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ERBIL POLYTECHNIC UNIVERSITY

Investigation of the Mechanical Properties and Wear Resistance of Al6061 Composites Fabricated by Stir Casting Method

A Thesis Submitted to the Council of the College of Erbil Technical Engineering at Erbil Polytechnic University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical and Energy Engineering

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2023

DECLARATION

I declare that the master thesis entitled: "*Investigation of the Mechanical Properties and Wear Resistance of Al6061 Composites Fabricated by Stir Casting Method*" is my own original work, and hereby I certify that unless stated, all work contained within this thesis is my own independent research and has not been submitted for the award of any other degree at any institution, except where due acknowledgement is made in the text.

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I confirm that I have reviewed the thesis entitled *"Investigation of the Mechanical Properties and Wear Resistance of Al6061 Composites Fabricated by Stir Casting Method"* from the English linguistic point of view, and I can confirm that it is free of grammatical and spelling errors.

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EXAMINING COMMITTEE CERTIFICATION

We certify that we have read this thesis entitled *"Investigation of the Mechanical Properties and Wear Resistance of Al6061 Composites Fabricated by Stir Casting Method"* and as examining committee, examined the student (*Khoshy Hamza Hassan*) in its content and what related to it. We approve that it meets the standards of a thesis for the degree of Master in Mechanical and Energy Engineering.

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DEDICATION

This thesis is dedicated to my beloved family, who has been a constant source of support and encouragement during the challenges of my studies. I wholeheartedly thank my loving parents, who have always loved me unconditionally and whose good examples have taught me to work hard for the things I aspire to achieve.

My beloved siblings, stand by me and help me in all things, great and small.

I dedicate this work and give special thanks to all my friends who supported me until my research was fully finished.

I am genuinely thankful to have you all in my life.

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ABSTRACT

Aluminium matrix composites (AMCs), which have better tribological and mechanical properties than other conventional alloys, have a lot of potential for important uses in the automotive, defense, aerospace, marine, agricultural, and nuclear engineering industries. In this work, attempts were made to construct AMCs reinforced with various weight percentages of different reinforcement particles, namely boron carbide (B_4C), titanium diboride (TiB_2), and silicon carbide (SiC), in order to improve the tensile behaviour, hardness, and wear resistance. The reinforcement particles with different weight percentages (1, 3, and 5%) were added to Al6061 using the stir casting technique. This work can be divided into two parts: in the first part, the reinforcement particles were added separately (single-reinforcement composite), while in the second part of this work, hybrid composites (hybrid-reinforcement) were fabricated. The tensile strength, hardness, and wear of the AMCs were investigated. Each experiment was repeated three times to ensure repeatability, and an average was taken. In addition, an optical microscope and a scanning electron microscope were used to characterize the AMCs. The SEM examination shows that the reinforcement particles are distributed evenly throughout the Al6061 matrix. The results of the first part of this investigation show that adding different amounts of TiB_2 and B_4C separately, i.e., as single-reinforcement composite, enhanced the ultimate tensile strength, the composites' hardness, and their wear resistance. The most interesting thing to come out of the data is that adding a small amount of TiB_2 particles increases the hardness of the composites much more than previous research has shown. The results also showed that by adding 1 % wt. of B_4C, and 3 wt.% of TiB_2, the composites had a lower wear rate and higher wear resistance compared to the base alloy. The findings also showed that by adding 5% wt. of SiC, the wear resistance and hardness were enhanced compared with the base alloy. However, 1 % wt. of the particles has a higher ultimate tensile strength.

In the second part of this study, an attempt has been made to fabricate hybrid aluminium matrix composites (Al6061/3% B_4C+TiB_2) at various proportions of TiB_2 (1, 3, 5% wt.). The results showed that (Al6061/3%B_4C+5%TiB_2) has a higher hardness and tensile strength. Due to the porosity in the samples, (Al6061/3%B_4C+1%TiB_2) has a lower wear rate and is more resistant to wear. The most obvious finding to emerge from this study is that adding TiB_2 particles reinforced with Al6061 as a matrix has higher results compared to the other particles that are used.

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NOMENCLATURE AND ACRONYMS

All symbols are also defined in the text.

Symbol	**Description**	**Units**
W_1	Weight before test	g
W_2	Weight after test	g
W_r	Wear rate	mm^3
ΔW	Wear amount	g
ρ	Density	g/cm^3

ABBREVIATIONS AND ACRONYMS

AA	Aluminium Alloy
Al	Aluminium
Al_2O_3	Aluminium Oxide
AMCs	Aluminium Matrix Composites
ASTM	American Society for Testing and Materials
B_4C	Boron Carbide
BN	Boron Nitride
C	Carbon
CMC	Ceramic Matrix Composite
CO	Carbon monoxide
Cr	Chromium
Cu	Copper
EDX	Energy Dispersive X-ray
Fe	Iron
Gr	Graphite
HAMCs	Hybrid Aluminium Matrix Composites

HB	Brinell Hardness
HCl	Hydrochloric Acid
HF	Hydrofluoric Acid
HNO_3	Nitric Acid
HV	Vickers Hardness
Mg	Magnesium
MgO	Magnesium Oxide
MMCs	Metal Matrix Composites
Mn	Manganese
Mo	Molybdenum
Ni	Nickel
P	Phosphorus
PMC	Polymer Matrix Composite
rpm	Revolution per minute
S	Sulfur
SAF	Sandvik Austenitic Ferritic stainless steel
SEM	Scanning Electronic Microscope
Si	Silicon
SiC	Silicon Carbide
Ti	Titanium
TiB_2	Titanium Diboride
Zn	Zinc
Zr	zirconium

CHAPTER ONE

INTRODUCTION

Aluminium matrix composites (AMCs) have emerged because of advancements in mechanical and wear characteristics and uses of composites based on lightweight metals. Presently, AMCs are considered as the most promising materials for structural and functional applications. As reinforcement, many materials, including Al_2O_3, TiB_2, B_4C, SiC, and graphite, have been used to improve the matrix's mechanical and tribological properties. This chapter contains four parts. The first part is an overview of the study. The problem statement has been described in part two. The aims of the study are highlighted. Finally, this chapter has mentioned the layout of the thesis.

1.1 Overview

Studies of materials show the importance of the fact that when the chemical and physical properties of the components are incompatible, a new substance is created that is different from the actual components. Additionally, due to the inability of pure metals or conventional materials to meet the demands of modern products and due to their high specific modulus, superior strength, and damping capacity, composites have replaced conventional materials (Kerni *et al.*, 2020). Two or more materials are combined to form composites with diverse chemical and physical properties, resulting in enhanced quality and performance over the separate components. Composites are made of reinforced material, which may be continuous or discontinuous, and a matrix in which it is embedded. Reinforcement phase materials might be in the form of whiskers, fibers, or particles. The materials used in the matrix phase are continuous. Ceramic matrix composites (CMCs), metal matrix composites (MMCs), and polymer matrix composites (PMCs) are the three most frequent materials used in the industry (Ashik and Sharma, 2015). Figure 1.1 demonstrates that the two essential components of any composite material are matrix and reinforcement (Yao, Zhou and Zhou, 2019). Reinforcement is the primary component of a composite and takes the bulk of the composite material's weight. Reinforcement must be hard (in some case soft), brittle, and strong to take the structure's weight. A matrix is the part of a composite that completely covers the reinforcing material. In a composite, the matrix's function is to distribute the load to the supporting components, protect the often-brittle reinforcements from outside and from environmental influences, and keep the whole composite structure together (Selvam, Dinaharan and Rai, 2020). The composite materials` characteristics are influenced by various factors, including the type of the reinforcement and matrix (Elanchezhian *et al.*, 2018).

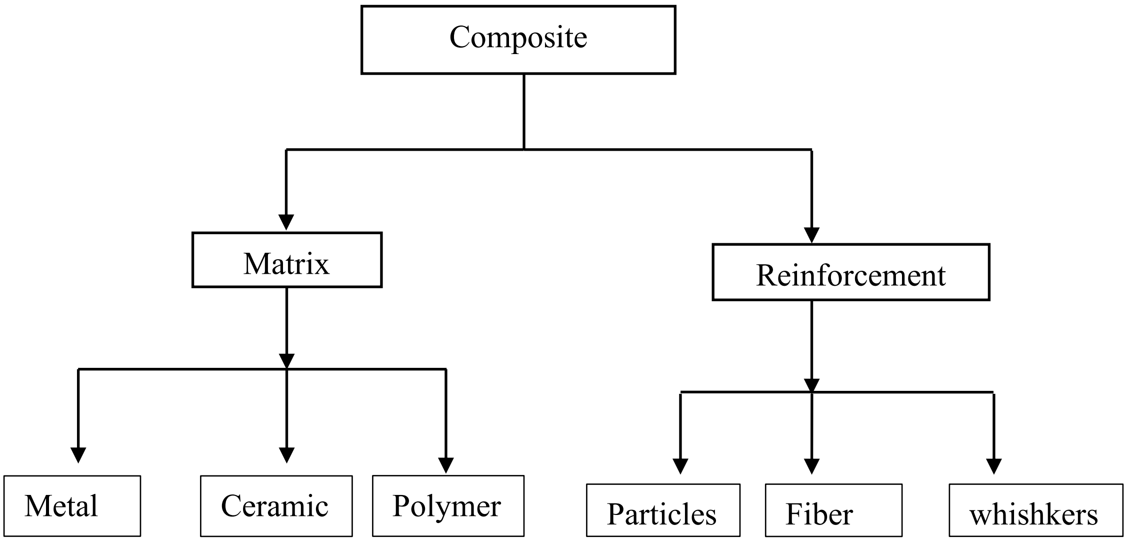


Figure 1.1 Components of composites (Yao, Zhou and Zhou, 2019).

CMCs were made to fix the problems with typical technical ceramics such as zirconia, silicon nitride, aluminium nitride, silicon carbide, and alumina, which break simply under thermomechanical or mechanical stresses due to tiny flaws or scratches (McKimpson and Scott, 1989). The most popular material used to manufacture them is ceramic fiber, which includes oxides, carbides, and other materials trapped in a matrix. Ceramic materials are used in both matrix and reinforcement. Most of the time, these material are used to make electrical and electronic parts and parts for cars (Basutkar and Kolekar, 2015a).

