fatigue strength, and fracture toughness. Another aspect is that its thermal expansion coefficient is low and it is insusceptible to low-temperature embrittlement. It is frequently used in aerospace, biomedical implants, marine, and performance-engineered applications.

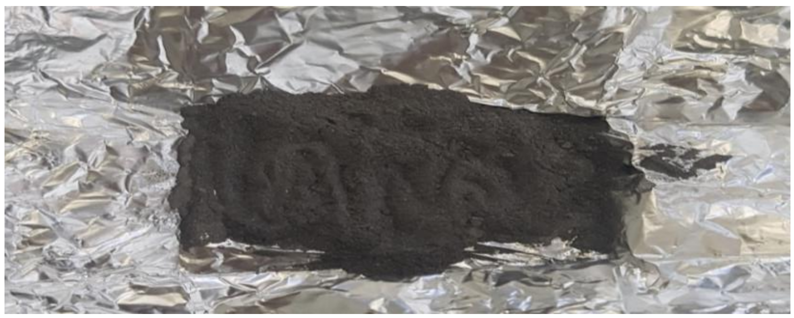


Figure 3-3 Titanium Alloy powder

Table 3.3 Material properties of the Ti-6Al-4V alloy(Marazani, n.d.)

Property	Value
Hardness (HRC)	36
Density (g/cm3)	4.42
Yield tensile strength (MPa)	870
Ultimate tensile strength (MPa)	923
Fatigue strength (MPa)	510
Modulus of elasticity (GPa)	113.8
Elongation (%)	14
Thermal Conductivity (W/ mK)	6.7
Specific Heat Capacity (J/ kgK)	560
Electrical resistivity (μΩm)	1.7

3.2.4 Molybdenum Disulfide

Molybdenum disulfide is an inorganic compound composed of molybdenum and sulfur. Its chemical formula is MoS_2. Molybdenum disulfide is used as a dry lubricant.

Figure 3-4 Molybdenum disulfide powder

Table 3.4 Property of Molybdenum disulfide (Rahmati et al., 2014)

Type	Molybdenum disulfide
Color	Lead Gray to Black
Crystal structure	Hexagonal-Layered
Density g/cm^3	5.06
Molecular weight (gr/mol)	160.06
Melting point (℃)	1185
Thermal conductivity at 300 K (W/cm-K)	0.014
Coefficient of friction	0.03-0.06
Hardness (Mohs Scale) basal plane	1-1.5

3.3Research Methodology Flow Chart

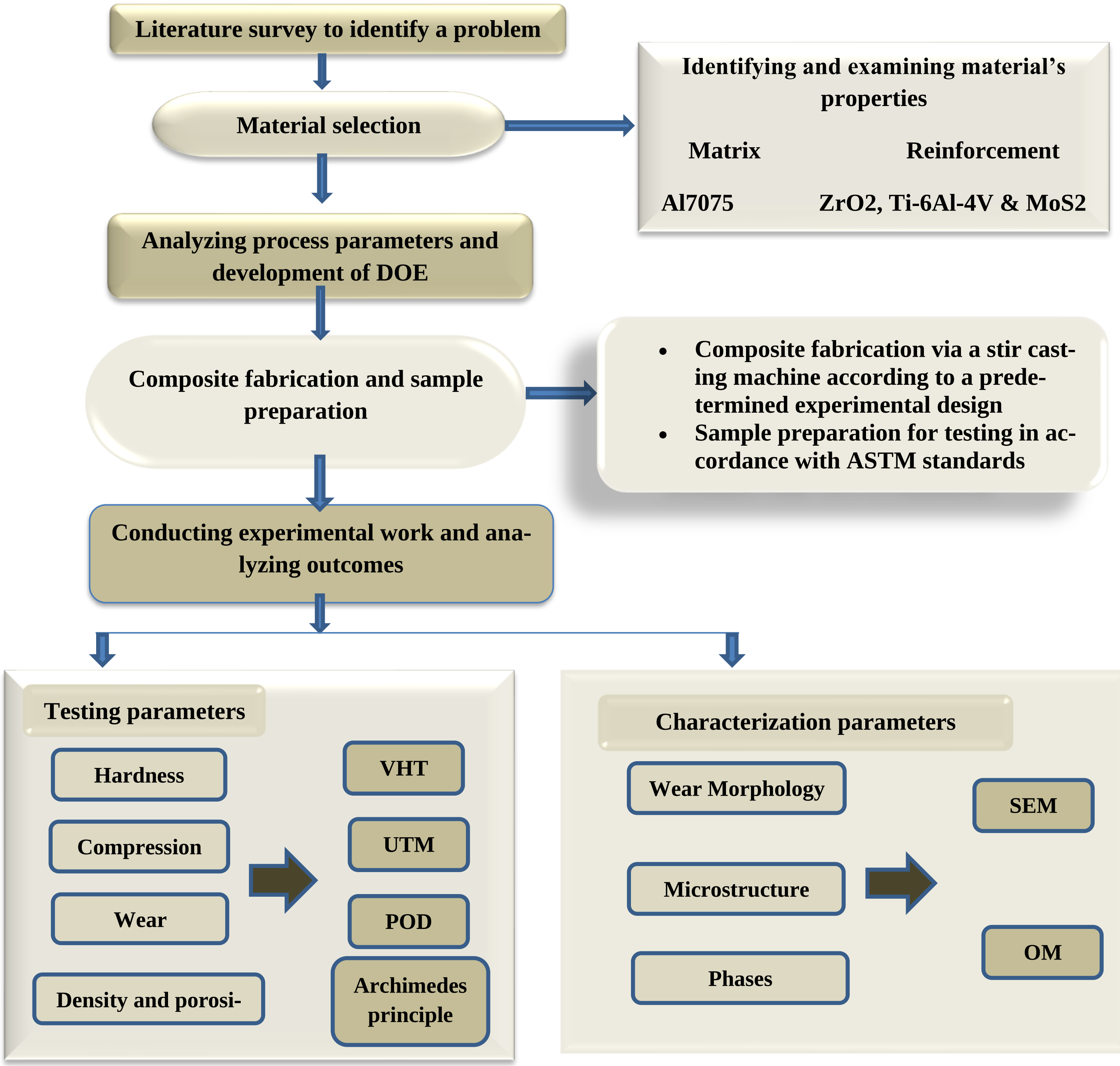


Figure 3-5 Research Methodology Flow Chart

3.3.1 Experimental Optimization of process parameters

To determine the optimal weight percentage of reinforcement and matrix combination for the fabrication of Al7075-based hybrid metal matrix composite, response surface methodology (RSM) design was employed using Minitab statistical software. The aim of the process optimization was to minimize the theoretical density of the composites, which will serve as an indicator for uniform reinforcement distribution and reduced porosity, which are critical quality attributes in metal matrix composites fabrication.

3.3.1.1 Design of experiment

The experiment design was structured using Central Composite Design (CCD) in RSM, two continuous input variables are considered:

- Factor A: Weight percentage of Zirconium Dioxide (ZrO2)
- Factor B: Weight percentage of Titanium Alloy (Ti-6Al-4V)

The Molybdenum Disulfide (MoS2) content was held constant at 2 wt% for all samples based on literature guidelines and preliminary trials, and was therefore not included as variable in the optimization model. A total of 13 experiment runs were generated using CCD scheme to evaluate the combined effect of ZrO2 and Ti-6Al-4V reinforcement levels based on the theoretical density of fabricated composites.

3.3.1.2 Response variable

The composites theoretical density for the response variable is calculated for each of 13 design points using the rule of mixtures:

$$\rho \text{ composite} = (\textstyle\sum_{n}^{i=1} wi \times \rho i) \qquad (3.1)$$

Where:

ρ composite = theoretical density of composite (g/cm^3)

wi= weight fraction of each component (Al7075, ZrO_2, Ti-6Al-4V, MoS_2)

ρi = density of each component

Table 3.5 RSM Experimental Runs and Theoretical Density values

No.	Al7075	ZrO_2	Ti-6Al-4V	MoS_2	Theoretical density
1	91.5	1.5	5.00000	2	2.81079
2	88	2.50000	7.50000	2	3.0475
3	88	5.00000	5.00000	2	3.079
4	88	5.00000	5.00000	2	3.0789
5	91.5	5.00000	1.5	2	3.02265
6	88	5.00000	5.00000	2	3.0789
7	88	5.00000	5.00000	2	3.0789
8	93	2.50000	2.50000	2	2.96699
9	83	7.50000	7.50000	2	3.191
10	84.5	8.5	5.00000	2	3.17945
11	88	7.50000	2.50000	2	3.1105
12	84.5	5.00000	8.5	2	3.13535
13	88	5.00000	5.00000	2	3.0789

3.3.1.3 Statistical Analysis of Theoretical Density Using ANOVA

The reinforcements content process parameters on theoretical density of Al7075 metal matrix composite was analyzed by Analysis of Variance (ANOVA).

Table 3.6 ANOVA results are presented obtained from Minitab Software.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	0.102894	0.020579	13.87	0.002
Linear	2	0.094515	0.047257	31.86	0.000
ZrO2	1	0.081684	0.081684	55.07	0.000
TC4	1	0.012831	0.012831	8.65	0.022
Square	2	0.008379	0.004189	2.82	0.126
ZrO2*ZrO2	1	0.006866	0.006866	4.63	0.068
Ti-6Al-4V * Ti-6Al-4V	1	0.000771	0.000771	0.52	0.494
2-Way Interaction	1	0.000000	0.000000	0.00	1.000
ZrO2* Ti-6Al-4V	1	0.000000	0.000000	0.00	1.000
Error	7	0.010383	0.001483		
Lack-of-Fit	3	0.010383	0.003461	1730510.36	0.000
Pure Error	4	0.000000	0.000000		
Total	12	0.113277			

- The regression model is highly significant at P and F values of 0.002 and 13.87, respectively, which indicates a strong relation between the input factors (ZrO2 and Ti-6Al-4V content) and the theoretical density response.

- ZrO2 (P=0.000) indicated having the strongest effect on the increase of theoretical density. Ti-6Al-4V (P=0.022) also contributes, but to a much lesser extent.
- The quadratic terms ZrO_2^2 and Ti-6Al-4V ^{2} have P values of 0.068 and 0.494, respectively, which suggests a minimum curvature effect within the chosen range of response surface, which is not statistically significant.
- The interaction term (ZrO_2 x Ti-6Al-4V) has no significant effect with a p-value of 1000, indicating independent influence of the density of the two factors without synergistic behavior. The lack of fit is highly significant (P = 0.000). However, with zero pure error, this is often due to replicates existing that share exactly the same response values (e.g., when center points are duplicated). This condition artificially increases the lack-of-fit test and is unimportant in this context.

The statistical analysis verifies that the effect of ZrO_2 content was the most predominant factor on the composite theoretical density. Although Ti-6Al-4V is also a major reinforcing phase, interaction between the two reinforcements can be ignored. The model is suitable for optimization and is useful as a good prediction environment in the design space.

3.3.1.4 Surface Plot Analysis

The 3D surface plot is shown in Figure 3-6 describes the relationship of the two primary reinforcement components (ZrO2 and Ti-6Al-4V) and the theoretical density of the developed Al7075-based composite. This visualization provides some idea of how different reinforcement combinations influence the density of the composite.

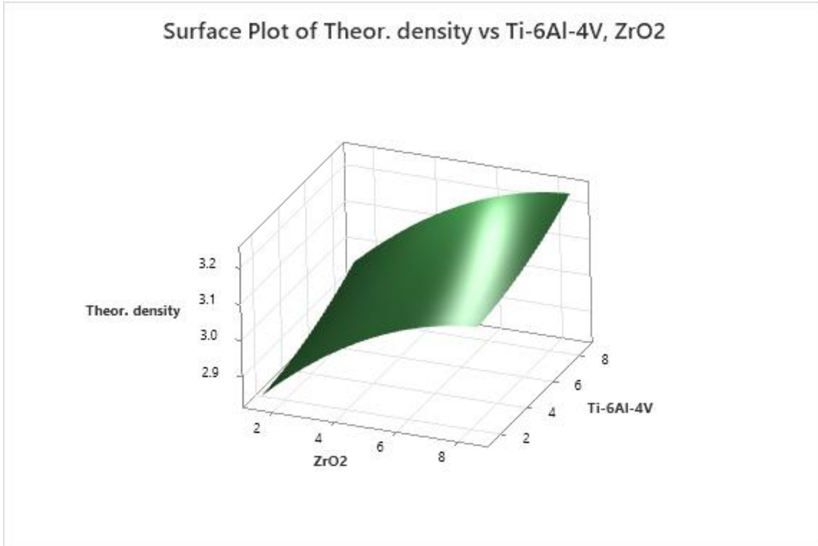


Figure 3-6 Surface plot

- The surface has positive curvature with increased values of ZrO_2 and Ti-6Al-4V indicating that the theoretical density increases with increasing weight percentages of any of the reinforcements.
- A greater increase in density is found on the axis of ZrO_2, which means its single effect is stronger than that of Ti-6Al-4V, this is consistent with the ANOVA result in which ZrO_2 had the lowest P value and highest F-ratio.
- The fact that the surface is smooth and continuous indicates that the relationship between the variables and the response is sufficiently represented by the model without any significant interaction effect as it was confirmed by the statistical analysis.
- The best density is located in the top right corner of the surface, in which the ZrO2 and Ti-6Al-4V reach the maximum values (near the ~7.5–8.5 wt. %).

In conclusion the influence of higher content of both reinforcements, particularly ZrO_2, is apparent from the surface plot, which maximizes the theoretical density in the composite system. The effective plot implies the statistical results that the individual linear terms are significantly higher than other terms, and there is less interaction between ZrO2 and Ti-6Al-4V in comparison.

3.3.1.5 Contour plot analysis

In order to visualize more clearly the influence of the amount of reinforcement (Ti-6Al-4V and ZrO_2) on theoretical density in two dimensions, a contour plot was created from the RSM model in Minitab. It gives a simple and flattened graphical representation of the interaction between the two variables and also the predicted response (theoretical density).

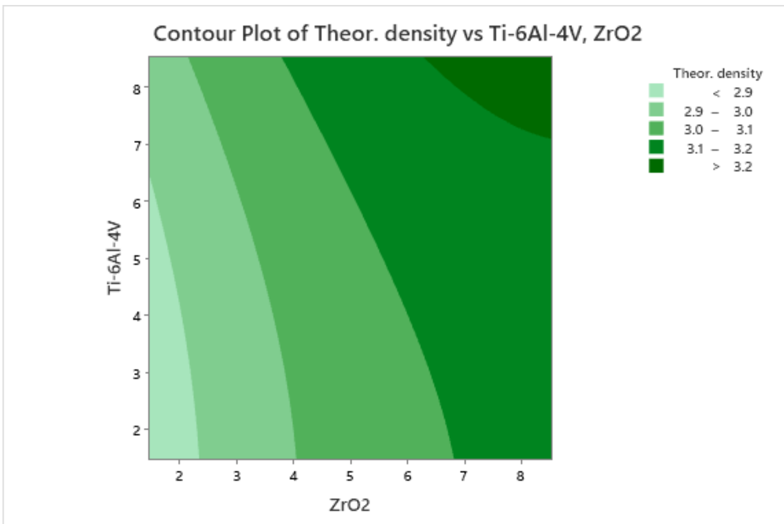


Figure 3-7 Contour plot

- The contour plot displays continuous bands of gradients corresponding to different ranges of theoretical density.
- The density rises with the increasing levels of both Ti-6Al-4V and ZrO_2, with the highest density area (> 3.2 g/cm^3) at the top right corner of the design space, where the levels of ZrO_2 are over 7% and the levels of Ti-6Al-4V are over 7%.
- The contour vertical lines suggest that the influence of ZrO_2 on theoretical density is more significant than Ti-6Al-4V. The ANOVA analysis also verifies this, as the F-value of ZrO_2 is significantly greater and the P-value is far lesser.
- Absence of curvature of the contours, which indicates minimal or no interaction between Ti-6Al-4V and ZrO_2, agrees with the result of the statistical model of an interaction term that is not statistically significant (P = 1.000).

In general, the contour plot confirms that the highest theoretical density is achieved when both reinforcements are at high levels, in this case ZrO_2. It is a useful aid for identifying probable pairs of reinforcement ratios that result in the densest and potentially most homogeneous composite.

3.3.1.6 Residual analysis

Residual analysis was used to determine residual adequacy and validity of the regression equation employed in estimating theoretical density. The residuals account for difference between actual values and values estimated by the RSM model. Four basic diagnostic plots were used to test for normality, randomness, and homoscedasticity of residuals.