In PMC, fibers serve as reinforcement, while polymers of organic serve as a matrix. Compared to those of the matrix, the strength and elasticity of the reinforcement are greater. The reinforcement typically has substantially greater elastic modulus and stronger than the matrix. Therefore, fibers serve as the primary load-bearing component. A matrix material with a lot of sticking power is needed to connect fibers securely (Advani and Hsiao, 2012).

Metal matrix composites (MMCs) with two or more reinforcement materials, known as hybrid metal matrix composites. Because of their greater wear resistance, higher strength, lighter weight, increased fatigue resistance, and better dimensional stability compared to traditional composites, they have attracted a lot of attention in the materials study field (Gireesh, Prasad and Ramji, 2018). Aluminium and its alloys are among the most studied types of matrix material for MMCs because aluminium is the most used metal in the industry (Sagar, Suresh and Sampathkumaran, 2021). Aluminium matrix composites (AMCs) are promising materials for many different uses due to their high-quality mechanical and physical characteristics.

An AMCs is an artificial material that consists of a minimum of two chemically distinct components, one of which is aluminium and the other of which is reinforcement (Reddy, Kesavan and Vijaya Ramnath, 2018). As compared to pure aluminium, AMCs materials have increased tensile strength, decreased weight-to-strength ratios, increased hardness, and decreased thermal expansion coefficients (Soltani *et al.*, 2017). Because of its improved properties, AMC is increasingly important in sectors that use high-profile standard metals (Soltani *et al.*, 2017; Garg *et al.*, 2019; Varshney and Kumar, 2021)

AMCs may be reinforced using a variety of materials. Popular reinforcing materials include SiC, TiB_2, B_4C, Al_2O_3, fly ash, and graphene (Kumar and Kumar, 2015; Bhaskar, Kumar and Patnaik, 2019). Because of their wide range of reinforcing options, aluminium-reinforced composites show great promise in many industries, including transportation, aerospace, electronics, and communications (Kumar and Kumar, 2015). Metal matrix composites can be made with a number of different methods, such as deposition, powder metallurgy, diffusion bonding, infiltration, and stir casting (Kandpal, Kumar and Singh, 2017). Figure 1.2 depicts the categorization of processing techniques as they are used in various processing stages (McKimpson and Scott, 1989). The manufacturing procedure used to create the composite impacts the performance characteristics of materials (Aktaş and Diler, 2018). Density distribution, hardness distribution, wettability, clustering/agglomeration, homogeneity, reinforcement distribution, etc., may be affected by the production procedure, which in turn can influence the mechanical behaviour of the material (Panwar and Chauhan, 2018). The most commonly used to synthesize MMCs is the stir casting method. In this method, the matrix is combined with the fractured reinforcement, while the molten metal is constantly stirred by an impeller or stirrer, usually made of graphite. The desired shape is achieved by pouring the liquid into a mould (Annigeri and Veeresh Kumar, 2017).

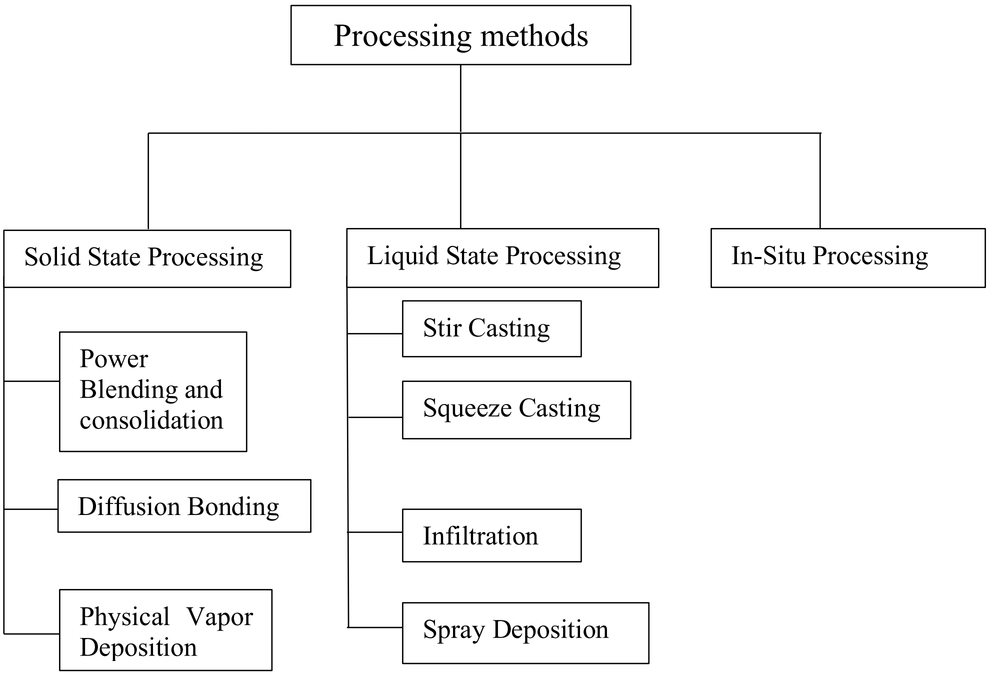


Figure 1.2 Processing method of MMCs (McKimpson and Scott, 1989).

1.2 Composite Classification

The term "composite" refers to manufactured materials that consist of two or more constituent parts. They are generally created to enhance the quality of more conventional materials. The characteristics might include mechanical and wear (Selvam, Dinaharan and Rai, 2021). These characteristics are the primary justification for being a suitable alternative to conventional materials utilized in different industries, including automotive, aerospace, and others.

Composites are composed of a continuous part mixed with one or more discontinuous parts. The continuous part is the matrix, while the discontinuous part is the reinforcement, which is usually more rigid and stronger. Either the sum of the qualities of the component parts, expressed as a percentage, or the synergistic interactions between the constituents might account for the composite properties, leading to enhanced or improved properties. The following factors are crucial in establishing the composite's properties. Some of these factors include the reinforcement/matrix ratio, the adhesion capabilities at the reinforcement/matrix contact, the reinforcement geometry, and the properties of reinforcement materials and the matrix (Malaki *et al.*, 2021). Because of their structure and properties, composite materials find use in many different areas. Composites may be used to fabricate a wide variety of multi-part machine components, including intake manifolds, cylinder heads, and engine blocks (Pastuszak and Muc, 2013).

According to the kind of matrix and reinforcement utilized, composites could be grouped. More than half of the material is a matrix, and the purpose of the reinforcement is to provide the properties that are lacking in the matrix. According to the matrix material, Figure 1.3 is a plaint diagram explaining the categorization of composites (Gavalda Diaz *et al.*, 2019). As mentioned earlier in this chapter, matrix materials may be made of metal, ceramic, or polymer according to the specifics of the intended usage (Bauri and Yadav, 2018). As a result, according to the kind of matrix used, composites are referred to in this category.

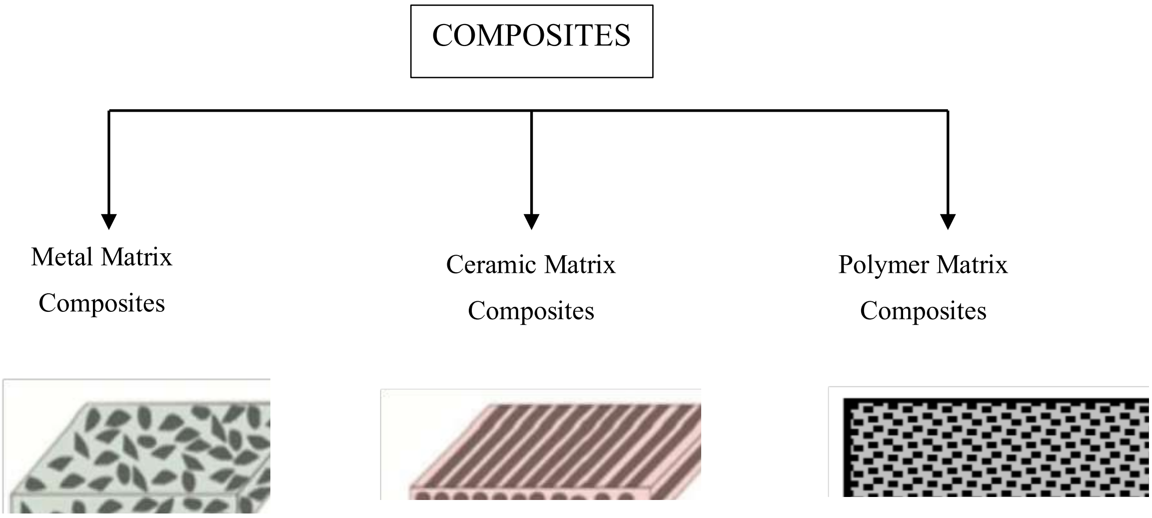


Figure 1.3 Classification of composites according to matrix material (Bauri and Yadav, 2018)

MMCs are the main focus of this study. Consequently, the following section heading will discuss and offer details on MMCs, including their characteristics and production methods.

1.2.1 Metal Matrix Composites

The matrix of the MMC may be made of various metals and metal alloys, including aluminium, magnesium, copper, iron, titanium, and their respective alloys (Gavalda Diaz *et al.*, 2019). Ceramic and metal may both be used as reinforcing components (Mahesh Kumar and Venkatesh, 2018). Compared to their unreinforced matrix counterparts, MMCs can function at greater temperatures. The advantages of MMCs over monolithic alloys are as follows (Ceschini *et al.*, 2017):

- Reduce weight by using materials with a high specific ratio of strength-to-density. (Specific strength).
- Fatigue resistance and enhanced wear resistance.
- Stability in dimensional.
- Stability at high temperatures

MMC aims to make materials that combine the benefits of metallic materials with those of second-phase (reinforcement) materials. Because of their better particular stiffness and strength, MMCs are preferred for structural applications compared to unreinforced alloys. MMCs are advantageous because of their strong wear resistance, low density, high-temperature limitations, and enhanced specific stiffness and strength. The type of reinforcement is an essential factor to consider when selecting a matrix. An analysis of each material's properties and bonding with each other is the basis for choosing the MMC material (Garg *et al.*, 2019). Depending on the matrix materials, MMCs are categorized into several classes. Aluminium–matrix composites (AMC) are the ones that have been studied the most because they are used so often in the industries of aerospace and automotive. Mainly due to its superior strength, lower density, enhanced temperature characteristics, increased stiffness, wear resistance, and controlled thermal expansion (Haghshenas, 2016).