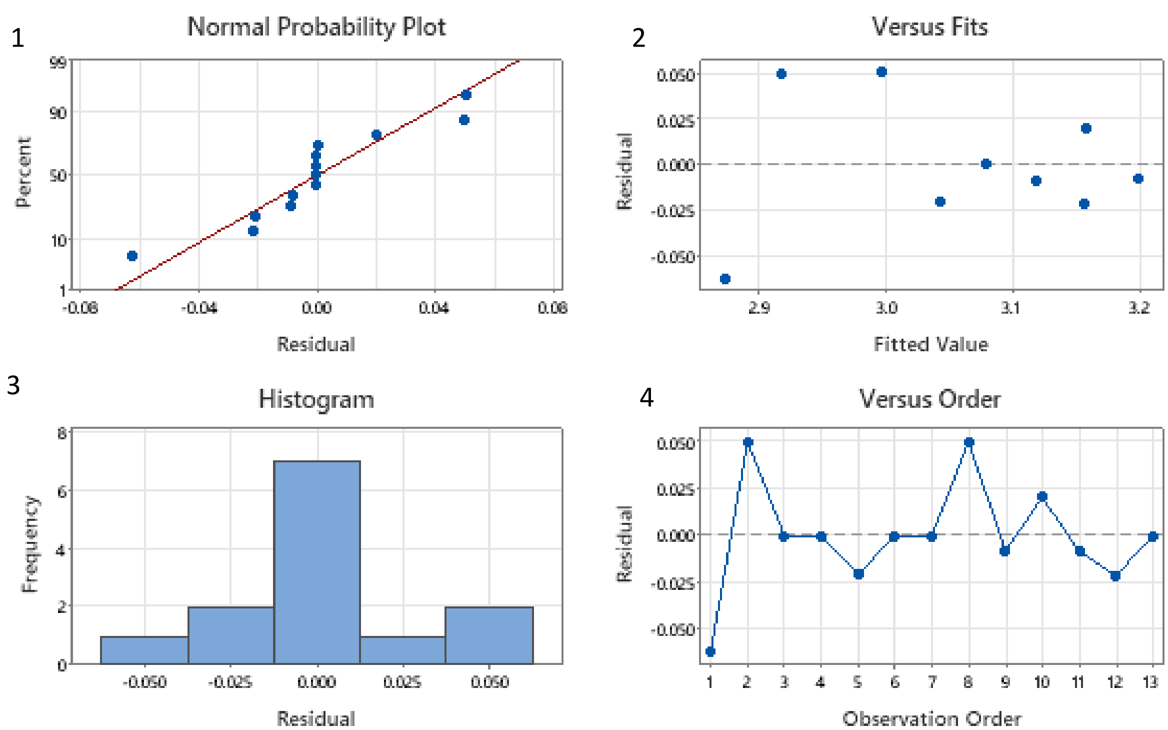


Figure 3-8 Residual plots for theoretical density

(1) Residuals closely fit the reference line in the normal probability plot, indicating they approximately have a normal distribution, which fulfills the assumption applied in ANOVA, as well as in regression.

(2) Residuals versus Fitted value exists no pattern in this plot, with residuals spreading randomly around zero. This confirms the homoscedasticity assumption (constant variance) since it suggests that the variance of the error does not depend upon fit.

(3) The histogram of residuals is approximately symmetric as well as bell-shaped, as it confirms residuals have a normal distribution.

(4) The residuals versus observation order plot contains no pattern or trend along runs of observations. This suggests that no extrinsic factors nor time-dependent effects affected measurements in taking data.

The residual analysis verifies that residuals should be strongly normally distributed. Variance stays constant over fitted values. Residuals are not correlated in time Thus; the regression equation is statistically valid and can be used to predict as well as optimize in the range of the experiment.

3.3.1.7 Pareto chart

The Pareto chart of standardized effects, Figure 3.X, reveals those factors most significantly affecting the theoretical density of Al7075/ZrO_2/ Ti-6Al-4V composite. The critical t-value at a confidence level of 95% (α = 0.05) is represented by the vertical red reference line.

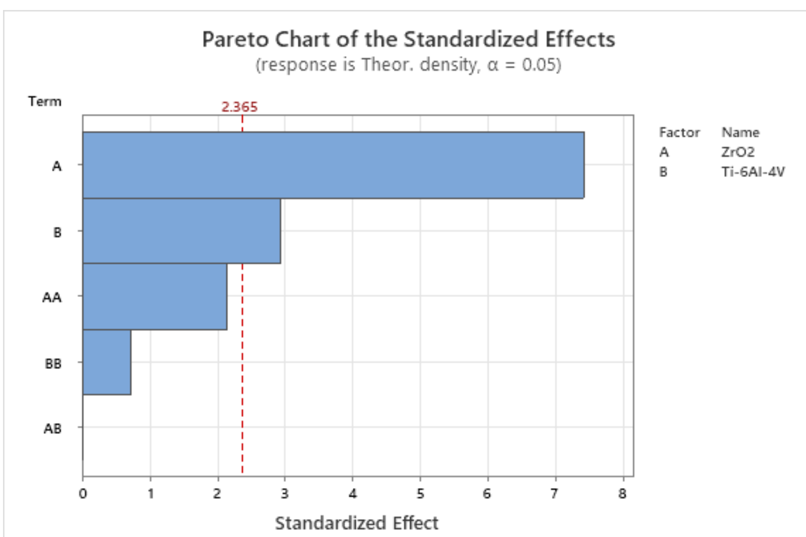


Figure 3-9 Pareto chart of standardized effect (response is theoretical density, α= 0.05)

- Factor A (ZrO_2) also produces the highest standardized effect (~7.5), far beyond the reference line. This validates that the dominant factor influencing theoretical density is ZrO_2 content.
- Factor B (Ti-6Al-4V) also surpasses a threshold, but its impact is smaller than that of ZrO_2.
- There are quadratic effects (AA, BB), but these are below threshold levels of significance, in agreement with ANOVA, where square terms were insignificant.
- The interaction term (AB) is practically zero, confirming that there exists no meaningful interaction between ZrO_2 and Ti-6Al-4V in the system.

3.3.1.8 Optimization summary and conclusion

The optimization of the theoretical density of stir-cast hybrid composites of Al7075 reinforced by ZrO_2, Ti-6Al-4V, and MoS_2 was carried out by Response Surface Methodology (RSM) in Minitab. It was done by employing central composite design (CCD), where ZrO_2 and Ti-6Al-4V contents changed while that of MoS_2 remained constant at 2 wt.%.

The regression equation showed a high statistical fit ($P = 0.002$), with residual checks indicating the goodness of fit of model assumptions. Out of the two major reinforcement factors:

- ZrO_2 was found to have the greatest impact towards raising theoretical density ($F = 55.07$, $P < 0.001$).
- Ti-6Al-4V also caused a significant but smaller effect ($F = 8.65$, $P = 0.022$).
- No significant interaction between ZrO_2 and Ti-6Al-4V ($P = 1.000$).

These findings were supported by surface plot, contour plot, and Pareto chart visualizations, which illustrated that the optimum values for a density of over 3.2 g/cm^3 resulted in high levels of both reinforcements most strongly with more than 7 wt.% of ZrO_2.

This model forms a valid foundation for determining reinforcement ratios that optimize densification as well as minimize porosity in the composite product.

Depending on the optimized process parameters based on density of reinforcements (ZrO_2 and Ti-6Al-4V), the lowest five densities are selected. They are shown in the following table 3.7.

Table 3.7 Theoretical density of selected samples

No.	Al7075(%)	Zro_2(%)	Ti-6Al-4V (%)	MoS_2(%)	Theoretical density
1	93	2.5	2.5	2	2.96699
2	91.5	1.5	5.0	2	2.81079
3	88	2.5	7.5	2	3.0475
4	91.5	5.0	1.5	2	3.02265
5	88	5.0	5.0	2	3.0789

3.3.2 Identifying matrix and reinforcement

Al7075 alloy was selected as the matrix, and zirconium dioxide (ZrO 2), titanium alloy (Ti-6Al-4V), and molybdenum disulfide (MoS 2) as reinforcement phases for this study. Selection of these materials was due to their capabilities of enhancing the mechanical and tribological properties of the composite. ZrO_2 was added for hardness and wear resistance, Ti- 6Al-4V for strength and compatibility of aluminium, and MoS2 to improve solid lubricity and reduce friction when sliding. The choice was performed based on the characteristics demanded for the application, such as increasing hardness, wear resistance, and self-lubrication. Material selection was also guided by economic and raw material availability and compatibility with the stir casting process. The incorporation of ceramic, metal, and solid lubricant reinforcements targeted a relatively balanced enhancement in the mechanical and tribological performance of the composite.

3.3.3 Experimental design for fabrication of composite

The composite was fabricated using a stir casting machine with the aid of an experimental design based on the significant process parameters such as stirring speed, stirring time, and wt% of reinforcing percentage at a fixed pouring temperature of 700 °C for all the samples. The experimental conditions are based on the optimum conditions in the literature to fabricate aluminum matrix composites by a stir-casting process. The fabrication was conducted under a constant stirring speed of 500 rpm and a stirring time of 30 minutes for a consistent dispersion of the reinforcements in the molten Al7075 matrix. The content of reinforcing phase was adjusted based on weight percentage for five samples to investigate mechanical effects. In all samples, 2 wt.% MoS_2 was added as a solid lubricant in order to improve wear resistance and to minimize frictional losses. According to research, adding MoS_2 in little amounts, like 2%, effectively enhances tribological characteristics without degrading the mechanical strength of the composite, avoiding negative effects like porosity and decreased hardness are two problems that can arise from higher MoS_2 values (N. Singh et al., 2022). By keeping the amount at 2%, lubrication's advantages are maximized and any possible disadvantages are reduced. Studies reveal that a 2% MoS_2 additive in the Al7075 composites could improve both tribological and mechanical properties. MoS_2 helps to improve the wear resistance by decreasing friction due to its self-lubricating behavior; 2% is optimized to achieve a balance, such that problems like porosity or decreased hardness are not observed at higher levels (Prabhu Deva et al., 2024) ZrO_2 and Ti-6Al-4V as second reinforcements to increase the hardness and strength. These reinforcements were preheated on the thermal basis before being charged into the melt to enhance wettability and bonding with the aluminum matrix. The matrix–reinforcement interface was also enhanced by continuous mechanical stirring under vortex conditions to reduce agglomeration and porosity during solidification. The study also provides a systematic exploration of the effects of the different content ratios of ZrO_2 and Ti-6Al-4V while maintaining a constant MoS_2 content on the tribological properties of Al7075-based hybrid composites.

Stir casting process parameter: Stir casting process parameters are essential in influencing the properties of Aluminum-based Metal Matrix Composites (MMCs). Some of the process variables that must be kept in mind during the preparation of AMMCs in order to get maximum mechanical properties are: stirring time, stirring temperature, and pouring temperature. A speed of 500 rpm will be adequate for the dispersion of reinforcement particles in the molten matrix to have better particle dispersion, enhancing the mechanical properties of the composites (Ali, 2020). One should be careful of defects such as porosity and microcracks that may develop at high stirring speeds. for the case of string A 30-minute stirring time is sufficient to ensure good mixing and wetting of the reinforcement particles by the molten aluminum, improving the uniformity of the structure. Few studies are conducted at 30-minute intervals, but generally speaking, longer stirring times improve the mechanical properties of composites (Anand, 2024). Maintaining the stirring temperature at 700°C ensures that the aluminum matrix remains in a molten state, which facilitates particle incorporation through proper mixing. This temperature is standard for stir casting to achieve the best viscosity and to ensure uniform reinforcement distribution (Kuttan, 2024).

Table 1.8 Operating Conditions for Stir Casting Process

S. No	**parameters**	**levels**	**unit**
1	Stirring Speed	500	rpm
2	Stirring Time	30	minute
3	Pouring Temperature	700	°C

Table 3.9 Experimental design for fabrication

samples	**compositions**	**Wight percentage**
Sample-1	Al7075	93%
	ZrO_2	2.5%
	Ti-6Al-4V	2.5%
	MoS_2	2%
Sample-2	Al7075	91.5%
	ZrO_2	1.5%
	Ti-6Al-4V	5.0%
	MoS_2	2%

Sample-3	Al7075	88%
	ZrO_2	2.5%
	Ti-6Al-4V	7.5%
	MoS_2	2%
Sample-4	Al7075	91.5%
	ZrO_2	5.0%
	Ti-6Al-4V	1.5%
	MoS_2	2%
Sample-5	Al7075	88%
	ZrO_2	5.0%
	Ti-6Al-4V	5.0%
	MoS_2	2%

3.3.4 Determining weight (in mass) for matrix and reinforcement inquiries

The total mass of matrix and reinforcement, which is utilized for the preparation of the Al7075/ZrO2/Ti-6Al-4V/MoS_2 composite samples, was calculated according to the number of the samples needed for the hardness measurements, compression tests, microstructure analysis, wear tests, and hot deformation (extrusion) treatments. Each specimen had a 33 mm diameter and 70 mm length, including the machining allowance. Reinforcing weight percentage has a considerable effect on the mechanical and tribological properties of the developed composite samples. from extensive literature review that the volume fraction of a reinforcement in metal matrix composite should be less than 25% to avoid porosity, attain uniform distribution, and for attainment of proper densification during processing (Choudhury et al., 2025). Thus, in the selected reinforcement percentage of 12%, the zirconia (ZrO_2) is 5 %, the titanium alloy (Ti-6Al-4V) is 5%, and the molybdenum disulfide (MoS_2) is 2 %.

The required material volume for a cylindrical sample is calculated using the formula:

$$V_m = \frac{\pi}{4} D^2 \times L \qquad (3.2)$$

Where,

V_m= volume of mold in mm^3,

L=length of mold in mm, and
D=diameter mold in mm

The length of mold= 70mm

The dimeter of mold = 33mm

$V_m = \frac{\pi}{4} \times (33mm)^2 \times 70mm$

V_m= 60mm^3

Based on the weight percentage specified in the experimental design, the mass of the matrix (Al7075 alloy) and reinforcements (ZrO2, Ti-6Al-4V, and MoS_2) in each sample for the specified composition is estimated by:

$$m_{x=V_m \times \rho_x \times y} \tag{3.3}$$

Where m_x is mass of reinforcement or matrix, ρ_x is density of matrix and reinforcement and "y" is weight percentage of reinforcement and matrix. Since weight percentage of molybdenum remains constant in all samples it is calculated as follows.

Mass of molybdenum, $m_{x=V_m \times \rho_x \times y}$ = 59.87 cm^3×5.06g/ cm^3 × 0.02= 6.05g

sample 1

Weight used for Al matrix is:

Weight (in mass), $m_{(Al)}$ = 59.87 cm^3 *2.81 g/ cm^3 *0.93 = 156.45g

Weight used for Zirconium and Titanium is:

$m_{(ZrO2)}$ = 59.87 cm^3 *5.68 g/ cm^3 *0.025 = 8.5g

$m_{(TC4)}$ = 59.87 cm^3 *4.42 g/ cm^3 *0.025 = 6.62g

sample 2

Weight used for Al matrix is:

Weight (in mass), $m_{(Al)}$ = 59.87 cm^3 *2.81 g/ cm^3 *0.915 = 153.93g

Weight used for Zirconium and Titanium is:

$m_{(ZrO2)}$ = 59.87 cm^3 *5.68 g/ cm^3 *0.015 = 5.1g

$m_{(TC4)}$ = 59.87 cm^3 *4.42 g/ cm^3 *0.05 = 13.23g

sample 3

Weight used for Al matrix is:

Weight (in mass), $m_{(Al)}$ = 59.87 cm^3 *2.81 g/ cm^3 *0.88 = 148.04g

Weight used for Zirconium and Titanium is:

$m_{(ZrO2)}$ = 59.87 cm^3 *5.68 g/ cm^3 *0.025 = 8.5g

$m_{(TC4)}$ = 59.87 cm^3 *4.42 g/ cm^3 *0.075 = 19.84g

sample 4

Weight used for Al matrix is:

Weight (in mass), $m_{(Al)}$ = 59.87 cm^3 *2.81 g/ cm^3 *0.915 = 153.93g

Weight used for Zirconium and Titanium is:

$m_{(ZrO2)}$ = 59.87 cm^3 *5.68 g/ cm^3 *0.05 = 17g

$m_{(TC4)}$ = 59.87 cm^3 *4.42 g/ cm^3 *0.015 = 3.96g

sample 5

Weight used for Al matrix is:

Weight (in mass), $m_{(Al)}$ = 59.87 cm^3 *2.81 g/ cm^3 *0.88 = 148.046g

Weight used for Zirconium and Titanium is:

$m_{(ZrO2)}$ = 59.87 cm^3 *5.68 g/ cm^3 *0.05 = 17g

$m_{(TC4)}$ = 59.87 cm^3 *4.42 g/ cm^3 *0.05 = 13.23g

The total weight (in mass), of the matrix and reinforcement for the fabrication are as follows:

m_T (Al) = m_{Al} in (S1 +S2 +S3+S4+S5) = (156.45+153.93+148.04+153.93+148.046) g = 760.404 g

m_T (ZrO_2) = m(ZrO_2) in (S2+S3+S4+S5) = (8.5+5.1+8.5+17+17) g =56.1g

m_T (TC4) = m (TC4) * (S2+S3+S4+S5) = (6.62+13.23+19.8+3.96+13.23) =56.88g

m_T (MoS_2) = m(MoS_2) * (5 sample) = 6.05g *5 =30.25g

3.2.5 Equipment's Used to Fabricate and Prepare Composite Sample

Instruments and apparatus are used for the preparation and fabrication of Al7075-based metal matrix composite samples reinforced with ZrO_2, Ti-6Al-4V, and MoS_2 described in this section. The sample preparation procedure was designed so that the weight of the final samples was correct, homogeneous mixing was achieved, compaction and sintering/extrusion were properly done, and they were machined to reach the dimensions required for the ASTM tests of mechanical and tribological tests further on.

Table 3.10 shows the equipment utilized for fabricating hybrid aluminum matrix composites and the apparatus employed for preparing experimental samples.

Table 3.10 Composite fabrication and sample preparation equipment's

No.	**Equipment's**	**Function**
1	Furnace	For melting the matrix material (Aluminum)
2	Stirrer	For uniform distribution of reinforcement throughout the matrix material
3	Hand drill	To give a rotation speed for the stirrer joined to it
4	crucible	A graphite material where the material melted in
5	mold	For shaping the molten mixture in to a sample
6	Digital analytical balance	To the weight materials or samples.
7	File/rasp	To remove fine amounts of material from a workpiece.
8	Caliper	To measure the linear dimensions of the samples.
9	Sand paper	To remove the damages for obtaining a flat surface
10	Grinder/ polisher	To obtain flat and scratch free surface.
11	Scanning electron microscope (SEM)	To obtain surface morphology and fractography
12	Optical microscopy	To analyze the microstructure of the developed composite
13	Vickers hardness machine	For determining the hardness property of the samples
14	Universal testing machine (UTM)	To test the compressive load resistance of the specimens

15	Pin On Disk Apparatus	To test the wear rate and friction behavior of specimen
16	Minitab statistical software	to conduct statistical analysis such as hypothesis testing, regression analysis, and ANOVA

I. Digital balance

analytical precision balance was employed for the weighing of materials during sample preparation. The balance has a high resolution of 0.1 mg, with a weighing capacity of 252 g and weighing pan diameter of Ø90 mm, and is an ideal size for the measurement of matrix and reinforcement powders.

II. Furnace

A furnace is a heating device used to melt materials at high temperature. It can be powered by electric or fuel energy. In the furnace the Aluminum 7075 alloy in melted in the crucible at temperature of 700°c. To build furnaces, the following components are used; Body frames (plates and angles), refractory bricks, ceramic blankets, crucibles, heating coils, thermocouples, temperature controllers, voltmeters, ammeters, step-down transformers, and so on.

3.3.6 Fabrication of composite procedure

In this research, for the fabrication of aluminum metal matrix composite, a liquid metallurgy specifically stir casting is used. In this section the process parameters and procedures of fabrication is presented.

3.3.6.1 Stir casting route for fabrication of AMMC

Liquid metallurgy is generally considered the most appropriate technique for the fabrication of aluminum composite materials because it provides an economical method of production in large quantities and gives near-net-shaped components. Of all the techniques belonging to this group, the stir casting process is the most effective and economical. Stir casting is both simple and low-cost, making it highly adaptable for manufacturing aluminum-based composites. There are several stages during the manufacturing process of the samples, the first step was calculating the amount of reinforcement power and matrix based on the volume of mold. The precisely calculated amount powder of reinforcement and the matrix was measured in analytical precision balance with weight capacity of 252g/0.1mg. Then the stir casting manufacturing equipment’s are prepared. To minimize oxidation during the melting and stirring process, argon gas was continuously purged into the furnace chamber as an inert shielding atmosphere.

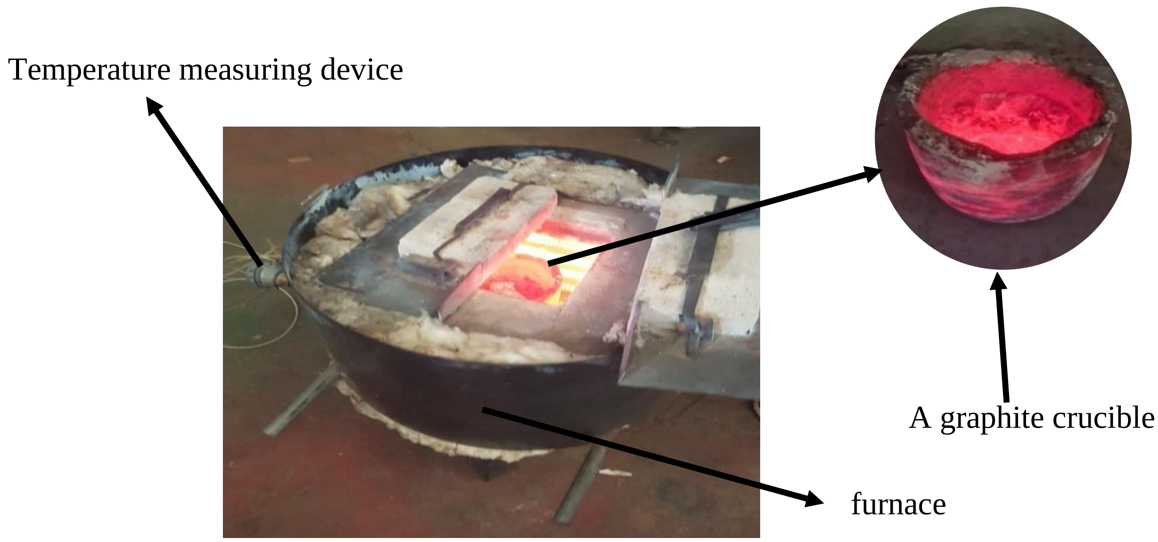


Figure 3-11 Schematic diagram of stir casting method

After preparation of the stir casting setup, the furnace with the crucible is preheated then the aluminum metal matrix will be added. Aluminum melts around 700°C, the temperature of the furnace is controlled by a temperature sensor device in which a thermocouple is attached between the furnace and the device. Then the reinforcements will be added one by one for the best result.

Figure 3-12 Temperature sensor

ZrO_2 is a ceramic material that is stable at high temperatures, so it needs preheating around 500°C for improved wettability and to avoid settling, as it has a high density of 5.68 g/cm^3. It is then slowly added to the vortex of constant stirring speed of 500 rpm for about 2-3 minutes to disperse it properly. Ti-6Al-4V is a metallic powder that may melt partially into the Al matrix and will be preheated to around 400°C-500°C to help reduce thermal shock and improve matrix bonding. After preheating, it will be poured gradually into the vortex after ZrO_2 and stirred again for another 2-3 minutes. At last, MoS2, a solid lubricant, is more sensitive to decomposition at high temperature, so it is added at last to reduce the chance of thermal breakdown. Finally, after adding all reinforcements, stirring will be continued for about 5 minutes to ensure a uniform mixture, and settle for around 1-2 minutes so bubbles can escape. Then a mold is preheated to around 150°C-200°C. After removing any slug formation. Then the composite is poured slowly into the mold (33mm diameter and 70 mm height) using a tong turbulence is avoided as much as possible to prevent porosity.

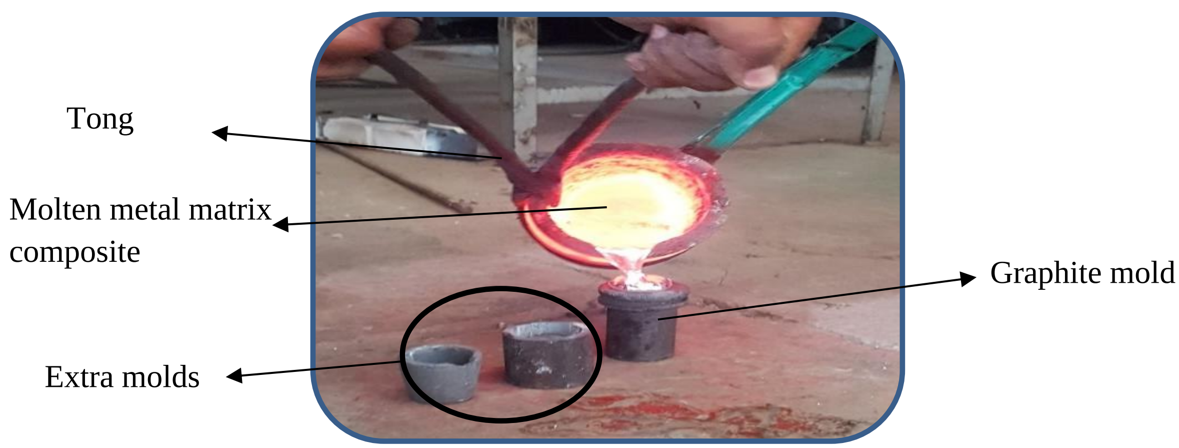


Figure 3-14 Poring of the melt composite in to the mold

Figure 3-15 Final casted samples

3.3.7 The tools and equipment's used for sample preparation.

Table shows instruments and apparatus used for the preparation samples for experimenting the developed hybrid Aluminum metal matrix composite.

1) Machining and cutting

A lathe is a machine tool that rotates a workpiece about an axis of rotation to perform various operations such as cutting, sanding, knurling, drilling, deformation, facing, threading, and turning with tools that are applied to the workpiece to create an object with symmetry about the axis. Tapper turning were performed on the fabricated composites samples as per the desire of different experimentation ASTM standards.

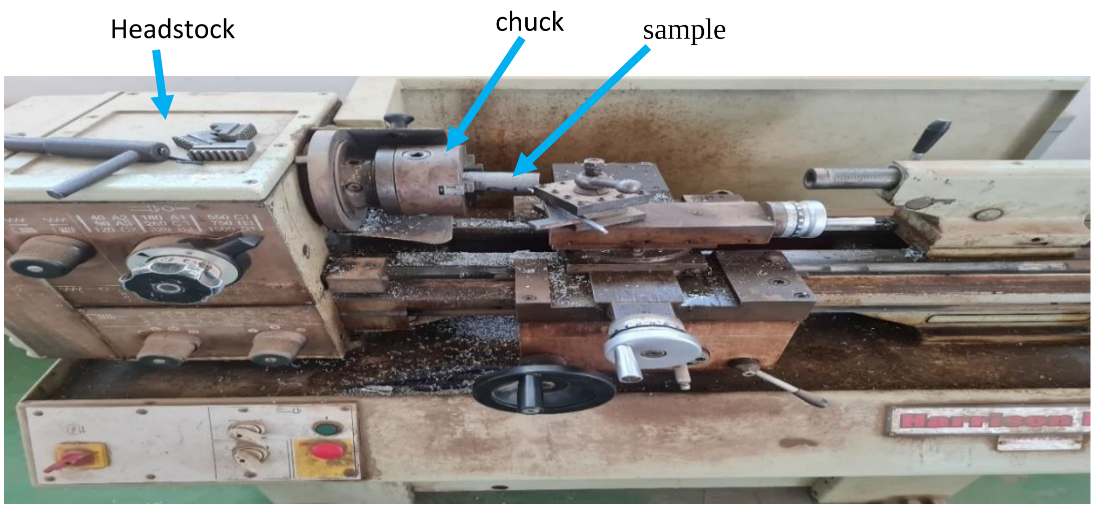


Figure 3-16 Sample machining on lathe

Figure 3-17 Fabricated Al7075-based hybrid composite samples (S1–S5) after turning operation.

2) Density and Porosity Measurement

Density, a fundamental property of materials, indicates a substance's mass for a given volume. For mono- or hybrid metal matrix composites (MMCs), density becomes crucial in defining structural behavior, homogeneity of materials, and level of porosity. Theoretical composite material density can also find expression via the rule of mixtures, considering each ingredient's (matrix as well as reinforcements) volumetric contribution along with inherent densities. This involves calculating corresponding individual densities of the reinforcement materials as well as that of the matrix material, their percentage weights converted to a volume fraction (Charan Nayak et al., 2020), and then employing the expression provided by:

$$\rho_{th} = (V_m \times \rho_m) + (V_r \times \rho_r)^n \qquad (3.4)$$

where: ρ_{th} is the theoretical density of the composite, V_m, V_r are the volume fraction of matrix and reinforcement, ρ_m, ρ_r are the densities of the matrix and reinforcement.

Experimental density may be ascertained through Archimedes' principle, which is best suited for irregular and porous samples. It is expressed in terms of fluid (generally water) displacement and obeys Archimedes' law of a buoyant force by a fluid on a body immersed in it.

According to Archimedes principles, the Al/ZrO2/ Ti-6Al-4V /MoS2 hybrid composite's actual or experimental density was determined. The cast sample was first weighed in air (Wair), and it was then suspended in distilled water (Wwater) to be weighed there. (Agrawal, 2021).

Figure 3-18 Measurement of experimental density in distilled water

Equation was used to determine the casted composite's real or experimental density as follows:

$$\rho_{actual} = m\frac{m\text{air}}{m\text{air} - m\text{water}} \times \rho_{water} \qquad (3.5)$$

where $m$air = mass of composite in air and $m$water = mass of composite in distilled water, and ρ_{water} = density of distilled water at 25°C 1g/cm3.

Table 3.11 theoretical and actual density of five samples

Samples	Theoretical density g/cm^3	Actual density g/cm^3
S1	2.96699	2.9202
S2	2.81079	2.6396
S3	3.0475	2.6793
S4	3.02265	2.7946
S5	3.0789	2.9196

The porosity is determined based on both experimental and theoretical density measurements of the fabricated samples (Sahoo & Parida, 2021).

$$P = 1 - \frac{\rho\text{actual}}{\rho\text{th}} \qquad (3.6)$$

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

3) Microstructural Characterization of Composite

Microstructural analysis is carried out on all the combinations of the fabricated composite. and hybrid composites using an optical microscope to know the fair distribution of reinforcement and for grain particle size volume fraction measurement.

a) Optical microscope (OM)

Optical microscopy (OM) is often also called light microscopy, as it is based on a focused beam of light for the examination of samples through a system of lenses. it’s important is the determination of the constituents and microstructure of materials. These can be different phases in metal alloys. Microscopes can be designed for illumination with incident (reflected) light or transmitted light. The former is commonly called metallurgical microscopes since they are used for observation of metals or ores (see ore and smelting slag) which are opaque (Figueiredo, 2018). In this study OM was used to investigate the distribution of reinforcement on base matrix.

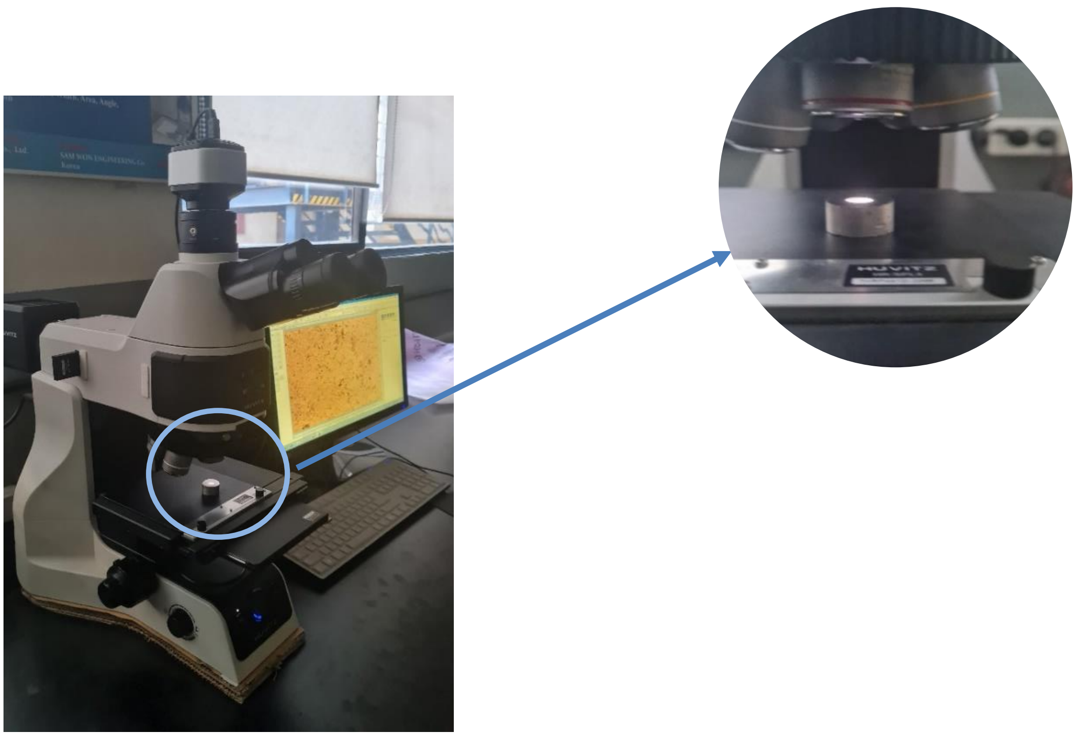


Figure 3-19 *Huvitz HR-300 Metallurgical Microscope used for microstructural analysis*, with magnification up to X1000, multiple imaging modes (BF, DF, POL, DIC), and a digital camera for 2D measurements

b) Scanning electron microscope (SEM)

Scanning electron microscopes play a very significant part in microstructure study and are thus relevant to any research concerning processing, properties, and performance of materials with regard to their microstructural features. The SEM provides information relating to topographical features, morphology, phase distribution, compositional differences, crystal structure, crystal orientation, and the presence and location of electrical defects (Leonard et al., 2012). The samples were taken for rough grinding operation for dimensions using files. It was then exposed to grinding using sand papers from coarse to fine grades with the orientation of 90°. Sequentially, the sandpapers of 220, 260,800, 1200, and 2200 grades were used and assisted with an air blower after each grinding operation in order to remove debris The samples were then polished to prepare a flat, scratch-free, and mirror-like surface.

c) X-Ray Diffractometer

X-Ray Diffractometer (XRD) is an instrument used for measuring and analyzing the structure of a material from the scattering pattern produced when a beam of radiation or particles interacts with it and This machine is used for different purposes, including identifying unfamiliar substances for use in crystallography inspection, imaging crystal structures, and phase determination. Before the X-Ray Diffractometer (XRD) instrument is used, x-rays are directed at the sample then atoms in the crystal lattice scatter the x-rays. After that, a diffraction pattern will be formed then the detector records the angles and intensities of diffracted beams, and it will be analyzed. For the analysis, a powdered sample is used as shown in the figure 3.X.