1.2.2 Ceramic Matrix Composites

Ceramic Matrix Composites (CMCs) are a distinct and relatively new structural material class, it may vary with the interphase type and processing route (Krenkel and Reichert, 2017). CMCs were made to fix the problems with common technical ceramics including zirconia, silicon nitride, aluminium nitride, silicon carbide, and alumina, which are readily damaged by mechanical or thermomechanical pressures due to imperfections such as scratches. CMCs are both a subset of ceramics and a subset of materials of composite. Typically, to create them ceramic fibers are encased in a matrix, such as oxides, carbides, and other materials (Basutkar and Kolekar, 2015). Silicon carbides are often used in CMCs as matrix and reinforcements. However, silicon carbide reinforcements may be made in various shapes and sizes to achieve the desired characteristics (Trinh and Sastry, 2003). Compared to metals, all composite materials offer strong damage resistance, better specific characteristics (high strength-to-weight ratio), and great stiffness throughout various machining conditions. As a result, they are a viable alternative to traditional materials in many technical applications. CMC has several applications in transportation, electricity, electronics, and aerospace. In addition, glass CMCs are widely used in blades of turbine, planes of high-speed civil transport, and planes of supersonic (Rosso, 2006).

1.2.3 Polymer Matrix Composites

Polymers have a much more intricate structure than metals or ceramics. They are inexpensive and simple to process. The matrix in PMC is made up of organic polymers, while the reinforcement is made up of fibers. The reinforcement typically has substantially greater strength and elastic modulus than the matrix. It resulted in fibers being able to support the load-bearing component. However, a matrix material with a sufficient range of characteristics to strongly link fibers together is required. In addition, the matrix material may help to transmit the loads to the fiber in a suitable manner and distribute them evenly. Therefore, in polymer matrix composites, the performance of fiber, matrix, and the interface between them directly affects the performance of all the structures (Kessler, 2012; Khashaba, 2013).

1.3 Reinforcement Types

Compared to the matrix, reinforcement is more rigid and durable. It is called the dispersed or reinforcement phase. The initial functions of reinforcements are to support the matrix structure, bear incoming loads, and enhance material volume (Selvam, Dinaharan and Rai, 2021). A composite material's strength depends a lot on its reinforcement, which could be in a random or continuous pattern in the matrix, as well as its shape, type, ratio, distribution, and direction (Selvam, Dinaharan and Rai, 2021). Materials of carbon-based (nanotubes of carbon, graphene, etc.), wolfram (W), boron carbide (B_4C), tungsten carbide (WC), titanium carbide (TiC), silicon carbide (SiC), titanium diboride (TiB_2), and aluminium oxide (Al_2O_3) are the most common particle reinforcing components in MMCs (Tjong and Ma, 2000). They are usually includes the following characteristics (Haghshenas, 2016):

- Low density
- Excellent mechanical properties and chemical characteristics

- Good thermal stability
- High tensile and compression strength
- Young's modulus is high.
- Economic effectiveness

Different sizes and types of reinforcements may be used for various purposes (Mistry and Gohil, 2018). As shown in Figure 1.4, composites may be divided into three categories, each with two subcategories, based on the reinforcing type and form (Sahraeinejad, 2014).

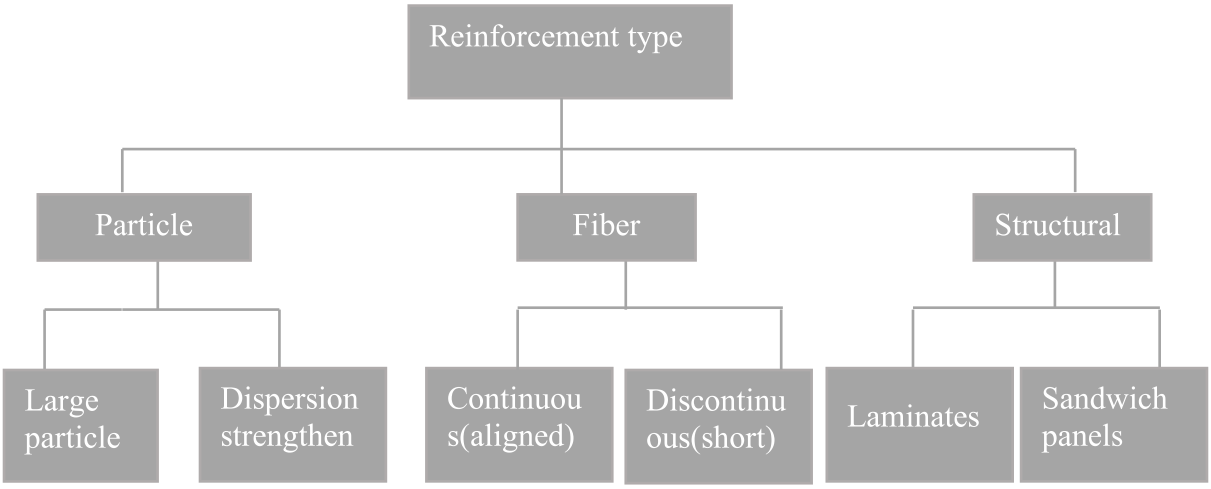


Figure 1.4 Schematic classification of composites (Abramovich, 2017).

Some ways that MMCs could be categorized are as follows (See Figure 1.5) based on reinforcing geometry (Bauri and Yadav, 2018). The mechanical and physical characteristics of MMC materials are impacted by several components, such as the reinforcement choice, the manufacturing technique, the structural qualities of the reinforcements, and the reinforcement's ability to absorb moisture from the matrix while being produced (Gupta and Wong, 2015) . So, it's important to know how to choose the right reinforcement and what its qualities are.

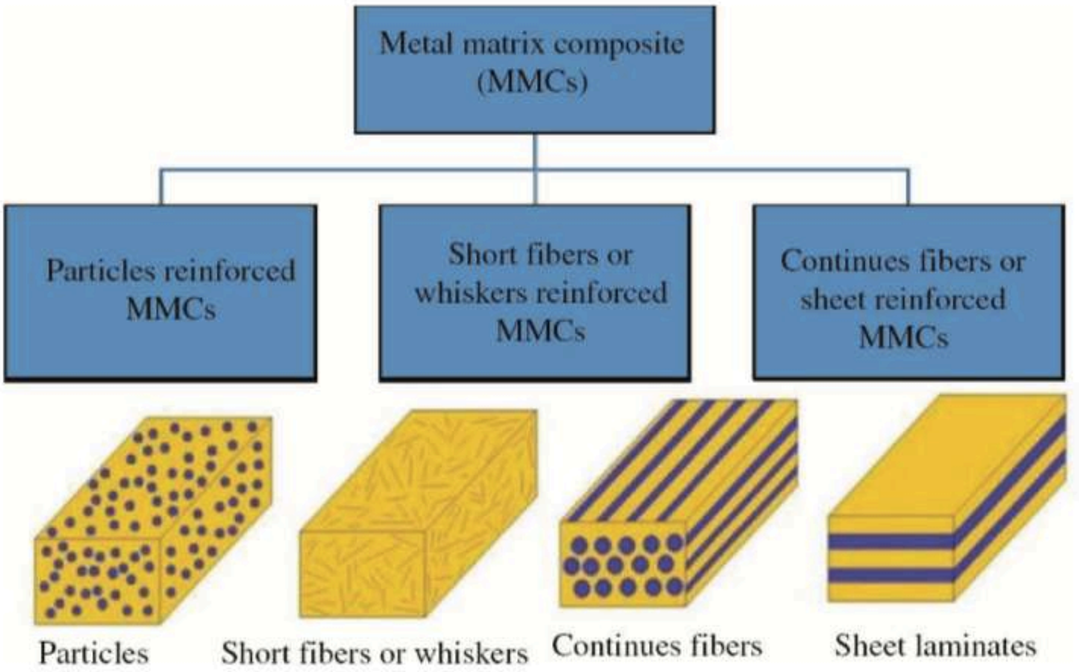


Figure 1.5 Metal matrix classification based on the kind of reinforcement(Mistry and Gohil, 2018).

Since particle-reinforced composites are the focus of this investigation, more detail about the particle reinforcement is given in the next section.

1.3.1 Particle Reinforcement

Particles that may be integrated into a matrix could be either nanometer- or micron-sized. Components' particle reinforcing may be spherical, cube-shaped, homogeneous, or of varying forms that are randomly lined up in the matrix (Mistry and Gohil, 2018). Composites of dispersion-strengthened and large particles are the two main categories of particles. Based on the reinforcing or strengthening process, these two are distinguished. Figure 1.6 illustrates the particle-reinforced composite.

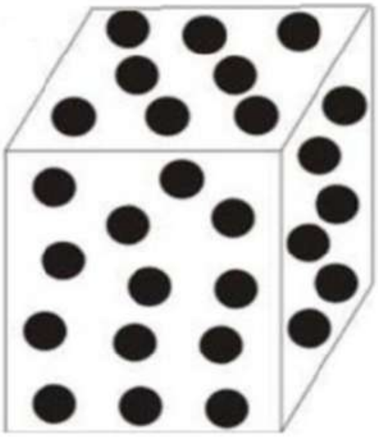


Figure 1.6 Particle reinforcement (Pastuszak and Muc, 2013)

In a metal matrix, hard ceramic particles are utilized as reinforcement due to their greater hardness and thermal resistance. Typical particle materials are boride (TiB_2, ZrB_2, WB), carbides (B_4C, ZrC, SiC, TiC, W_2C, WC), nitrides (BN, AlN, TiN, ZrN), and oxides (ZrO_2, Al_2O_3, Cr_2O_3) (Dieringa and Kainer, 2012). It is known that the interaction between the matrix and the reinforcement affects the final characteristics of MMCs, along with the size and volume percentage of the reinforcing components (Malaki *et al.*, 2021). The mechanical characteristics of a metal matrix may be optimized when thermally stable ceramic particles have been evenly dispersed throughout the matrix (Tjong and Ma, 2000). MMCs of particle-reinforced are desirable because of their isotropic characteristics, inexpensive cost, and monolithic technology production (Chawla and Shen, 2001).

1.3.2 Fiber Reinforcement

A fiber may be identified by its long length with its small diameter. A reinforcement's ability to provide attributes to a composite is affected by its dimensions. Fibers are an extremely effective way to increase the matrix's fracture resistance since their large dimension inhibits the production of incipient fractures characteristic of the reinforcement that might otherwise cause failure, particularly with matrixes of brittle. Fibers are not immediately usable in engineering applications due to their modest cross-sectional dimensions. Therefore, fiber composites are made by combining them with matrix materials. The matrix holds the fibers together, which also transfers stresses to the fibers and protects them from damage caused by the environment and handling. Discontinuous fiber-reinforced composites place a greater premium on the matrix's load transfer function than continuous fiber composites (Chandel and Bhatia, 2015; Haghshenas, 2016; Singh and Kumar, 2019). The fiber reinforced composite is shown in Figure 1.7.

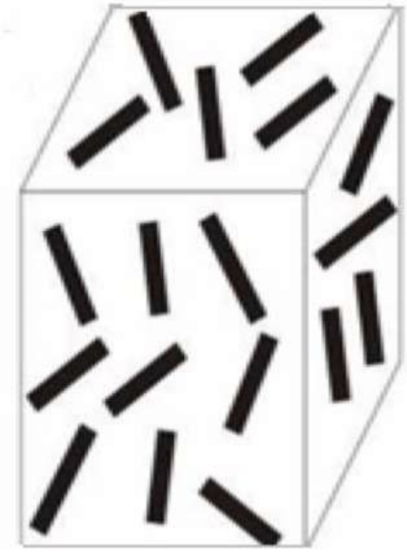


Figure 1.7 Fiber reinforcement (Pastuszak and Muc, 2013).

1.3.3 Whiskers

Whiskers have been produced using organic compounds and various materials, including oxides, halides, metals, and carbides. The costs for whisker composites are higher than those for particle composites. In most cases, the strength of tensile in single-crystal whiskers is much greater compared to that of discontinuous reinforcement such as polycrystalline flakes, particles, or chopped fibers. The whisker-reinforced composite can potentially have improved characteristics, but it is hampered by the damage and fracture that occur during secondary production. Both discontinuous and whiskered fibers are less expensive than continuous fibers, with whiskers costing more (Hashmi.J, 1999).

1.3.4 Laminates

Material layers are held together by a matrix made up of laminate composites. Most of the time, these layers are set up to strengthen the link between the matrix and the reinforcement. The purpose is to provide excellent strength and cheap cost at a lower weight. Depending on the final use, these laminates' fiber reinforcement may be either unidirectional or bidirectional. Unidirectional laminates, angle-ply, cross-ply, and symmetric laminates are all types of composite laminates. Plywood is a well-known example of a laminar composite (Chandel and Bhatia, 2015; Haghshenas, 2016). Figure 1.8 Shows laminate reinforcement.

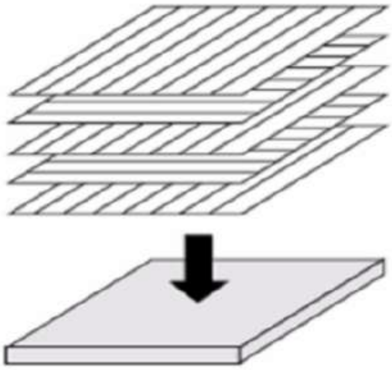


Figure 1.8 Laminate reinforcement.

1.3.5 Hybrids Reinforcement

Typically, in a single matrix phase a hybrid composite consists of two or more different fibers. The most popular hybrid composite has a polymeric resin matrix with reinforcing phases of glass or carbon fibers. A hybrid composite's overall qualities are higher than those of a composite with a single fiber reinforcing phase (Nanko, 2009).

1.4 Drawback of Composite Material

Aside from the many advantages of composites, there are some drawbacks which are (Randbaran *et al.*, 2020):

- High material costs when compared to steel and aluminium.
- Lack of techniques for high-volume manufacture.
- Lack of a database while designing composite components.
- Parameters like temperature, dimensional stability, and chemical resistance may affect properties.

1.5 Application of Composite Material

The composites can be used and applied to various products and processes. Can mostly put these into the following groups (Shukla, 2011):

- High-Performance Area: The aerospace industry dominates this technological spectrum, which has applications in the launch of aircraft, and the transportation of chemicals, satellites, and missiles, among other things. However, the technical requirements are higher since consumption is low.
- High volume/commercial area: A wide variety of commercially manufactured technical and consumer goods fall into this category. Agriculture, automobiles and transportation, pollution prevention, and engineering are marked-use fields. There is less of an emphasis on cutting-edge technology than there is in the high-performance sector.
- Specialty area: This includes applications with special needs. The volume and technological level might be high or low, but product

development is based on other factors. As an example, biomedical applications are one such field.

Composites have been essential to human existence for thousands of years, from allowing early civilizations to construct buildings to enabling improvements in modern technology. Composites are used in various of everyday items, from construction to engineering to medicine, energy, transportation, sports, and automobiles (Pastuszak and Muc, 2013).

1.6 Processing Techniques of AMCs

AMCs may be fabricated utilizing different methods including stir casting, also called liquid state, semisolid, and powder metallurgy (Mohanavel, Rajan and Senthil Kumar, 2015).

1. When it comes to treating materials in a liquid condition, stir casting has proven to be the most popular and profitable option. Because it is cost-effective and applicable to mass production, controlling composite structures is easier, as it is almost net-shaped (Mohanavel *et al.*, 2018).
2. Powder metallurgy is a manufacturing process in which raw materials are ground into a fine powder and then pressed into a mould to get the desired form (Pasha *et al.*, 2020). Included in the four phases are:
    - Powder Production
    - Blending or Mixing
    - Powder Compaction
    - Sintering
3. Squeeze casting often referred to as forging of liquid metal, is the outcome of forging and casting processes. Initially, the metal is put into the die`s bottom, which has already been heated. After pouring the material into the mould, the cylinder-shaped material tank maintains a steady loading

pressure of around 300 tones until the casting process is complete. The material in the mould will start to shrink as it begins to cool down. The cylinder will keep applying pressure to put metal into the mould, resulting in a stronger and finely detailed casting (Dhanashekar and Senthil Kumar, 2014).

Conventional metal matrix composite production processes are more time-consuming and complex, resulting in casting defects such as porosities, be holes, and shrinkages. In the mechanical and tribological characteristics of the composites, the manufacturing technique, size, weight percent of reinforcement, and matrix alloy of the composites all have a function. Liquid-state processing provides many benefits over solid-state processing, including stronger matrix-particle bonding, simpler and more cost-effective methods for constructing matrix structures, closer net form, and a broad range of materials (Vencl *et al.*, 2010). The most popular method for manufacturing liquid AMCs is called stir casting (Gopalakrishnan and Murugan, 2012). While for creating composites of metal matrix, stir casting is a great technique, there are numerous factors that must be considered. First, it is not easy to ensure that the reinforcing material is distributed equally due to the wettability, chemical interactions, and the reinforcing material in composites formed on a cast metal matrix as well as porosity of the matrix alloy (Pasupathy, 2021). In order to get the best outcome, throughout the matrix alloy the reinforcing material must be evenly distributed. It must optimize the bonding or wettability between these materials, for achieving the highest characteristics of the composite of metal matrix. The porosity must be kept at a minimum. There must be chemical interactions between the matrix alloy and reinforcing components (Hashim, Looney and Hashmi, 1999). Wettability is the ability of a liquid to appear on the surface, when it comes to the spread ability of liquids on a solid surface. There are several ways to fix the problem of low wettability (Razzaq *et al.*, 2017).

1) Reinforcement particles are heated before use.
2) The addition of wettability agents.
3) Addition of fluxes
4) Reinforcement particles will be coated.
5) The technique of compo casting

1.7 Wettability

In manufacturing cast metal matrix composites, wettability is a significant issue that must be solved. Wettability is described as a liquid's spreading capacity over a surface of solid. In addition, it specifies the degree of contact between a solid and a liquid. The melt must moisten the ceramic phase for the solid ceramic phase to be successfully included in the casting. As a surface chemistry and surface tension issue, the ceramic wetting by the metal of molten is a problem. Chemistry of particle surface, including contamination and oxidation, chemistry of melt surface, and chemistry of oxide layer, must be considered. The fundamental techniques for enhancing wetting are (a) raising the solid's surface energy, (b) by lowering the liquid matrix alloy's surface tension, and (c) lowering the energy of interfacial between solids and liquids at the particle-matrix contact (Hashim, Looney and Hashmi, 1999; Malaki *et al.*, 2021). The majority of engineering approaches used to enhance wettability are classified as follows (Razzaq *et al.*, 2017):

1. Preheating the particles of reinforcement

The reinforcement is heated to reduce moisture and make them compatible with molten aluminium. By heating the reinforcement phase, wettability is increased with the metal matrix material or liquid alloy. It is evident from the powder's color shift that ceramic particles must be heat treated or calcined before being dispersed into the melt to eliminate release adsorbed gases, organic contaminants and unburned carbon content (Abramovich, 2017). It is discovered that preheating the particles of reinforcement utilized as fillers in producing composites improves the reinforcing particles dispersion and interfacial strength (Miyajima and Iwai, 2003).