Figure 3-20 Powdered samples for XRD analysis

d) Compression test

Compression strength is the ability of a material or structure to bear loads that generally decrease in size. By definition, a material's ultimate tensile strength is the amount of uniaxial compressive stress that is reached when the material fails entirely. A compressive test and a uniaxial compressive load are frequently used in experimental measurements of compressive strength. A universal testing machine (UTM) with a load capability of 50KN was used to perform the compression test on a cylindrical specimen that had been manufactured in accordance with ASTM E-9 standard and had a length to diameter ratio of 3mm (L = 18mm and 6mm diameter). The specimens were loaded until they are fractured.

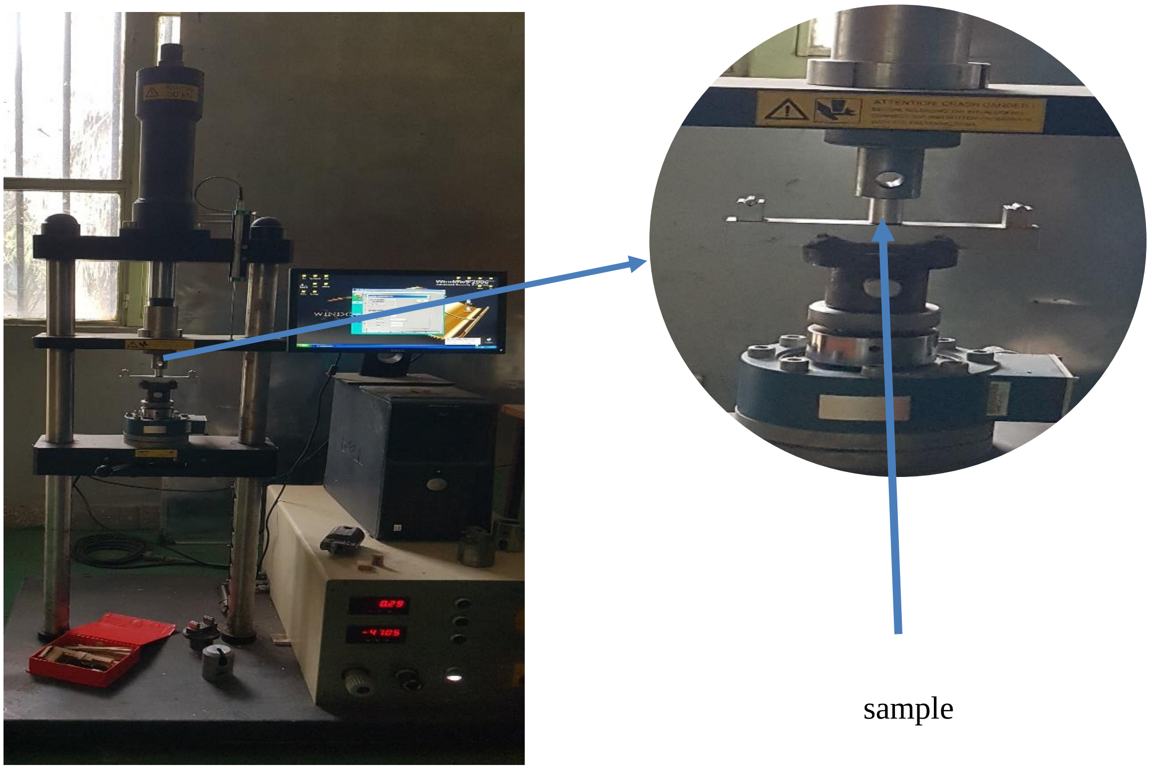


Figure 3-21 Universal testing machine (UTM) setup for compression test

e) Pin on Disk Test

Friction and wear (typically wear rates and wear resistance) characterization of materials is typically performed using various types of tribometers, with the pin-on-disk test being probably one of the most common. The popularity of the method is due to its relative simplicity and abundance of the tribological contacts that can be well described by a simple pin-on-disk motion from dry contacts of bolt screws to rail wheels to rail contact and to lubricated contact of biological implants. The test typically allows testing several motion modes, such as unidirectional and fretting modes, and recently any other complex motion patterns.

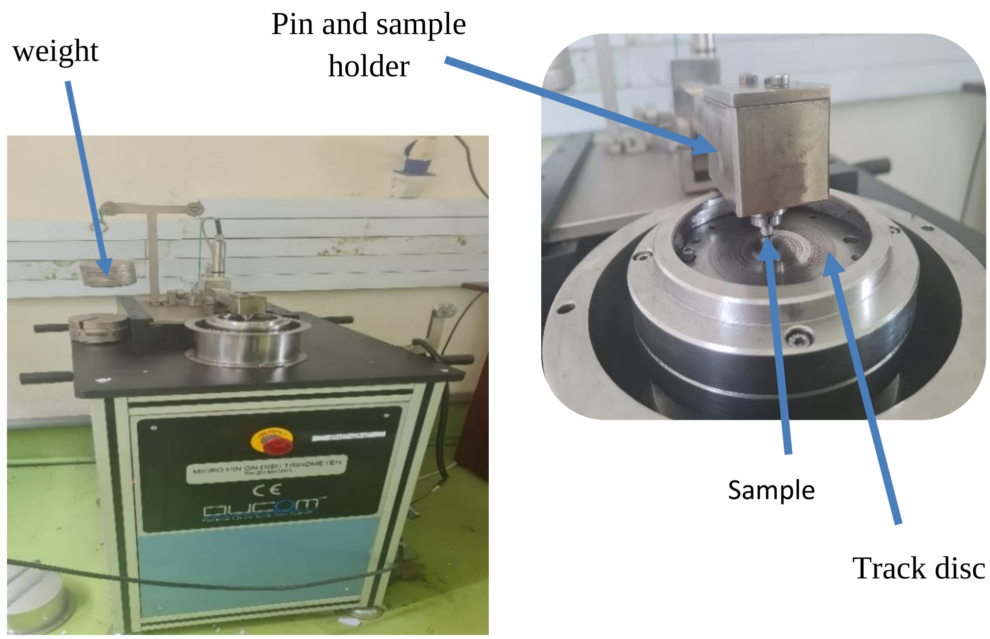


Figure 3-22 Schematic diagram of a pin on disk test

Typically, the tests are performed under the testing standard of ASTM G99 of dimensions of 6mm diameter and 12 mm height. The samples are first prepared by polishing using sand paper. The wear property of the samples was evaluated under the specified test parameters of 30N load applied on a 50mm diameter wear track for about 5 minutes, with a rotation speed of 250 rpm.

Table 3.12 Wear test parameters used during the pin-on-disc experiment according to ASTM G99.

Parameter	**Value**	**Unit**
Load (W)	30	N (Newtons)
Track diameter (d)	50	mm
Sliding time (t)	5	minutes
Rotational speed (n)	250	rpm
Pin diameter	6	mm
Pin height	12	mm
Standard	ASTM G99	—

Eq. 3.13 was used to obtain the wear rate of the Al MMCs samples (Gnanaraj & Prabhu, 2022).

$$W.R = \frac{Wb - Wa}{pi \times d \times n \times t} \quad (3.7)$$

Where Wb represents the weight of the samples prior to wear, Wa denotes the weight of the samples after wear, WL indicates the weight loss (Wb − Wa), d is the diameter of the wear track on the wear disc, n refers to the rotational speed in revolutions per minute, and t represents time.

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Introduction

This chapter of the research discusses different properties of the composites that were fabricated. It also covers results on density, porosity, relative density, hardness, and compressive strength of the mechanical properties.

4.1.1 Density and Porosity

Density and porosity are interrelated qualities that characterize the compactness and void space within a material. The theoretical density of hybrid composite material prepared in the current research work is calculated using the rule of mixture as shown in equation (3.4). The measured density, on the other hand, is calculated using the rule of Archimedes' principle, as shown in Equation (3.5). Porosity of all hybrid composite material can be calculated based on appropriate analysis and measurement techniques using Eq. (3.6). Figure 4.1 plots the theoretical and actual density of Al7075 hybrid matrix composites, which is also exhibited by Table 4.1. Since it can clearly show that the theoretical density amount is higher for the entire sample that was measured, it is a result of impurities and voids created in the fabrication process.

samples	**Theoretical density g/cm^3**	**Actual density g/cm^3**	**Porosity**
1	2.96	2.92	1.5
2	2.81	2.63	6.09
3	3.04	2.67	12.08
4	3.02	2.79	7.54
5	3.07	2.91	5.17

Table 4.1 Density and Porosity of hybrid Al7075 matrix composite

Comparison of theoretical and actual values of the five composite samples indicates that with an increase in weight percentage of high-density reinforcement materials like ZrO_2 and Ti-6Al-4V, theoretical density increases as a result of higher values of their densities in comparison to that of the base material, Al7075. The actual values of all samples, however, happen to be lower than their corresponding theoretical values, which indicates that there exists an occurrence of porosity—resulting from particle clustering, poor wettability, and air entrapped during stir casting. The samples containing higher amounts of Al7075, like Sample 1, contain a lower difference in theoretical and actual values, which suggests higher flow and packing of materials. For samples with higher reinforcement amounts, there occurs a higher difference as a result of difficulty in making a homogeneous distribution. This indicates that denser reinforcements increase theoretical values but can also lead to hindering of complete densification as a result of processing, hence higher porosity and lower actual values. In the context of aluminum matrix composites (AMMCs), porosity values above 6–7% are generally considered high due to their adverse impact on mechanical integrity (Ali, 2020). Based on this, Samples 2, 3, and 4 fall into the high porosity range, likely caused by agglomeration or gas entrapment.

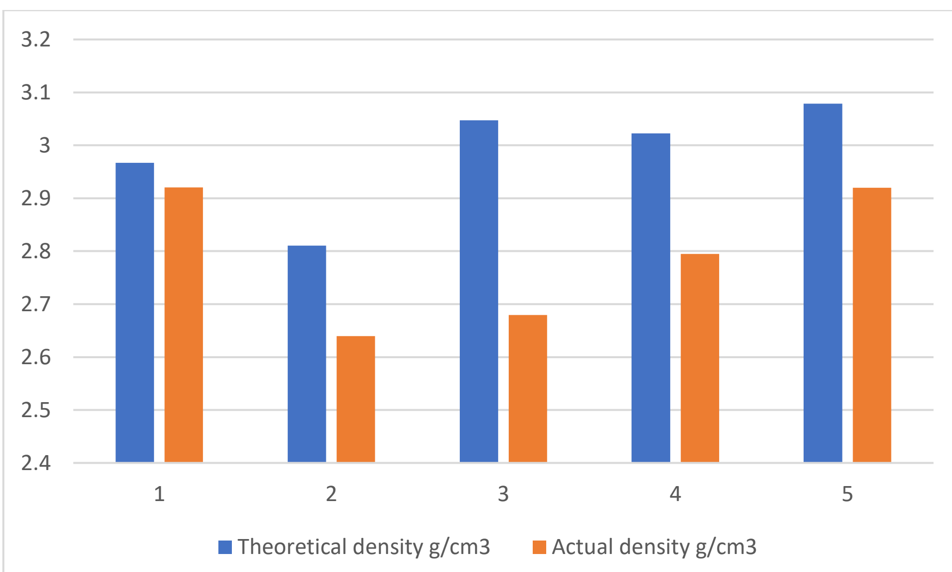


Figure 4-1 Theoretical and actual density of Al7075-Zro_2- Ti-6Al-4V -MoS_2 hybrid composite

Porosity values in fabricated Al7075-based hybrid metal matrix composites exhibit a visible trend impacted by reinforcement type and percentage used i.e., ZrO_2, Ti-6Al-4V, and MoS_2. Among all samples, Sample 1 (2.5% reinforcement of ZrO_2 and 2.5% reinforcement of Ti-6Al-4V recorded the lowest porosity of 1.5%, which indicates excellent wetting, negligible agglomeration, and good dispersion of reinforcements. This concurs with (James et al., 2021) findings, who cited that low reinforcement percentages ensure improved wettability as well as better interfacial bonding of particles to the matrix. Contrary to this, Samples 3 (7.5% reinforcement of Ti-6Al-4V) and 5 (5.0% reinforcement of Ti-6Al-4V) have appreciably higher porosity values (9.97% and 12.08%, respectively), despite higher theoretical densities. This can be attributed to elevated melt viscosity, which generates non-uniform dispersion, agglomeration of reinforcements, as well as gas trapping during stir casting (Morsiya & Pandya, 2023). Furthermore, Sample 4 (5% reinforcement of ZrO_2) also records high porosity (7.54%), in support of the fact that non-metallic reinforcements such as ZrO_2 have poor wettability with molten aluminum, which leads to voids (Schramm et al., 2022).General observation of all samples supports a rule that as reinforcement quantity increases, there's a corresponding increase in porosity due to challenges in dispersing particles, improved resistance of melt, as well as higher chances of agglomeration (Annigeri & Kumar, 2018; Kulkarni et al., 2016). Balancing reinforcement amounts is key to minimizing porosity as well as better structural integrity in hybrid composites.

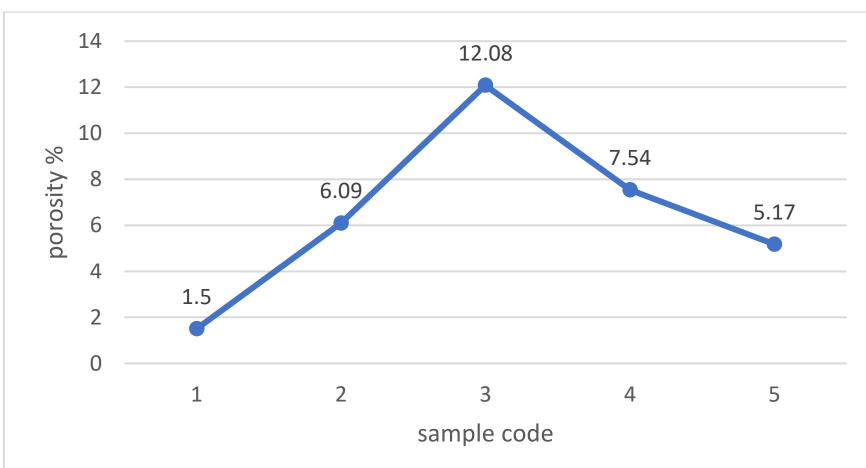


Figure 4-2 Porosity % of Al7075-Zro_2- Ti-6Al-4V -MoS_2 hybrid composite

4.1.2 Hardness Test

Hardness values for Al7075 hybrid composites exhibit a clear tendency towards increase with increasing percentage reinforcement inclusion of ZrO_2 and Ti-6Al-4V. Sample 1 recorded the least (151.2 HV), while Sample 5 recorded the highest (218.16 HV). The uniform increase in all the samples is primarily attributed to an increase in the combined percentage by weight inclusion of hard reinforcement. The addition of Ti-6Al-4V, an alloy with high strength and stiffness, and ZrO_2, a hard ceramic material, efficiently prevents dislocations from moving inside the aluminum matrix, increasing the material's resistance to local plastic deformation (Hu et al., 2018; H. Singh et al., 2022).