2. Wettability Agents Addition

By introducing reactive elements such as P, Zr, Ti, Ca, Mg, and Li, increasing the metal-ceramic systems wettability at the interface result from a chemical reaction. Reactive materials also reduce the melt's solid-liquid interfacial energy and the molten aluminium's surface tension (Hashim, Looney and Hashmi, 2001a). Increasing wettability is achieved by doping certain ceramic particles with elements that have a strong affinity for oxygen.

3. Fluxes Addition

K_2TiF_6 flux, or potassium fluorotitanate, is often utilized to assist the molten doping Al with B_4C particles and to improve the process of wetting between B_4C particles and molten Al. Al and B_4C are utilized to enable the molten Al doping with B_4C particles. Dhinakaran and Moorthy found that increasing the wettability of the matrix around B_4C particles through mixing the molten metal with K_2TiF_6 flux was an important improvement (Dhinakaran and Moorthy, 2014).

4. Coating the Particles of Reinforcement

Ceramic reinforcements with a metallic material, including graphite, titanium dioxide, aluminium oxide, or silicon carbide, have superior wetting behaviour and adhesion compared to their uncoated counterparts. Coating ceramic reinforcements are critical because they ensure little chemical contact between the reinforcement and matrix and increase interfacial strength integrity (Klauser *et al.*, 1996).

5. Compo Casting Technique

The high cost of fabrication associated with methods like stir casting makes it necessary to introduce a cost-effective method that may enhance wettability. The modified process of stir casting is also called slurry casting or compo casting, and it involves incorporating ceramic particles and lowering the casting temperature while the aluminium has a semisolid condition (Amirkhanlou *et al.*, 2011). Several researchers have observed ceramic particles' improved wettability and uniform dispersion in AMCs by utilizing the compo casting approach instead of stir casting (Ceschini, Minak and Morri, 2006; Amirkhanlou and Niroumand, 2012; Sajjadi, Ezatpour and Torabi Parizi, 2012).

Many variables influence wettability, including chemical reactions at the interface, the reinforcement roughness, porosity, atmosphere, time, and process temperature. Because particle reinforcements cannot penetrate the liquid metal when on the surface of the molten metal there is a layer of oxide. This shows a detrimental impact on wetting. Further, the gas generally covers the surfaces of the ceramic particles such that the material of molten matrix doesn't touch the ceramic surface and decrease the wettability. The surface characteristics of the particles is another component that has a significant function in the wetting process. Wettability may be reduced due to impurities absorbed by the particle surface (Hashim, Looney and Hashmi, 2001b).

1.8 Problem Statement

The demand for lighter materials with good mechanical properties has become the direction for research and development in modern transportation and aerospace applications. Alloys made of aluminium have several advantages, such as their light weight, great strength, and ductility. It has extensive use in the fields of automotive technology, aviation, aerospace, etc. However, the need for aluminium alloy is more significant in these areas. For instance, strength, hardness, wear resistance, and other performances must be improved.

In the current work, efforts were undertaken to improve an aluminium alloy's tribological and mechanical properties, and attempts were made to make AMCs. As a matrix material, Al6061 was employed, and it was then strengthened with several particles, including SiC, TiB_2, and B_4C.

1.9 Aims of the Study

Different reinforcements were used in this study, such as TiB_2, B_4C, and SiC, to improve the tribological characteristics and mechanical properties of the matrix by utilizing the method of stir casting. The objective of this investigation is as follows:

- Develop AMCs reinforced with various particles, including SiC, TiB_2, and B_4C, where the reinforcements were used in two different ways: as an individual (single-reinforcement composite) and as a hybrid (hybrid-reinforcement composite).
- Microstructural analysis of the fabricated composite.
- Examining the mechanical characteristics of the manufactured AMCs.
- Investigation of the wear behaviour of the AMCs.

1.10 Thesis Layout

The chapters of this thesis are organized under the following headings: Introduction, Literature Review, Experimental Work, Results and Discussions and finally Conclusions and Recommendations for Future Work. An outline of each chapter is provided below:

- Chapter One. Introduction. This chapter contains an introduction, which includes an overview of composites in general, reinforcement types, problem statements, and aim of the study.
- Chapter Two. Literature Review. This chapter includes a literature study of various composites, MMC structures, production techniques, and mechanical characteristics.
- Chapter Three. Experimental Work. This chapter describes the material selection, casting process, experimental setup, and mechanical test procedures.

- Chapter Four. Results and Discussions. The findings of the experimental results and the microstructure for the tribological and mechanical properties are listed and discussed.
- Chapter Five. Conclusions and Recommendations. The significant findings of this study are presented in this chapter, along with some recommendations for future studies.

CHAPTER TWO

LITERATURE REVIEW

This chapter reviews and briefly describes composite materials. The various matrix and reinforcement types were concluded. This section compares and contrasts several manufacturing processes, including two-step stir casting. As a result, this chapter discusses the work of several authors in the fields of AMC tribology and mechanical behaviour. They discovered that adding reinforcement improved the mechanical and tribological behaviour of AMCs.

2.1 Introduction

As mentioned in Chapter One, composites are substances generated through the combination of two or more basic materials having significantly different chemical and physical characteristics. Because of their desirable mechanical and tribological characteristics, composite materials are often employed for structural applications. A composite consists of a matrix, which has a substantially greater content than other materials, and reinforcement. The composites' properties depend on size, shape, reinforcement type, and the reaction level on the interface between the reinforced material and the matrix. A hybrid composite is formed when at least three different materials are used.

The matrix or base might be metal, polymer, or ceramic. The composite is known as a metal matrix composite (MMC) if the matrix is made of metal. While the composite is called as polymer matrix composite (PMC) if the matrix is a polymer. If the composite's matrix is ceramic, it is known as a ceramic matrix composite (CMC) (Stojanovic *et al.*, 2013). Reinforcements could be in the form of whiskers, particles, or fibers made of metals, ceramics, and polymers. Different ceramic particulates like aluminium nitride (AlN), alumina (Al_2O_3), magnesium oxide (MgO), graphite (Gr), titanium diboride (TiB_2), silicon nitride (Si_3N_4), titanium nitride (TiN), silicon carbide (SiC), and boron nitride (BN) are the primary particulate-reinforced materials (Veeresh Kumar, Rao and Selvaraj, 2011). The ultimate and yield strengths of the parent alloy are enhanced by the ceramic particles, but they have a detrimental effect on its ductility. In structural, thermal, wear, and electrical applications, metal matrix composites (MMCs) have the potential to be an attractive class of material. As a result, new structural composite materials are being developed. Compared with monolithic commercial alloys, these alloys demonstrate better strength-to-cost and strength-to-weight ratios (Suresh, Moorthi, *et al.*, 2014). The goal of creating composite materials of metal matrix is combining the advantages of both metals and reinforcements. Adding refractory particles of high-modulus and high-strength to a matrix of metal generates a material with intermediate mechanical characteristics between the refractory reinforcement and the matrix alloy (Hashim, Looney and Hashmi, 1999). Composites of metal matrix according to aluminium are gradually displacing conventional engineering materials. They are widely used in the military, transportation, aviation, marine, and aerospace industries due to their excellent wear resistance, strength-to-weight ratio, and thermal conductivity (Kala, Mer and Kumar, 2014).

To date, several studies have investigated the effect of particle reinforcement on aluminium alloys. The next section will review of the AMC work performed to date.

2.1.1 Silicon Carbide (SiC)

Carborundum is another name for silicon carbide (SiC), which is a combined of silicon and carbon. Since 1893, silicon carbide powder has been mass-manufactured and used as an abrasive (Nair, Tien and Bates, 1985). Engineering materials benefit from adding SiC reinforcement to an Al alloy matrix because of SiC's wear resistance, strength, and excellent hardness (Dinaharan *et al.*, 2016;

Davis, 2017). Stojanovic *et al.* (2013) investigated the tribological properties of a hybrid composite with an Al matrix. Al 2219 is reinforced with various amount of SiC and graphite. Graphite's soft particles enhance lubrication and minimize friction and wear, while silicon carbide particles increase the hardness and wear resistance. A pin-on-disc tribometer was employed for conducting tribological testing under the ASTM G99-95 standard. The volumetric percentage of SiC in the investigated samples ranged from 5% to 15%, with a particle size of 25μm graphite was applied with a 3 % volumetric share and 45 μm sized particles. The outcomes demonstrated the tribological and mechanical characteristics of the hybrid composites with matrix of aluminium changed by varying the percentage amount of reinforcement. According to tribological test, the friction coefficient of hybrid composites of Al/SiC/Gr decreases as graphite content increases. Wear can also be affected by particle size. Composite wear is reduced as graphite particle size increases (Stojanovic *et al.*, 2013). Sathish and Karthick (2020) added silicon carbide (SiC) to the AA7050 aluminium alloy at different weight percentages, such as 0%, 4%, and 6%. Using the design of experiments (Taguchi technique), the wear of these composites was investigated to improve the parameters of process. The best wear rates were obtained at a sliding velocity of 2 *m/s*, a reinforcement of 6%, and a sliding distance of 1800 meters (Sathish and Karthick, 2020). Vamsi *et al.* (2014) evaluated the impact of Al6061/SiC/Gr hybrid composite and Al6061 with SiC to compare the difference between the single reinforcement with the hybrid composite. To fabricate the composites, they used the method of stir casting. The reinforcement amount can be different between 5% and 15% in steps 5%. They concluded that the greatest tensile strength at 15% SiC/Gr was 192.45 *MPa*. Hybrid composites with SiC/Gr reinforcement performed better mechanically than those with just one reinforcement. It was reported that increasing the density of SiC and decreasing the density of hybrid particles of SiC/Gr (Vamsi and Xavior, 2014). Suresha and Sridhara (2012) have noticed that composites' hardness decreases as the reinforcement percentage increases. Slide friction of composites of hybrid aluminium reinforced with Gr particles and 2.5%, 7.5%, and 10% SiC, respectively, in equal weight fractions. The coefficient of friction is affected by the sliding speed and load, which has an average value of 0.269. However, the friction coefficient is unaffected by the reinforcement amount and the length of the sliding path (Suresha and Sridhara, 2012). Dey *et al.* (2020) evaluated wear characteristics of Al2024 matrix composites supplemented with and without silicon carbide (SiC) using the manufacturing process of stir casting. It determined the wear performance of the pin on disc tribometer through altering the velocity and sliding distance. The SiC particles weight fraction changed between 0% and 9% in 3% increment. Magnesium was added to the melt at a concentration of 2% to improve wettability. The findings revealed that a composite reinforced with 9 %SiC shows higher wear resistance. The wear rate of Al2024-SiC composites rises, as the velocity and sliding distance increase. Therefore, for speed applications and low-distance, SiC reinforced Al2024 alloy composites were used (Dey *et al.*, 2020). Al2024, Al7010, and Al7009 are high-strength aluminium alloys that Rao and Das (2010) investigated for their impact on the sliding wear properties of the matrix alloy and the impact of the SiC particle. Considering varied used force and 3.35 *m/s* constant sliding speed, composite materials were tested. As a result, 7010 alloy has the highest hardness while 2024 alloy has the lowest. Due to such findings, the 2024 alloy`s wear rate is the highest, while the wear rate of 7010 alloys is the least. The coefficient of friction rises, when the percentage of SiC enhances, and Al7010 has a higher friction coefficient. Depending on the alloy system, the seizure pressure varies; Al7010 showed the highest seizure pressure, while regardless of SiC concentration and processing condition, Al2024 showed the lowest seizure pressure. With enhancing applied pressure, the wear coefficient reduces until it reaches a minimum level and then rises again if the utilized force reaches a level close to the seizure of the specimen (Rao and Das, 2010). The effects of SiC on