Table 4.2 Hardness values of Al7075-ZrO_2- Ti-6Al-4V -MoS_2 hybrid composite

Sample code	**Hardness value (HV)**			**Average Hardness value**
	Trial 1	**Trial 2**	**Trial 3**	
1	140.3	154.0	159.3	151.2
2	152.0	157.6	162.8	157.46
3	157.6	169.3	172.9	166.6
4	209.5	190.7	201.9	200.7
5	220.5	211.6	222.4	218.16

The increase in hardness is also contributed to by enhanced load transfer from the ductile matrix to hard particles and also due to likely grain refinement by virtue of evenly dispersed reinforcements (KhademeelJamea, 2017).Significantly, Sample 4 with 5% ZrO_2 and 1.5% Ti-6Al-4V recorded greater hardness (200.7 HV) compared to Sample 3 with 7.5% Ti-6Al-4V and 2.5% ZrO_2 (166.6 HV), proving the superior role played by ZrO_2 in increasing hardness due to its ceramic nature. The highest hardness in Sample 5, containing 5% ZrO_2 and 5% Ti-6Al-4V, demonstrates a hybrid reinforcement synergistic strengthening effect whereby raising reinforcement level strongly increases surface hardness (Annigeri & Veeresh Kumar, 2018; Li et al., 2024).Accordingly, evidence is presented that hybrid reinforcement with specific content is effective in enhancing Al7075 composite mechanical performance. Although Sample 5 also has relatively high porosity (5.17%), the greater amount of hard reinforcement was enough to increase the hardness. This means the positive effect of reinforcement outweighed the negative effect of porosity.

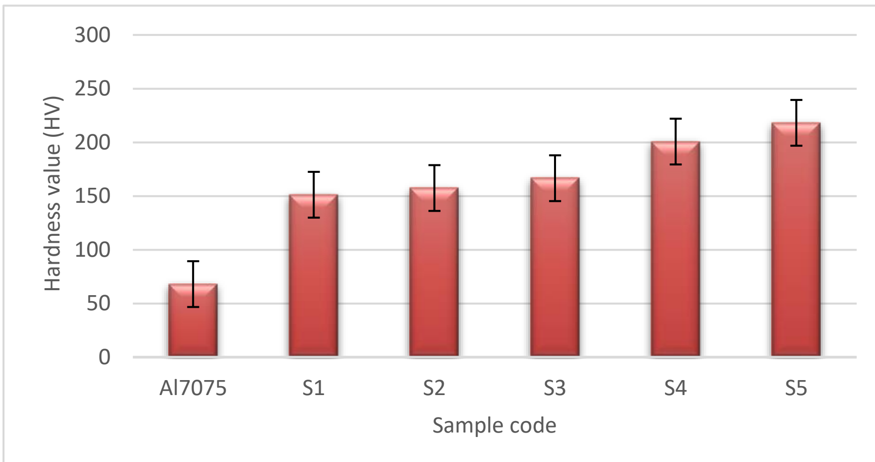


Figure 4-3 Hardness values of Al7075-Zro$_2$- Ti-6Al-4V -MoS$_2$ hybrid composite

The error bars in Figure 4-3 are the three independent measurements of hardness for every sample and represent the standard deviation. They give an indication of the different hardness values that are due to the repeatability of the measurement and allow for the visualization of the data consistency.

4.1.3 Compression test

The compression response of the Al7075 matrix and the hybrid composites reinforced with ZrO_2, Ti-6Al-4V, and MoS_2 were analyzed in the universal testing machine at the constant applied load of 50 kN. The bar chart representing the compressive strength of the samples from the experimental data is shown in Figure 4.4.

Unreinforced matrix of the Al7075 was characterized at 514 MPa, whereas the hybrid as well as different hybrid composites exhibited disparate compressive strength, such as 538 MPa

(S1), 547 MPa (S2), 521 MPa (S3), 591 MPa (S4), and 508 MPa (S5). Compared with all the other hybrid composites, Sample S4 showed the best compressive strength (591 MPa), reflecting the efficient load transfer contribution from the reinforcement phases in the composite. It is because the balanced composition of ceramic (ZrO_2) and metallic (TC4, MoS_2) reinforcements improves the load transfer through Orowan strengthening and strain hardening phenomena (Ye et al., 2019). However, Sample S5 exhibited lower compressive strength (508 MPa), a slight decline compared to the unreinforced matrix. Such a reduction may be attributed to greater porosity and potential agglomeration resulting from greater total reinforcement content. Such discontinuities in the structure lower the bearing capacity of the material. Notably, strikingly, although lower in compressive strength, Sample S5 exhibited the highest hardness. Such disparity indicates that surface hardness is affected more by the incorporation of hard reinforcements, whereas compressive strength is affected more by interior defects in the form of voids and poor bonding. This is in line with the research of (Ankur et al., 2021), which has reported that mechanical behavior will degrade when the reinforcement goes beyond an optimum. In total, the increasing strengthening trend from S1 to S4 verifies the advantage of hybrid reinforcement if it is well dispersed, whereas S5 indicates the limitation due to microstructural instability.

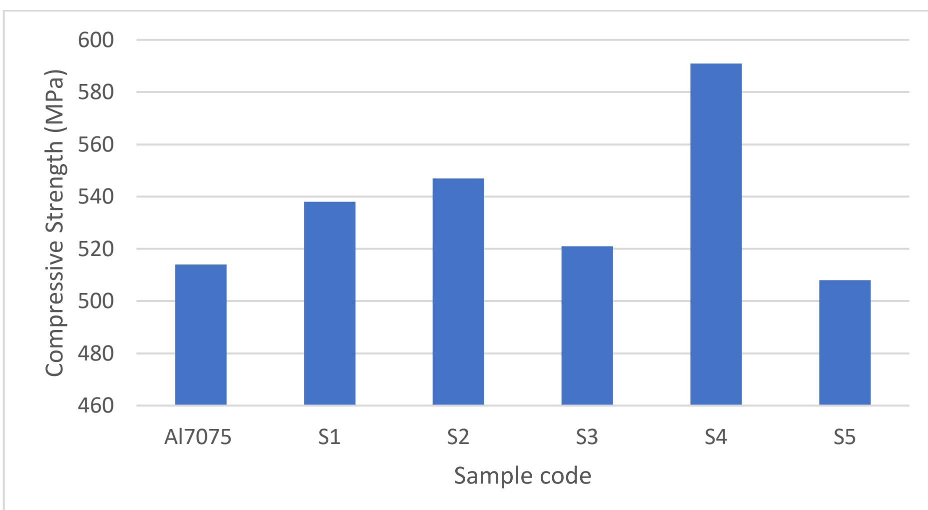


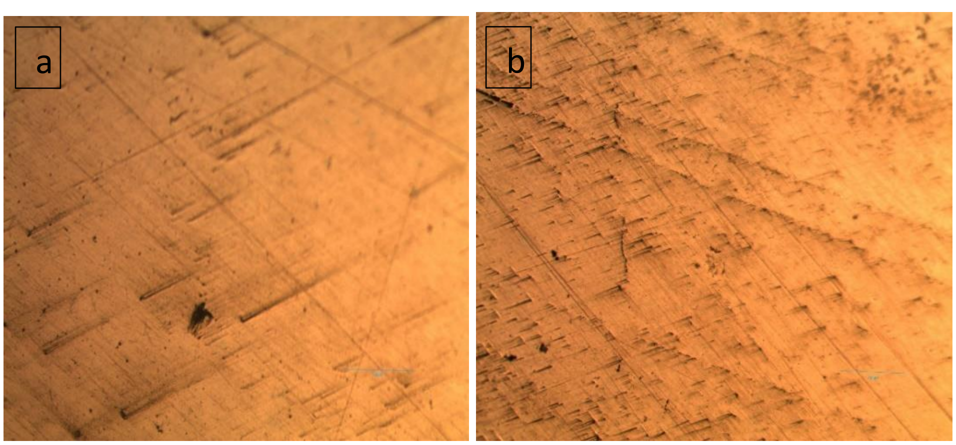
Figure 4-4 Compressive strength of Al7075 matrix and hybrid reinforcements

4.1.4 Microstructure of composite

The primary investigation throughout the process of material characterization was microstructure observation. Observations regarding patterns of microstructures can be used to reason about actual properties of studied specimens. All synthesized specimens are mentioned in more detail in the current work. The microstructure and phase of the composites were studied through an optical microscope and through a scanning electron microscope.

4.1.4.1 Optical Microscopy

Optical microscopy (OM) was used to investigate the reinforcement particle distribution in the aluminum matrix. The grain size was computed from an optical microscope image using imaging tools. Dependent on the OM image, the grain size was calculated using the line intercept method and ranged from 23.11µm to 104.56µm. From five trial values taken from various points of view of the specimen image, the average grain size for Sample 3 found is 52.44µm. Porosity level and grain size of generated composites with different weight percentages were investigated using ImageJ. With good agreement with the computed porosity level, the porosity percentage calculated for sample 1, sample 2, sample 3, sample 4, and sample 5 are 2.62 %,5.58% , 11.82% ,7.21% and 9.12% respectively.



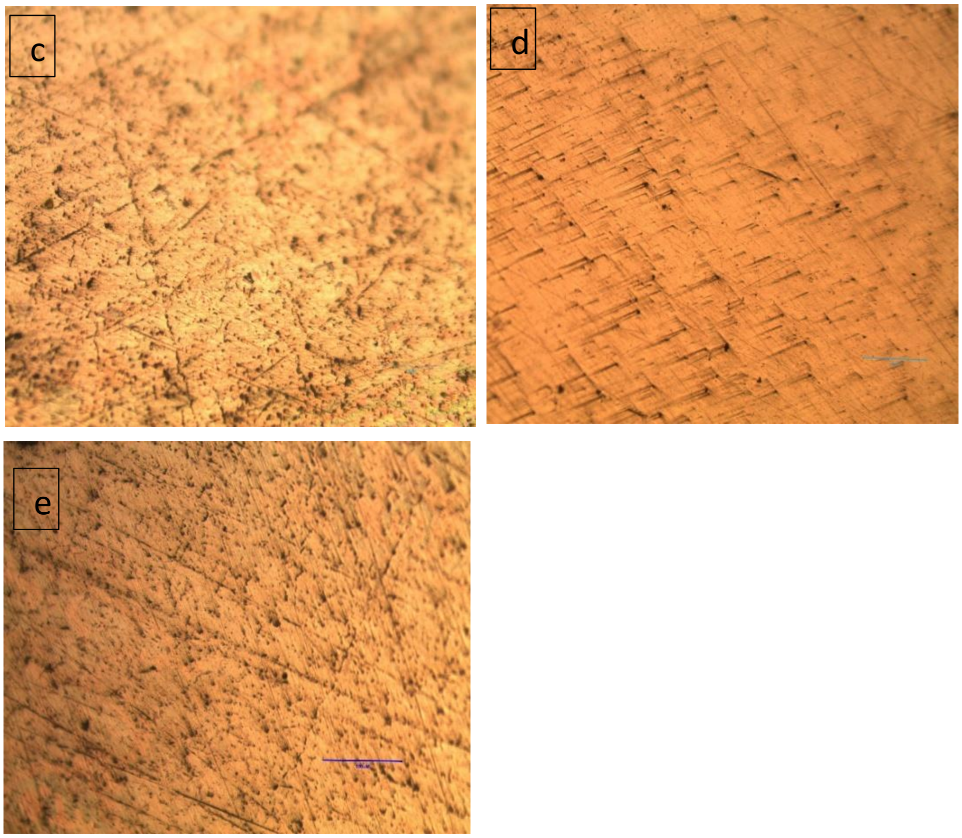


Figure 4-5 Image of optical microscopy for (a) sample 1 (b) sample 2 (c) sample 3 and (d) sample 4 (e) sample 5

4.1.4.2 Scanning Electron Microscopy

SEM microstructure observation of Al7075 hybrid composites reinforced with ZrO_2, Ti-6Al-4V, and MoS_2 indicates a well-integrated structure with less porosity and no visible agglomeration due to good fabrication through the stir casting process. The first microstructure presents ductile fracture behavior of the aluminum matrix along with bright and well-spaced ZrO_2 and Ti-6Al-4V particles and faint, flaky MoS_2 textures. More microstructures show polished surfaces with linear deformation lines and parallel grooves and do not show any evidence for reinforcement particles on their surfaces that testify to even subsurface distribution." High processing temperature assisted by high-speed stirring and extended duration of stirring facilitates clear reinforcement interfacial bonding and interfacial dispersion (Morsiya & Pandya, 2023).

However, small evidence for poor wetting in isolated zones is likely to be due to the inbuilt incompatibility of ceramic ZrO_2 with molten aluminum based on high surface energy and unsatisfactory affiliation with the matrix (Ali, 2020). This was inferred using SEM micrographs, which revealed faint interfacial gaps or weak adhesion with the surrounding matrix in some of the ZrO_2 particles, reflecting weak interfacial bonding, one common indicator of wettability problems. The addition of Ti-6Al-4V as a titanium alloy with better metallurgical compatibility with aluminum increases bonding and load transfer efficiency (G. Huang et al., 2018). Overall, optimum stir casting parameters were effective in suppressing agglomeration and achieving homogeneous reinforcement distribution, thus resulting in a structurally strong composite.

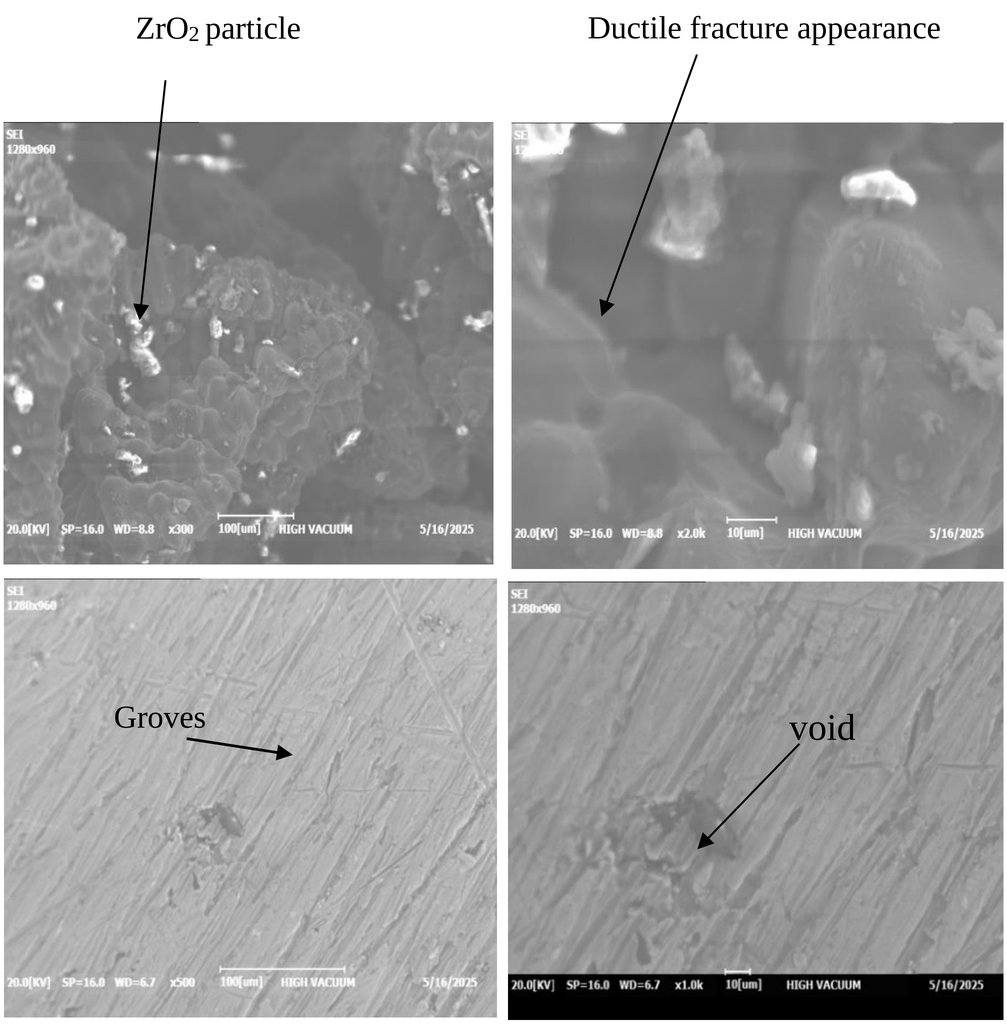


Figure 4-6 Composites SEM image analyzed with different magnification

4.1.4.3 XRD

The X-ray diffraction (XRD) analysis of the synthesized Al7075 hybrid metal matrix composites showed distinct primary peaks corresponding to the α-Al (face-centered cubic aluminum) phase, particularly at 2θ values, 38.5° (111), 44.7° (200), 65.1° (220), and 78.2° (311) which indicates that the aluminum matrix preserved its crystalline structure even after reinforcement addition. There were additional peaks between 20° and 40°, which were related to ZrO_2 (tetragonal and monoclinic phases) and Ti-based phases of Ti-6Al-4V, which confirm reinforcement of ceramic and metal materials into the matrix. The values are similar the XRD pattern obtained in (Sayed et al., 2022). Widening and a slight shift of maxima reveal lattice distortion or strain due to incorporated reinforcements. The absence of any harmful reaction products or intermetallic phases shows that there is appropriate compatibility and thermodynamic stability of chosen reinforcements utilized under processing conditions. Supporting evidence comes from previous works that depicted similar peak trends and retention of phases in Al7075 composites reinforced with ZrO_2 and titanium compounds and revealed similar peak styles and holding of phases in Al7075 composites reinforced with ZrO_2 and compounds based on titanium.