Al6351 has been assessed by Mohanavel *et al.* (2018). Different weight % of silicon carbide particles were made in a 4-percent stage from 0% to 20% utilizing the technique of stir casting. Further findings showed that the aluminium matrix composites mechanical characteristics are influenced by the composite's SiC particles weight percentage. The best mechanical features come from AA6351/20 wt.% SiC AMCs (Mohanavel *et al.*, 2018). In their investigation, Rahman and Al Rashed (2014) reported that adding SiC reinforcements to the aluminium (Al) matrix made it harder and better. AMC with 20% SiC reinforcement had the best hardness and tensile strength. They found that mixing particles of SiC with the Al matrix made the material more wear-resistant (Rahman and Al Rashed, 2014). Reihani (2006) investigated how the wear resistance, mechanical characteristics, and aging behaviour of 6061 aluminium alloys formed through the squeeze casting process is influenced by SiC particles. The foundation material was 6061 aluminium alloy. As a reinforcing phase, particles of SiC with mean mass particle sizes of 16 and 22 μm were employed. The study obtained increased tensile strength and greater ductility with reduced reinforcing particle size. Overall, such findings imply that through reducing the reinforcing particles size better mechanical properties are achieved (Reihani, 2006). Every technological advancement requires an enhancement in the composite materials` mechanical characteristics. In 2020, Sabry *et al.* (2020) published a paper describing how the wear rate in the Al–SiC-Gr hybrids is impacted by sliding velocity and applied load. AMCs made by varying the SiC volume fraction (5 %, 10 %, and 15 %) while the graphite utilized in composites remains the same (10%) and through stir casting is fabricated. The tensile strength and hardness enhanced from $65HV$ to $85HV$ and 490 MPa to 710 MPa correspondingly when graphite particles and silicon carbide were added. As the applied load enhanced, the wear rate likewise enhanced. Nevertheless, the velocity of sliding rises to 1.2 m/s. After that, it rapidly decreases (Sabry *et al.*, 2020). Rao and Das (2011) investigated that sliding speed and SiC concentration affects the composite materials and aluminium alloy wear behaviour. They used a 5000 m sliding distance for these experiments at sliding speeds between 0.52 and 1.72 m/s and particles of SiC of 10, 15, and 25wt. %. The data reveals that the temperature and rate of wear decline when the SiC concentration rises. Conversely, the coefficient of friction shows the opposite tendency (Rao and Das, 2011). Kumar *et al.* (2020) developed, characterized, and tested the effectiveness of aluminium alloy matrix-based hybrid composites containing graphite particles and silicon carbide. Aluminium alloy (Al + 8%Si + 4%Cu + 3%Mg) with silicon carbide additions of 3 wt. % and 6 wt. % and a constant 2 wt. % graphite particles content. Further analysis showed that 6% SiC at constant Gr reinforced composite has the greatest tensile strength ($234.57 MPa$) and hardness ($49.5 HB$) (Kumar, Rana and Purohit, 2019). In an investigation into AMCs, Moses *et al.* (2014) revealed that the ultimate microhardness of the AMCs and tensile strength (UTS) significantly increased by addition of SiC particles. 6061Alloy reinforced using SiC particles with various proportions (0, 5, 10, and 15 wt.%) were developed. The results indicated that from unreinforced Al6061 tensile strength and microhardness around 45 HV and 130 MPa but with 15wt. % SiC exhibits higher tensile strength and microhardness around 105 HV and 220 MPa. These results indicate a change from ductile to brittle in fracture mode, when SiC concentration enhanced (Moses, Dinaharan and Sekhar, 2014). Similarly, Laxmi and Sunil (2017) found that when Al6061 was reinforced with SiC, increasing SiC from 10% to 15% increased the composites hardness. After a 20% rise in reinforcing, hardness began to decrease (Laxmi and Sunil Kumar, 2017). In 2012, Veeresh and co-workers studied about Al6061–SiC composites dry and mechanical sliding wear. Liquid metallurgy was used to make Al6061 composites with 2–6 wt. % SiC of size particle $150 \mu m$. It has been demonstrated that the composite hardness is higher than its cast alloy matrix. Those filled-out composites have a harder surface. The composite material hardness of Al6061–SiC increases by 67% as the SiC concentration rises from 0% to 6%. In summary of the experimental work of ultimate tensile strength, the results show that between 0 and 6 wt.% silicon carbide particles, the final tensile strength in composite material improved by 86%. Another important finding was that composites' wear resistance is superior to base alloy. A rise in the applied sliding distances and load led to a rise in volumetric wear losses. Overall, the tribological and mechanical performances of Al6061–6 wt. % SiC composite is superior to composites of Al6061–2 wt. % SiC, Al6061–4 wt. %SiC, and Al6061 (Veeresh Kumar, Rao and Selvaraj, 2012).

2.1.2 Titanium Diboride (TiB_2)

Titanium diboride (TiB_2) has several desirable properties, including its excellent hardness (3400 *HV*), hight melting point (3225°C), Superior wear resistance, low specific gravity (4.5), great Young modulus (345–409 *GPa*), high elastic modulus, high electrical conductivity (22106), high thermal conductivity (110 $Wm^{-1} K^{-1}$ at 25 °*C*), good thermal stability, and excellent corrosion resistance (Sulima *et al.*, 2011). The wear mechanism and mechanical properties of Al6061 was reinforced with (0, 2, 4, 6, 8, and 10%) of TiB_2 has been examined by Suresh *et al.* (2014). The mechanical and tribological characteristics of the samples, including resistance to wear, hardness, and tensile strength, were improved by the addition of TiB_2. Significantly less wear is achieved with a composite containing 10% TiB_2. The alloy and composite wear properties are also greatly impacted by the debris size (Suresh, Moorthi, *et al.*, 2014). Gupta *et al.* (2020) discussed the impact of mixing TiB_2 with the mechanical and tribological characteristics of Al 1120, which is fabricated by stir casting. TiB_2 was incorporated into the matrix material Al 1120 at weight percentages of 2%, 4%, 6%, and 8%. Comparing with the base alloy, the Al 1120 reinforced with 8% TiB_2 has better tensile strength owing to the reinforcement's high percentage in the material of matrix that is 222.94 *MPa*. Increasing the TiB_2 content results in significant growth, but the rate of elongation decreases. The results reveal that the composite material's hardness increases as more TiB_2 reinforcement is mixed with the metal matrix

Al1120. Based on the findings of the impact tests, the matrix's ability to absorb energy improves in line with the amount of TiB_2 reinforcement, and about the result of the wear test was 200 *m* of sliding distance, and with Al alloy reinforced with 8%, TiB_2 weight loss is higher than based metal matrix but wear rate decreased compared to the based alloy (Gupta, Gangil and Ranakoti, 2020). The Al6061-TiB_2 composites were prepared by Suresh and Moorthi (2013) utilizing the stir casting technique, which is a liquid-state technique of mixing with a mechanical stirrer. For exploring the composites microstructure, a scanning electron microscope (SEM) was used. They studied the hardness, tensile strength, and wear resistance, so they found that adding TiB_2 to aluminium composites increases their wear resistance and the alloy matrix's hardness increases significantly. Increasing the amount of TiB_2 in the aluminium would enhance its strength. With the use of images in the microstructure, discovered a rise in the composition of TiB_2. Wear tests on the samples is performed, which determined the composite specimen's wear resistance characteristics and coefficient of friction (Suresh and Moorthi, 2013). Suresh *et al.* (2014) used a high-energy stir casting technique to study Al6061 aluminium alloys reinforced with different percentages of titanium diboride (TiB_2) to examine the TiB_2 influence on wear resistance and mechanical characteristics. Each of the weighted percentages of TiB_2 added was 0, 3, 6, 9, or 12. Based on the findings, increasing the amount of TiB_2 in the samples enhanced their mechanical characteristics including hardness, wear resistance, and tensile strength (Suresh, Moorthi, *et al.*, 2014).

2.1.3 Boron Carbide (B_4C)

As a ceramic particle, Boron carbide (B_4C) performs well in various applications due to its high thermal stability, chemical inertness, low density, and thermoelectrical properties. B_4C particles display superior mechanical and physical characteristics, including a high hardness and melting point, a high absorption capacity for neutrons, excellent chemical resistance, high impact strength, and robust resistance to abrasion (Suri *et al.*, 2010). In an investigation into B_4C, Karakoç *et al.* (2018) used powder metallurgy to make Al6061-B_4C composites, the most common solid-state processing method. With 5%, 10%, 15%, and 20% B_4C, composites of metal matrix reinforced. The findings indicated that in a matrix structure a homogeneous particle dispersion was obtained and that all specimens had increased relative density, tensile strength, and hardness (Karakoç, Karabulut and Çıtak, 2018). Kalaiselvan *et al.* (2011) carried out an investigation into the Al6061 reinforced with B_4C, varying reinforcement wt. % (4, 6, 8, 10, and 12 wt.%). Their findings indicated that the B_4C particles in the composite were well distributed. Used K_2TiF_6 flux with aluminium melt for improving the wettability of B_4C particles. The heat created by the flux reaction on the molten surface facilitated particle integration into the melt and improved bonding because of the local temperature elevation. Effective stirring and optimized process conditions led to a consistent distribution of reinforcements. The composites hardness and tensile strength increased as well, as the amount of B_4C particles increased (Kalaiselvan, Murugan and Parameswaran, 2011). In an investigation into the effect of B_4C particles, Rajesh *et al.* (2015) identified Al6061 as the composite and B_4C of metal matrix and the reinforcement fabricated utilizing the stir casting process. Al6061, reinforced with 0,7,9% B_4C, performed an investigation of the Al6061-B_4C composites` mechanical properties. The findings indicate that the distribution of B_4C in the aluminium matrix seems relatively consistent, as seen by SEM microphotographs. When compared to Al6061 alloy, the ultimate tensile strength increased 17.4% and 38.4% through adding 7% and 9% B_4C particles, respectively (Rajesh *et al.*, 2015). To determine the effects of adding B_4C particles to an Al6061-based alloy, Karabulut *et al.* (2016) used 5, 10, 15, and 20 Wt.% of B_4C as a reinforcement and Al6061 as a matrix material which is fabricated by using powder metallurgy methods. According to the results, the amount of B_4C in a composite specimen makes it harder, and 20 wt. % B_4C tends to make it the hardest, and Al6061/5wt.% B_4C has the best tensile strength (Karabulut, Karakoç and Çıtak, 2016). In another important study about surface roughness and friction coefficient at various loads, Priyan and Azad (2018) investigated adding B_4C to the matrix Al6061 through using the stir casting process. The amount of B_4C in an AMC ranges from 3%, 6%, and 9%. The results indicate that compositions containing 6% and 9% carbide of boron exhibited lower rates of wear at 2 *kg* and 4 *kg* load, respectively. With loads of (2, 3, 4 *kg*), the friction coefficient ranged between 0.40 to 0.86 (Priyan and Azad, 2018).

2.1.4 Hybrid Particles

Matrix composites of hybrid aluminium, or HAMCs, are composites of second-generation which could replace single-reinforced composites because their properties are better (Singh and Chauhan, 2016). Hybrid composites include more than one reinforcement in the matrix to improve its quality. One of these reinforcements, primary reinforcement, is applied to enhance the fundamental characteristics, while secondary reinforcement, is provided to improve a composite's properties. Therefore, the hybrid composite is a superior substitute material for advanced applications. As a result, a composite's qualities are determined by the reinforcements and matrix components used to form it (Singh and Chauhan, 2016; Awasthi *et al.*, 2018). Using the stir-casting method, composites of aluminium hybrid could be effectively fabricated. To the success of stir casting of hybrid composites, it is essential to consider the followings: temperature of alloy pouring, design of stirrer, speed of stirrer, temperature of preheating, type of particle, size of reinforcement particle, and type of mould (Sarada, Murthy and Ugrasen, 2015). Many published studies describe the role of matrix composite of hybrid metal. James *et al.* (2014) investigated a matrix composite of hybrid aluminium metal with titanium diboride and silicon carbide reinforcements. Stir casting was utilized to create composites with varying percentages of TiB_2 and a constant SiC content. The hardness test demonstrates that incorporating reinforcement SiC and TiB_2 raises the material's hardness. Hardness values decrease, however, when reinforcement is increased by up to 15%. Tensile test findings showed that adding reinforcement SiC to the base metal increased the composite's strength by 20%, whereas adding TiB_2 decreased strength by 50–60% (James *et al.*, 2014). In a significant research, Hillary *et al.* (2020), during their research, attempted to make hybrid composites out of Al6061, 5% SiC, and TiB_2. Utilizing a stir-casting process, the samples of metal composite were produced, with the quantity of 5%SiC reinforcement held constant and the amount of TiB_2 reinforcement varied between 2% and 10% by weight. According to the findings, increasing the percentage of TiB_2 in a material reduces its density and enhances its flexural strength, tensile strength, hardness, and impact strength (Hillary *et al.*, 2020). Another research by James *et al.* (2017) revealed that, according to the hardness test results, adding reinforcements in the metal matrix phase raised the hardness value by almost 50%. Emerging reinforcements including Al_2O_3, SiC, and TiB_2 were added to the matrix at 5%, 3%, and 2%, respectively. The addition of hybrid reinforcements does not noticeably enhance tensile strength (James *et al.*, 2017). Kumar *et al.* (2014) evaluated the impact that adding Al2219 has as a matrix and B_4C and MoS_2 as a reinforcement. Using a technique of stir-casting, the composite was manufactured. The findings revealed that by adding the secondary reinforcement MoS_2 of 3%, 4%, and 5% by mass, the tensile strength decreased by 16%, 26%, and 38%, respectively. But the density and the hardness increased comparing with the base alloy, and adding the reinforcement increased wear resistance (Kumar, Ravindranath and Shankar, 2014). In an investigation into the impact of adding graphite on the Al6061-TiB_2 properties, Suresh *et al.* (2014) found that the hardness value and tensile strength rises by introducing TiB_2 and graphite reinforcements into the Al6061 matrix. However, compared to Al6061, the composite is slightly less ductile (Suresh, Shenbaga Vinayaga Moorthi, *et al.*, 2014).

Based on the literature review of particulate-reinforced AMCs, almost all particles reinforced with AMCs have a large weight percentage of the reinforcement, but the present work was an attempt to determine the influence of adding a small amount of reinforcements on the porosity, hardness, tensile, and wear of Al6061. The effect of titanium diboride and boron carbide as reinforcement in Al6061 has hardly been investigated, despite researchers having created almost all possible AMCs.

2.2 Conclusion

The definition of composite materials and their types have been presented in this chapter. The reinforcement types were also stated. The disadvantages and the application of the composite materials were presented. In the last section of this chapter, the processing techniques of the metal matrix composite and the wettability have been defined, and the effects of adding different reinforcements and the mechanical and tribological properties have been reviewed.

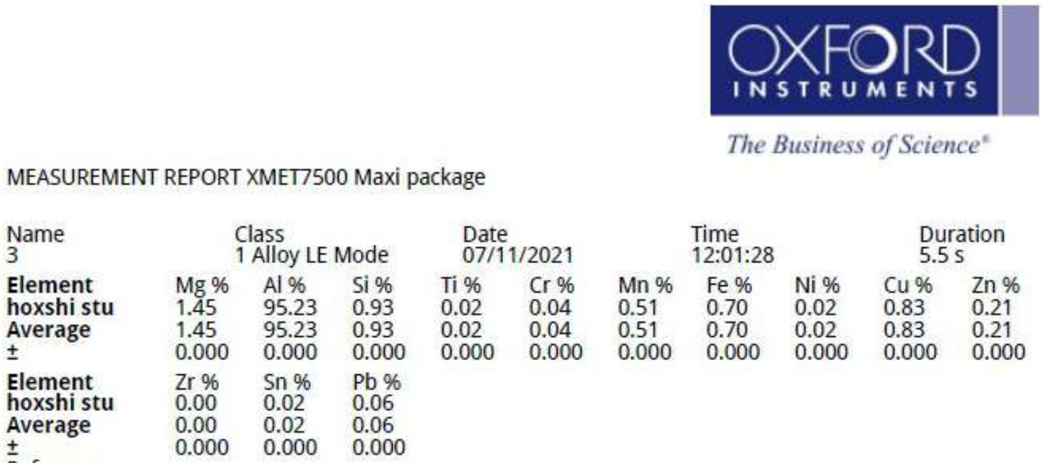
CHAPTER THREE

EXPERIMENTAL WORK

This chapter focuses on developing the AMCs reinforced with ceramic particles by the stir casting technique and investigating their mechanical properties and tribological behaviour. This chapter is separated into three parts. The first part introduced the materials employed in this research, including TiB_2, B_4C, SiC, and aluminium alloy (Al6061). The second part describes the process of stir casting, the steps of pouring the molted metals into the cast iron mould. The third part of this chapter includes the mechanical and tribological tests and sample preparation for the tests.

3.1 Material Selection

In this investigation, with the chemical composition using (X-MET 7500) portable X-Ray device, shown in Figure 3.1, the Al6061 alloy was selected as the material of matrix. As reinforcement, TiB_2 with particles sizes ranging from (2.5-13 μm), B_4C with particles size (44 μm), and SiC with particle sizes range from (8-32μm) were used in different weight percentages (1,3, and 5%). The physical properties of the materials that have been employed in this study is presented in Table 3.1.



MEASUREMENT REPORT XMET7500 Maxi package

Name	Class	Date	Time	Duration
3	1 Alloy LE Mode	07/11/2021	12:01:28	5.5 s

Element	Mg %	Al %	Si %	Ti %	Cr %	Mn %	Fe %	Ni %	Cu %	Zn %
hoxshi stu	1.45	95.23	0.93	0.02	0.04	0.51	0.70	0.02	0.83	0.21
Average	1.45	95.23	0.93	0.02	0.04	0.51	0.70	0.02	0.83	0.21
±	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Element	Zr %	Sn %	Pb %
hoxshi stu	0.00	0.02	0.06
Average	0.00	0.02	0.06
±	0.000	0.000	0.000

Figure 3.1 Chemical composition of Al6061.