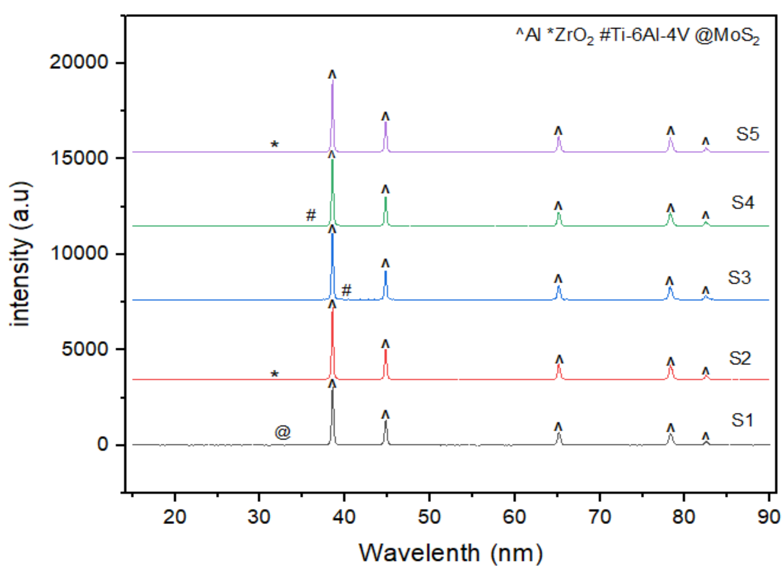


Figure 4-7 The XRD spectrum of samples at various reinforcement compositions

4.1.5 Wear test

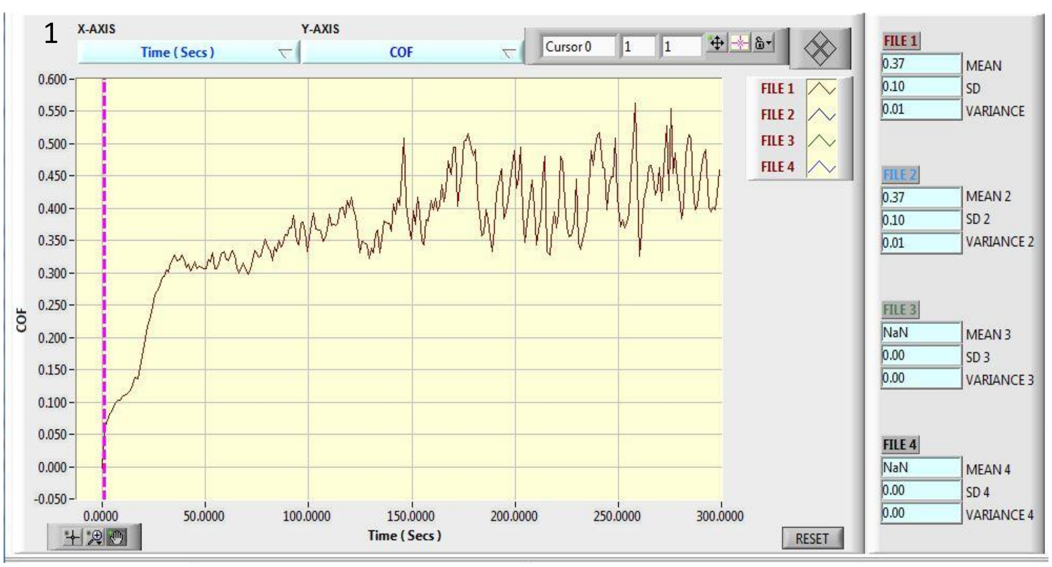
The hybrid metal matrix composites of Al7075 reinforced with various weight percentages of ZrO_2, Ti-6Al-4V, and MoS_2 were investigated to determine the wear behavior by applying a TR-20-MICRO pin-on-disc tribo-tester as per the ASTM G99 standard under dry sliding conditions. The tests were done at constant loading, 30 N, rotational speed, 250 RPM, and 5-minute duration of testing. The counter disc was made of hardened EN31 steel (~60 HRC) with a diameter of the wear track 50 mm. The sliding speed was computed by the equation:

$$V = \frac{\pi D N}{60} = \frac{3.14 \times 0.05 \times 250}{60} \approx 0.65 \text{m/s}$$

where:

- *D* is the wear track diameter (0.05 m)
- *N* is the rotational speed (250 RPM)

The wear performance was evaluated based on frictional force, coefficient of friction (COF), and wear rate for all samples (S1 to S5), with observations made on how reinforcement composition affects tribological behavior.



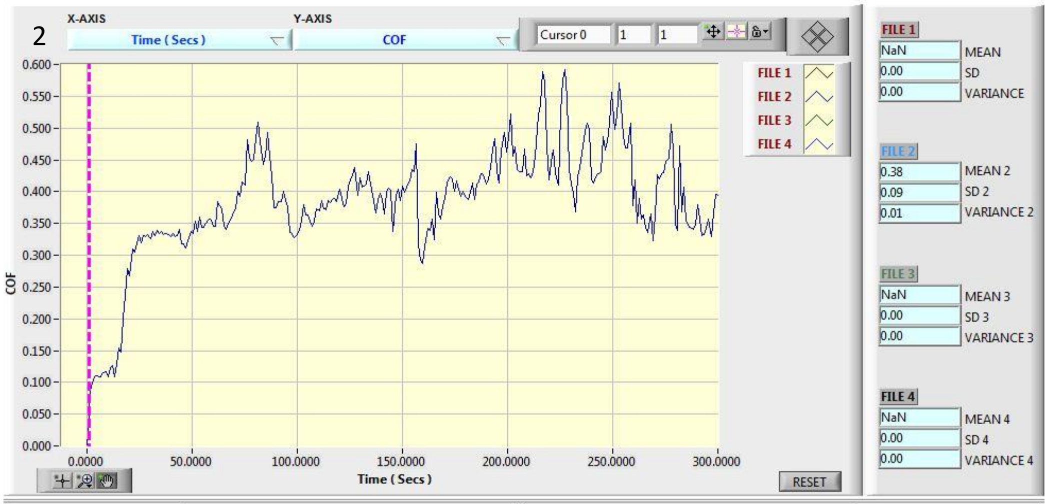


Figure 4-8 Coefficient of friction Vs time of sample 1 and 2

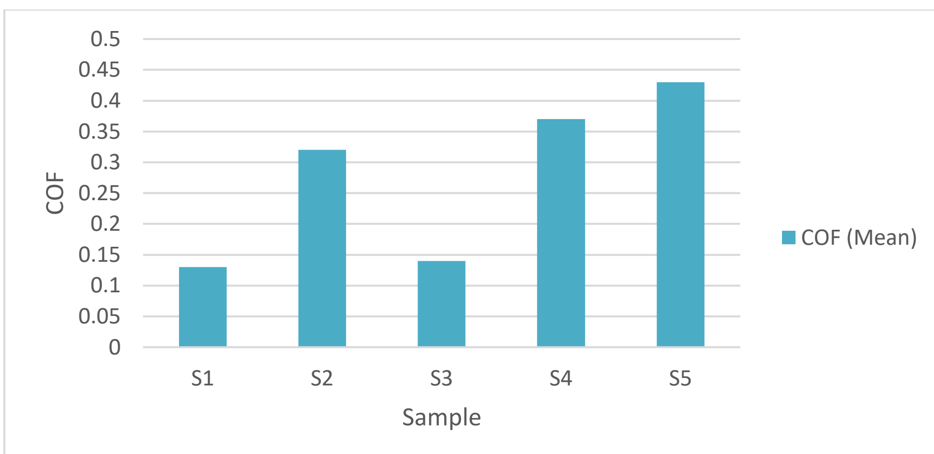


Figure 4-9 Average coefficient of friction (COF)

The frictional force as well as coefficient of friction (COF) were calculated to vary considerably from one sample to another. Amongst these, Sample S5 showed maximum COF of 0.43 and maximum mean frictional force of 12.94 N, followed by Sample S4, which showed each of 0.37 and 11.21 N, respectively. On the contrary, Sample S1 showed minimum COF of 0.13, and corresponding frictional force of 3.8 N. Such variations can be owing to the reinforcement content, dispersion, and type of particles in the matrix material. The higher content of reinforcement in S5 is likely to enhance the contact interfacial rigidity, hence increasing the frictional parameters (Ravindran et al., 2013).

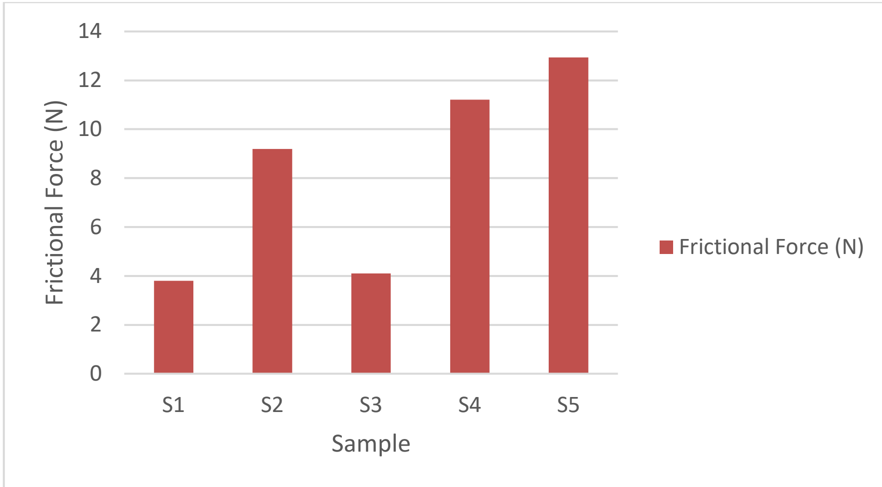


Figure 4-10 Average Frictional Force (N)

Wear, in microns, was quite dissimilar throughout samples. Sample S5 exhibited the minimum wear depth of 5.04 µm, showing even better wear durability, most probably due to synergistic strengthening as well as lubrication of reinforcement, especially MoS_2. Sample S2 exhibited maximum wear depth of 35.46 µm, depicting poor durability against wear despite recording moderate friction values.

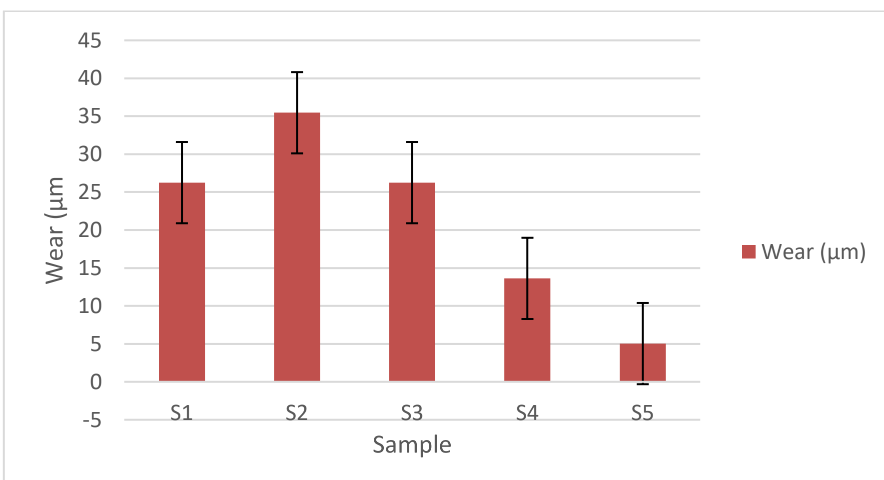


Figure 4-11 Wear in microns

In most cases, results indicate that increased reinforcement content offers higher wear resistance but is associated with higher frictional force and COF, as observed from Sample S5. The inverse relationship of friction and wear in samples (high friction but slight wear in S5) also supports that friction is not always a good measure of severity of wear. The result is in agreement with recent studies, which established that load transfer capacity, interfacial adhesion, and lubrication from solid reinforcements interact in intricate manners (Ali, 2020). Furthermore, Sample S1, which recorded the lowest hardness level (151.2 HV) also registered high wear depth of approximately 27.5 µm. In line with the common belief, materials with lower hardness are supposedly easy to wear out; however, when compared to Sample S2, which was more hard but equally more worn, it can be deduced that hardness does not entirely account for wear resistance. This inconsistency can be attributed to weak bonding, less homogeneous dispersion of reinforcement, or lack of proper lubrication in S1, possibly caused by the lack of adequate MoS_2 dispersion. In all, this demonstrates that wear resistance is affected by more than one aspect, such as the internal structure, reinforcement bonding, and the combined action of all added components, but not solely hardness.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this research, five samples were blended using stir casting with shifting weight percentages of aluminum 7075 alloy combined with different weight percentages of zirconium dioxide, titanium grade-5 alloy, and persistent molybdenum disulfide at 500 rpm stirring speed, 30-minute stirring time, and 700°C stirring temperatures to assess microstructure, density, porosity, compression strength, hardness, wear loss, coefficient of friction, and wear morphology. The conclusion is the following:

- A mixture of Al7075 and the reinforcements was effectively made by stir casting; the reinforcements were precisely measured and combined in the stir casting process and then machined to the desired parameters.
- Using Archimedes' principle, the actual densities were determined. The actual density was less than the theoretical density, and then the result of the porosity was calculated by using both the actual density and theoretical density. As the percentage of reinforcement increased, the porosity increased; high porosity was observed at Al7075/5Zro2/5Ti-6Al-4V/2MoS2.
- The optical microscope Images of the composite showed that the particles of the reinforcements were consistently spread throughout the aluminum alloy (Al7075) matrix and also helped to determine the porosity by optical microscope test. Observed high porosity at Al7075/5Zro2/5Ti-6Al-4V/2MoS2.
- Through a scanning electron microscope, the microstructure and phase of the composite were studied. Good fabrication of the stir casting process was effective in achieving homogeneous reinforcement distribution, thus resulting in a strong composite.
- The hardness of prepared hybrid aluminum matrix composite improved with an increase in the weight percentage of ZrO_2 and Ti-6Al-4V. The highest hardness was recorded on the Al7075/5Zro2/5Ti-6Al-4V/2MoS2 composite, with an average hardness value of 218.16HV. On the other side, the lowest hardness value was observed at Al7075 cast without reinforcement, which has an average hardness value of 68 HV. Thus, the hardness of Al7075 has increased by 150.16 HV.

- The X-ray diffractometer (XRD) shows the availability of the Al7075 and the reinforcement that are used.
- Compression strength was determined by applying 50KN force onto the spaceman. Compression strength of Al/5Zro2/1.5Ti-6Al-4V/2MoS2 was improved.
- By a pin-on-disc tribo-tester, coefficient of friction (COF) and wear were measured and studied. Al/5Zro2/1.5Ti-6Al-4V/2MoS2 showed maximum COF and maximum mean frictional force, and Al7075/5Zro2/5Ti-6Al-4V/2MoS2 showed good wear durability.

5.2 Recommendation

Because of its low cost, ease of use, and capacity to guarantee equal distribution of reinforcing particles, stir casting is recommended as the most practical method. It can be suggested that Al7075/5Zro2/5Ti-6Al-4V/2MoS2 composites are a good substitute for materials with higher densities that are used for automotive bodies, engine blocks, connecting rods, rotor drums and disks, etc., because they have demonstrated significant improvements in hardness, tensile strength, wear loss, and coefficient of friction when compared to the base material. With the right stir casting technique, it is possible to produce large quantities of hybrid aluminum alloy (Al7075) reinforced with ZrO2, 5 Ti-6Al-4V, and MoS2, which is utilized for automotive parts and increases machine strength, durability, and weight reduction. As a result, the machine uses less fuel and lasts longer. However, to strengthen future research, it is recommended to include baseline control samples such as unreinforced Al7075 and samples with individual reinforcements (e.g., only ZrO_2, only Ti-6Al-4V, or only MoS_2). This would enable a more precise evaluation of the synergistic effects of hybrid reinforcements and allow better comparison of individual contributions.

5.2.1 Future Work

The following studies are recommended for further research from various angles in the subject matter of hybrid metal matrix composites Al7075/Zro2/ Ti-6Al-4V/MoS2:

- Better quality composites are produced through the design and application of permanent casting molds.
- A key component of machining is looking into the machining characteristics and optimizing the machining parameters for this hybrid composite. The design of the stir cast-

ing setup, which utilizes a speed controller motor and temperature control unit with an atmosphere control system, allows for the optimization of process parameters and will result in a higher-quality composite.

- Research on hybrid composites also includes examining their mechanical, physical, and tribological characteristics as well as further processing them by extrusion, forging, heat treatment, and other methods.
- usage of a controlled mechanical stirrer rather than a hand-held one is recommended. A programmable stirring device having a constant rotational speed and automatic control would provide a more uniform shearing environment, increase reinforcement dispersion, and provide improved repeatability of results.
- Though the present work offers in-depth information regarding the mechanical and tribological behavior of hybrid composites with Al7075, further experimental analysis is advised. Considering constraints in terms of test setups and time, desired characterizations such as corrosion resistance, fatigue life, and impact strength were not undertaken. These are very important in aerospace and vehicular applications where the material will be exposed to harsh environments and will be under cyclic loads. Future work should involve electrochemical tests for corrosion, fatigue life analysis, and Charpy or Izod impact test to yield a holistic understanding of the material's structural suitability.

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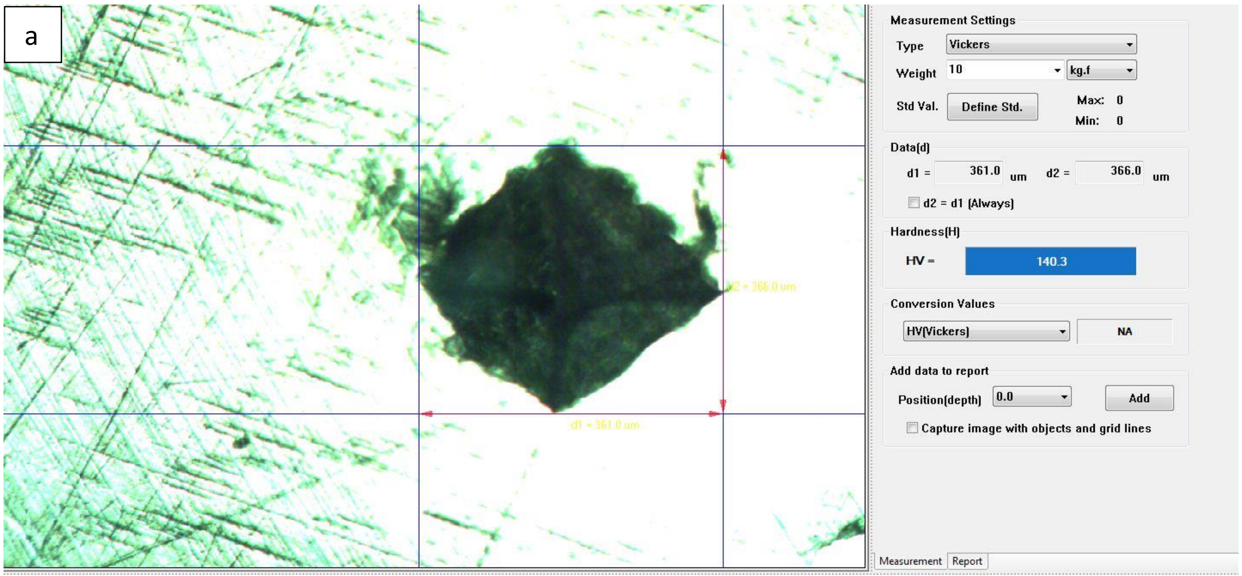
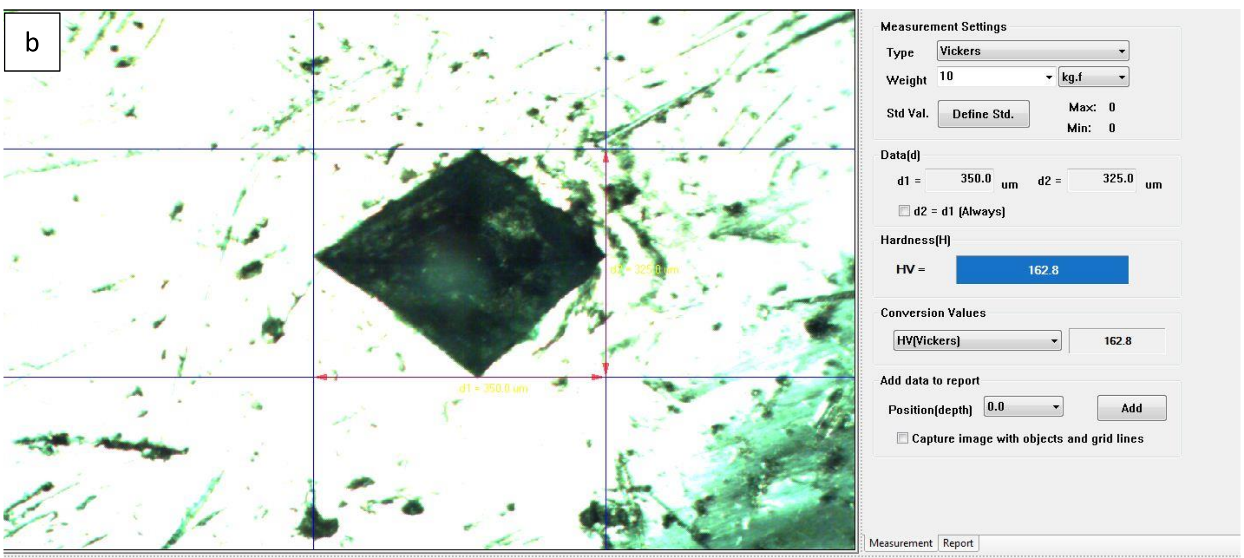
Appendix I: Micro-Hardness Result for S-1, S-2, S-3, S-4 and S-5 (From Vickers Hardness)





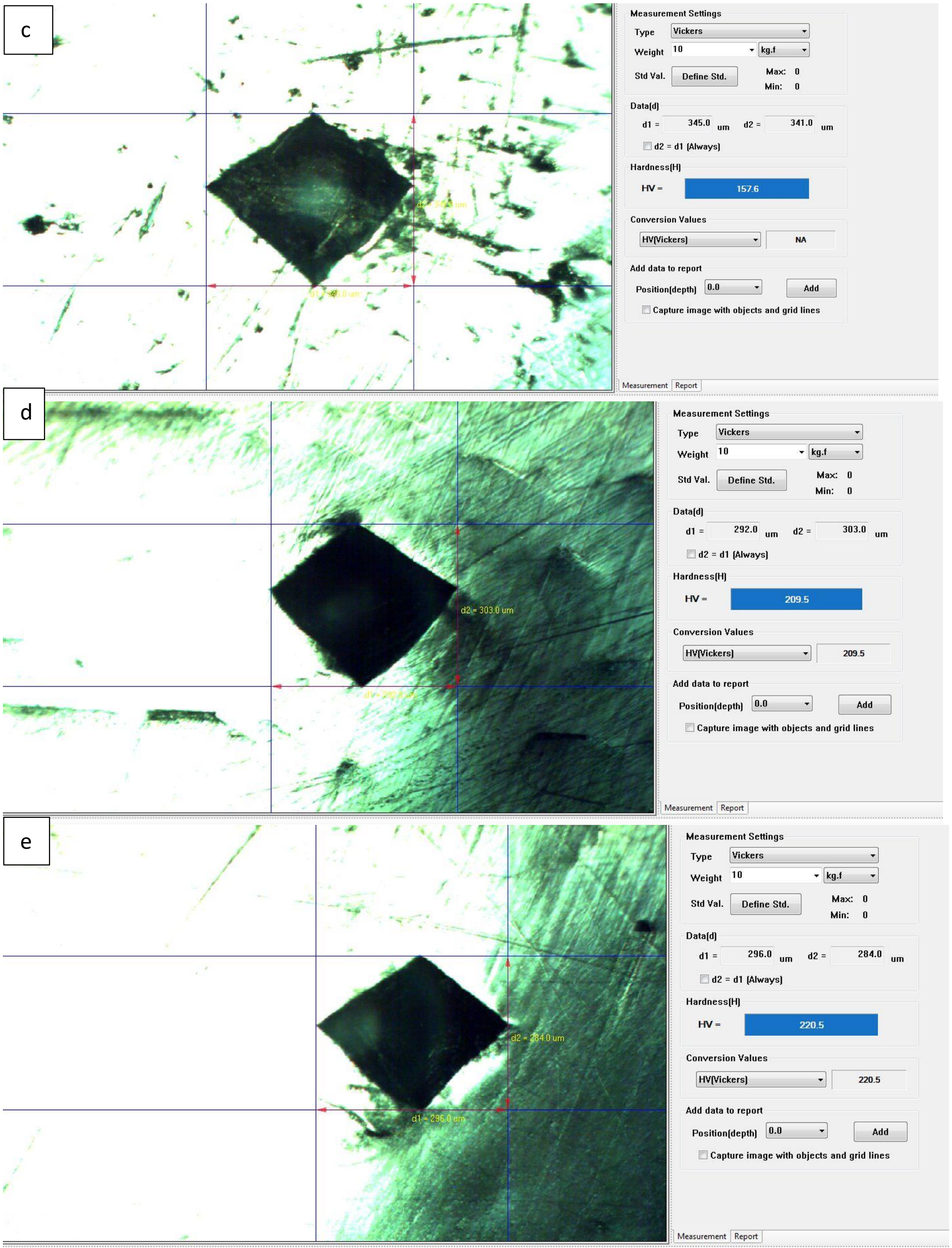
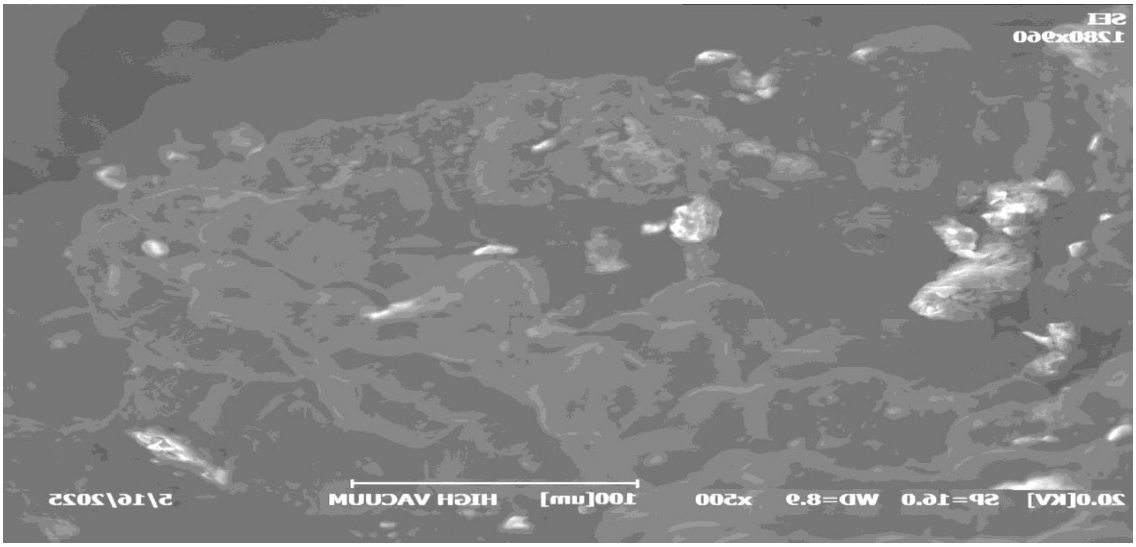
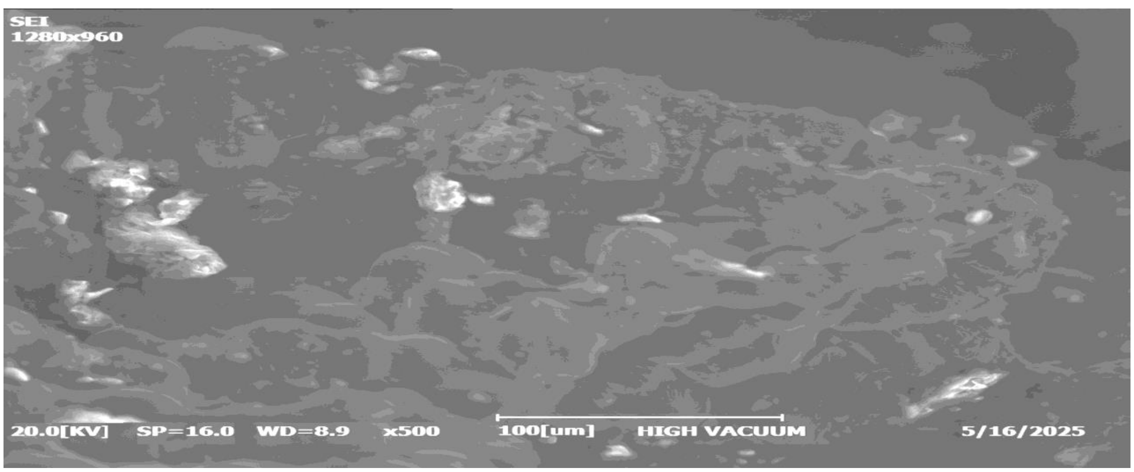
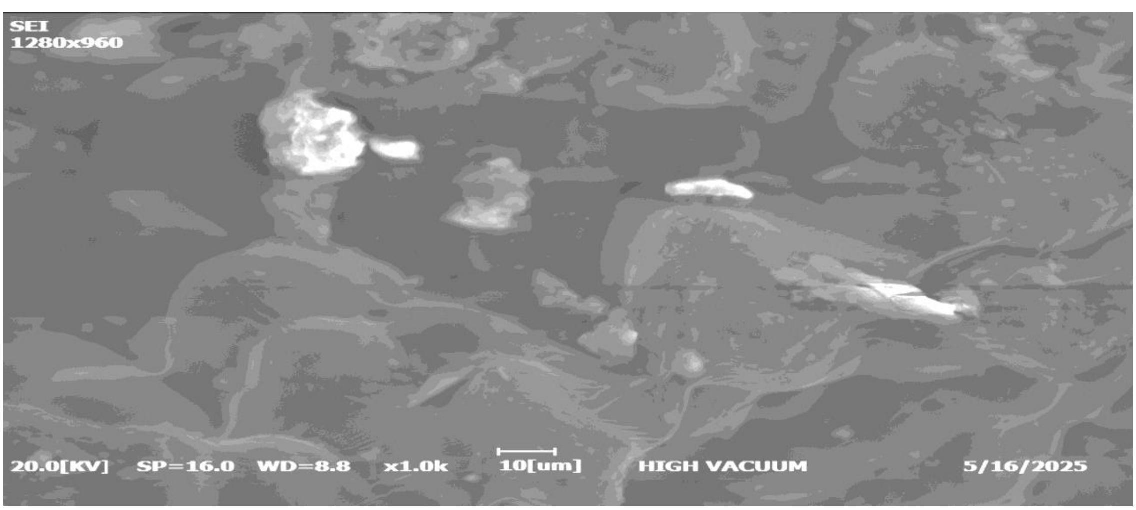


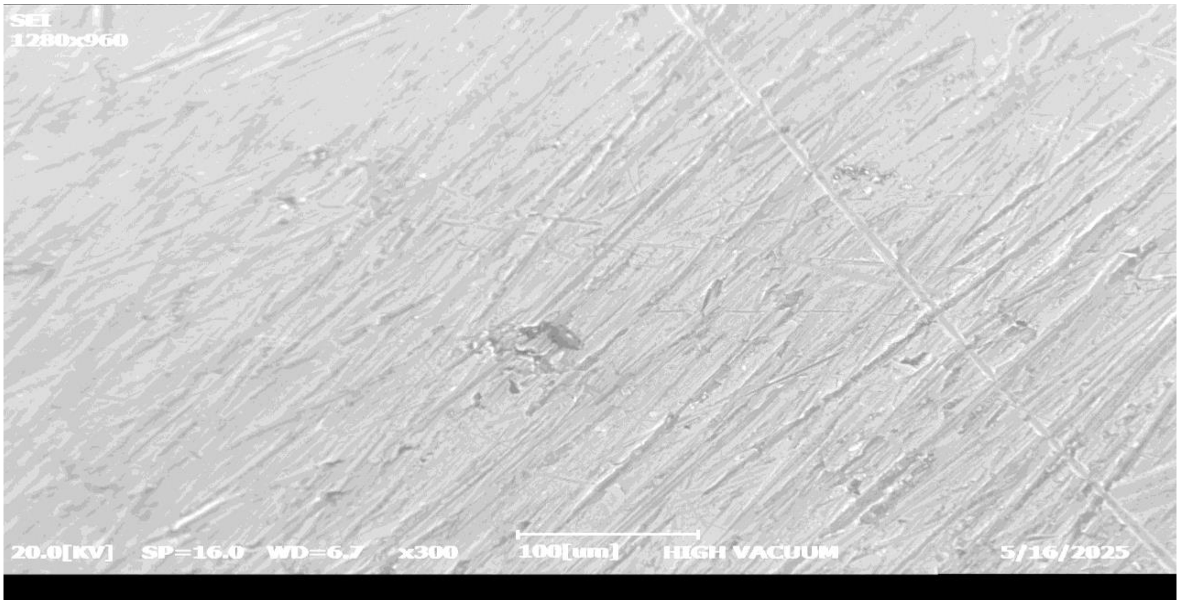
Figure A.1 Microhardness Vickers value of (a) sample 1, (b) sample 2, (c) sample 3, (d) sample 4, and (e) sample 5

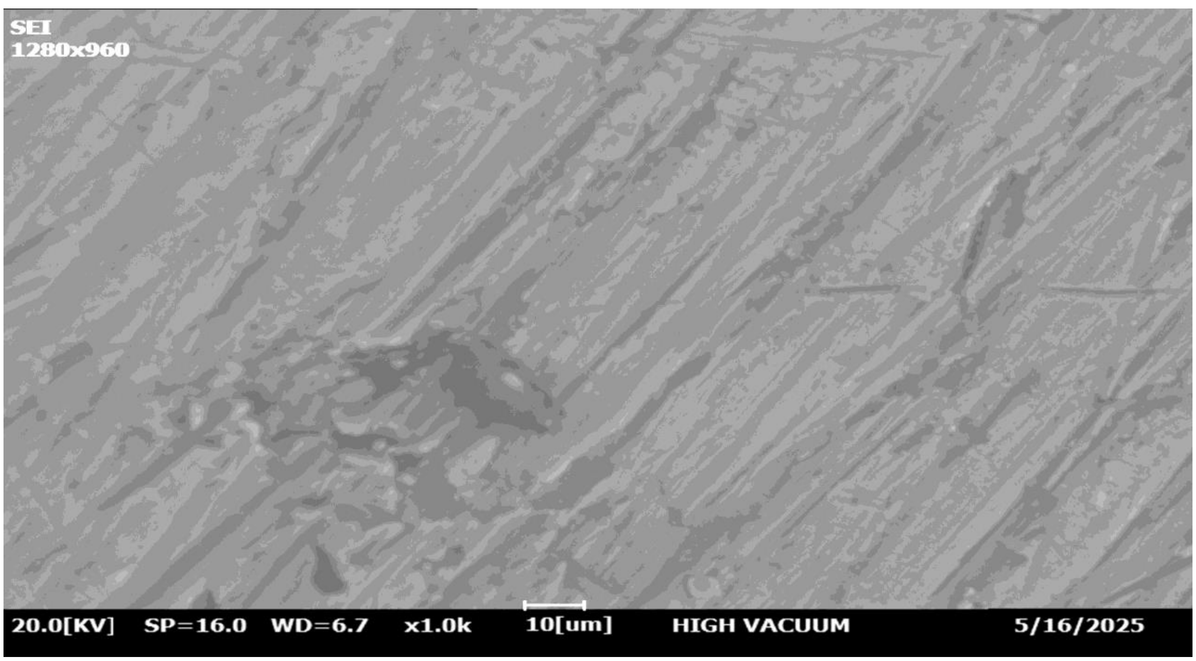
Appendix II SEM Result for S-1, S-2, S-3, S-4 and S-5








SEI
1280x960
20.0[KV] SP=16.0 WD=6.7 x300 100[um] HIGH VACUUM 5/16/2025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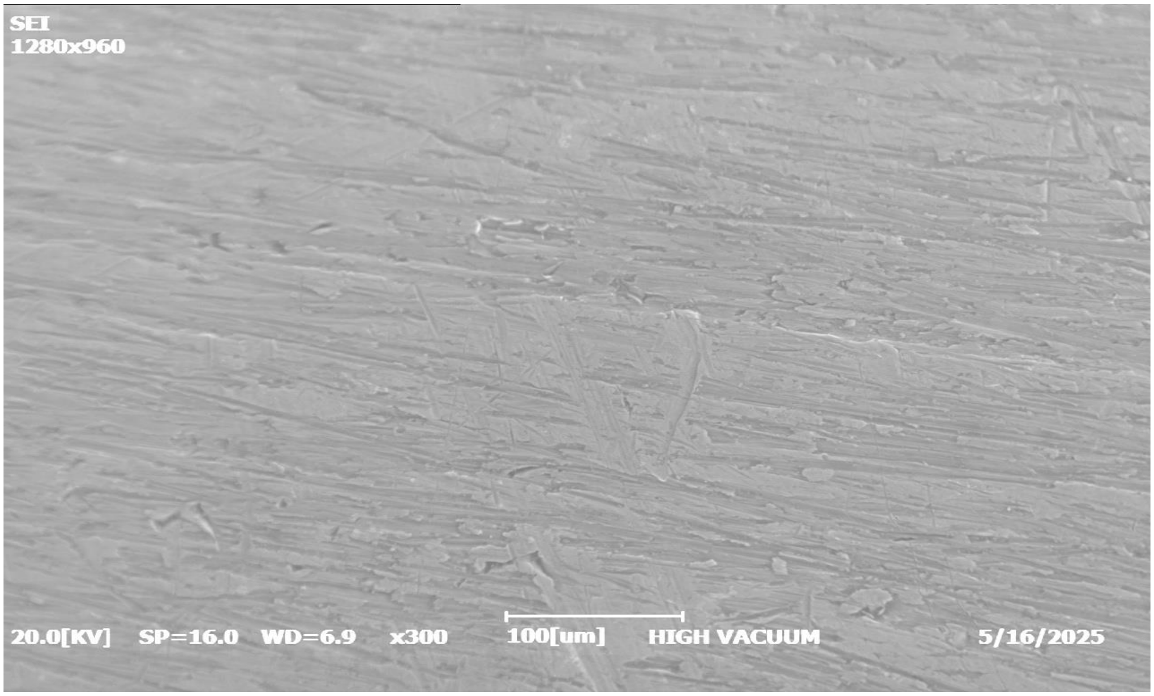
1280x960
20.0[KV] SP=16.0 WD=6.7 x1.0k 10[um] HIGH VACUUM 5/16/2025



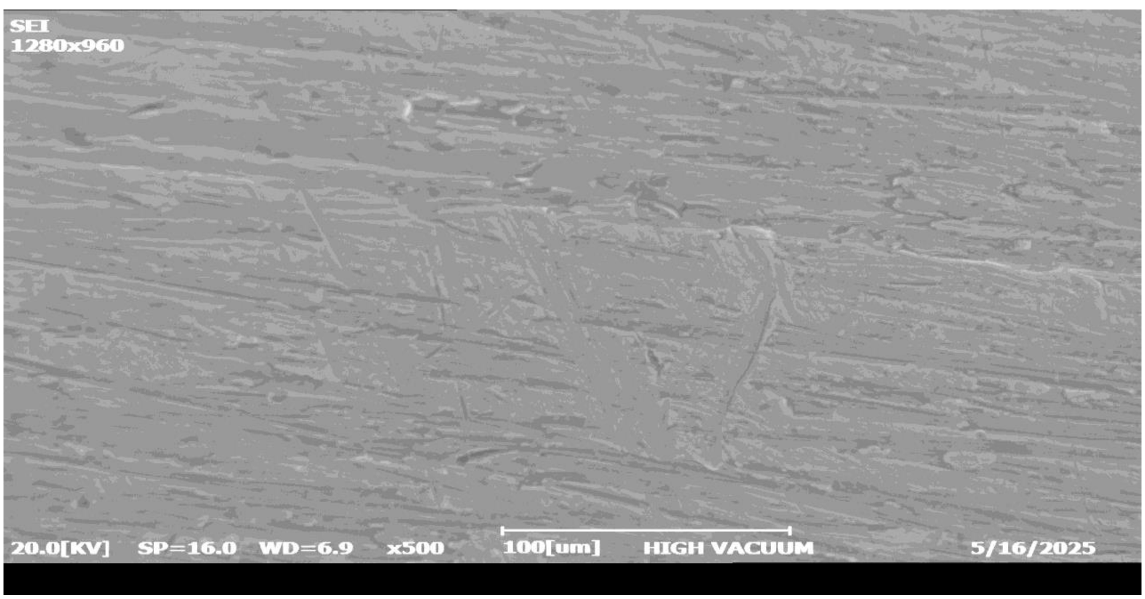
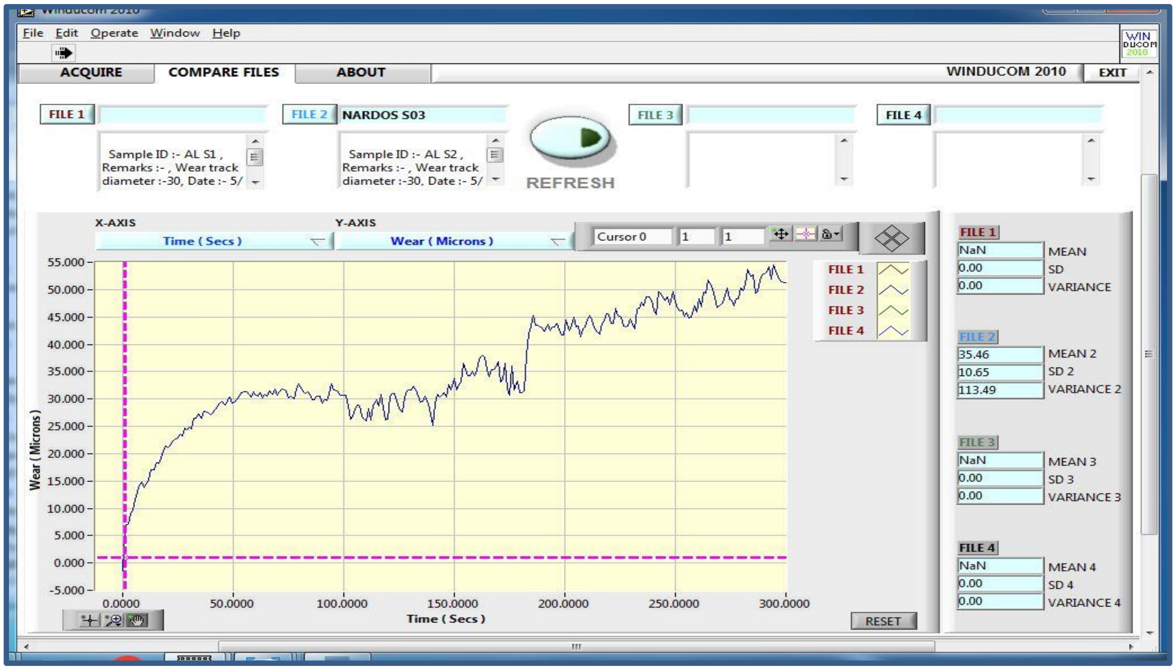
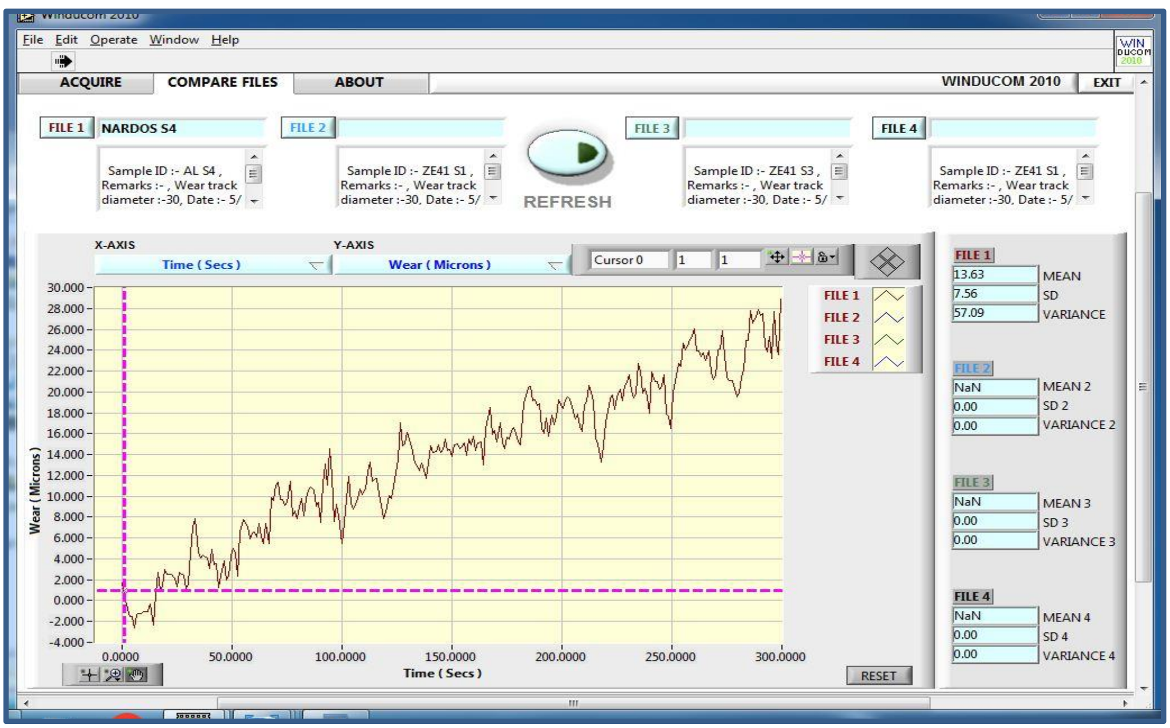


Figure A-2 SEM result of S-1, S-2, S-3, S-4 and S-5

Appendix III: Wear Rate Vs Time Result for Sample-1, Sample-2, Sample-3, Sample-4 and Sample-5 (From Pin On
Disc Apparatus)


File Edit Operate Window Help
ACQUIRE
COMPARE FILES
ABOUT
WINDUCOM 2010
EXIT
FILE 1
FILE 2
NARDOS S03
FILE 3
FILE 4
Sample ID :- AL S1 , Remarks :- , Wear track diameter :-30, Date :- 5/
Sample ID :- AL S2 , Remarks :- , Wear track diameter :-30, Date :- 5/
REFRESH
X-AXIS
Y-AXIS
Time (Secs)
Wear (Microns)
Cursor 0
Wear (Microns)
Time (Secs)
RESET
MEAN
SD
VARIANCE
35.46
10.65
113.49
MEAN 2
SD 2
VARIANCE 2
MEAN 3
SD 3
VARIANCE 3
MEAN 4
SD 4
VARIANCE 4


File Edit Operate Window Help
ACQUIRE
COMPARE FILES
ABOUT
WINDUCOM 2010
EXIT
FILE 1
NARDOS S4
FILE 2
FILE 3
FILE 4
Sample ID :- AL S4 , Remarks :- , Wear track diameter :-30, Date :- 5/
Sample ID :- ZE41 S1 , Remarks :- , Wear track diameter :-30, Date :- 5/
Sample ID :- ZE41 S3 , Remarks :- , Wear track diameter :-30, Date :- 5/
Sample ID :- ZE41 S1 , Remarks :- , Wear track diameter :-30, Date :- 5/
REFRESH
X-AXIS
Y-AXIS
Time (Secs)
Wear (Microns)
Cursor 0
Wear (Microns)
Time (Secs)
RESET
13.63
7.56
57.09
MEAN
SD
VARIANCE
MEAN 2
SD 2
VARIANCE 2
MEAN 3
SD 3
VARIANCE 3
MEAN 4
SD 4
VARIANCE 4

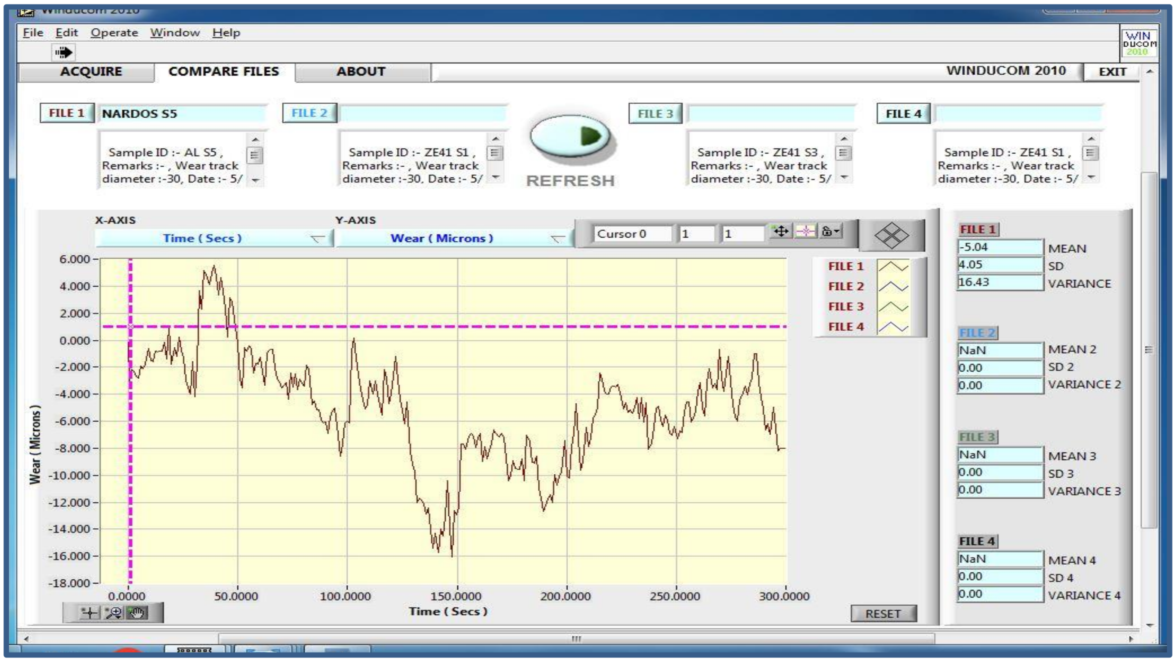


Figure A-3 Wear Rate Vs Time Result for Sample-1, Sample-2, Sample-3, Sample-4 and Sample-5