Table 3.1 Physical Properties of Al6061, TiB_2 (Suresh, Moorthi, *et al.*, 2014), B_4C (Auradi, Rajesh and Kori, 2014), and SiC (Pasha *et al.*, 2020).

Properties	Density g/cm^3	Tensile strength, *MPa*	Elastic modulus, *GPa*	Elongation, %	Hardness, *HV*
Al6061	2.7	126.2	68.9	12-17	81
TiB_2	4.52	338-373	345-409		3400
B_4C	2.5	500	480		3800
SiC	3.30	588	345		3000

Figure 3.2 and Figure 3.3 show the ceramic reinforcement and SEM images of the selected materials. In this work, for improving the wettability of the particles in Al6061, magnesium was employed.

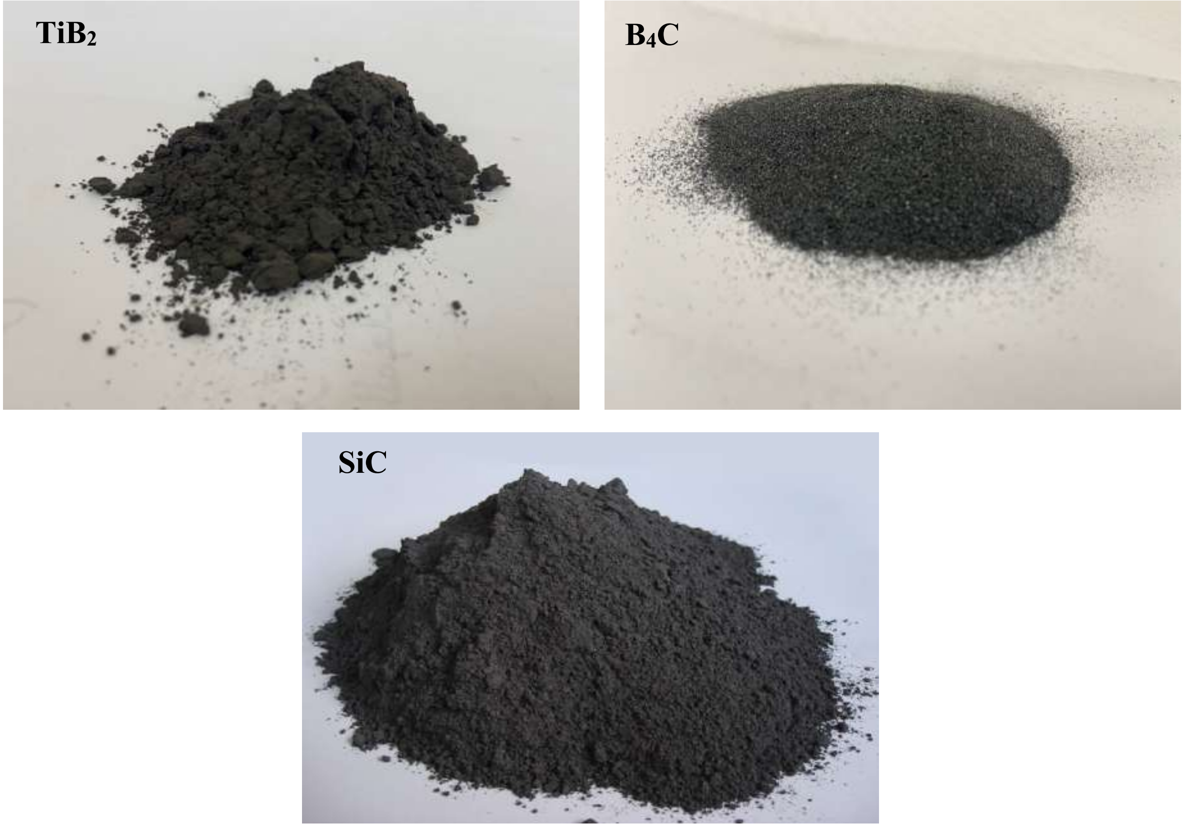
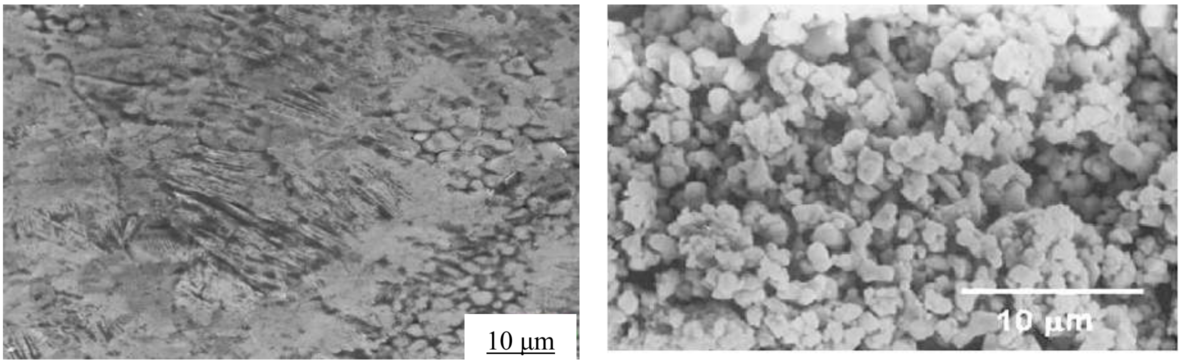
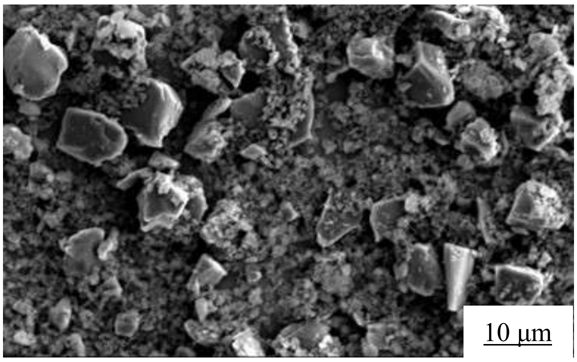


Figure 3.2 TiB_2, B_4C, and SiC particles.



(a) Al6061 (b) TiB_2 (Subramanian, Murthy and Suri, 2007)

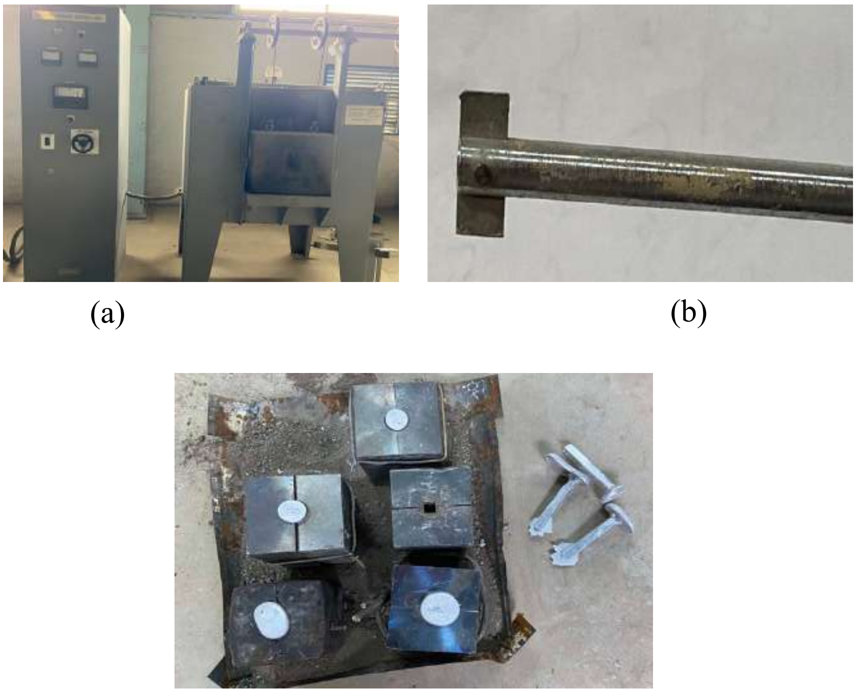


(c) SiC (Lee *et al.*, 2018)

Figure 3.3 SEM image for casted Al6061 and particles.

3.2 Casting Process

As mentioned in Section 3.1, the Al6061-reinforcements composite was prepared using the process of stir casting. This process is mainly composed of an electric furnace (Type: Nakanihon Ro Kogyo, Japan), with a heating capability of 1000 °*C* (See Figure 3.4a), and a graphite crucible with diameter of 70 *mm*, a height of 100 *mm*, and a melt capacity of 2 *kg*. The Al6061 alloy rod was cut into pieces of 70 *mm* in length to fit the crucible using a saw machine. First, the 700 *g* of Al6061 is melted at 800±50*℃*. As mentioned in Chapter Two, the particles of reinforced are preheated to 250° *C* for about 30 *min* to improve the wettability. After the Al6061-particles slurry had been preheated, the reinforced particles were added to the mixture and stirred with a modified two-step mechanical stirrer. Wettability is essential for particle dispersion in matrix materials, and 1% of magnesium is used for this purpose. A drill machine with a stir rod which is made of stainless steel (See Figure 3.4b) was used to stir the melt which specially designed and fabricated for this purpose, and it was heated before it was put into the slurry to remove the moisture. In order to better disperse the reinforced particles throughout the molten Al6061 alloy, the duration and speed of stirring operation were adjusted at 10 minutes and 600 *rpm*, respectively. Castings were obtained with various amounts of reinforcement particles. The moulds were preheated because it aids in the extraction of trapped gas from the slurry. If not addressed, it will contribute to porosity. Thus, it is an excellent way to prevent porosity. Prepared melts were instantaneously poured into preheated cast iron moulds cavity (diameter 20 *mm* and length 110 *mm*) (See Figure 3.4c) and maintained at ambient temperature to enable cooling of the mould. As illustrated in Figure 3.5 five moulds are used to fabricate different samples for various tests. These steps of making the Al6061-particles composite were done three times, each time with various particles.



(a) (b)

(c)

Figure 3.4 a) Electrical furnace, b) Stirring rod c) Cast iron moulds.

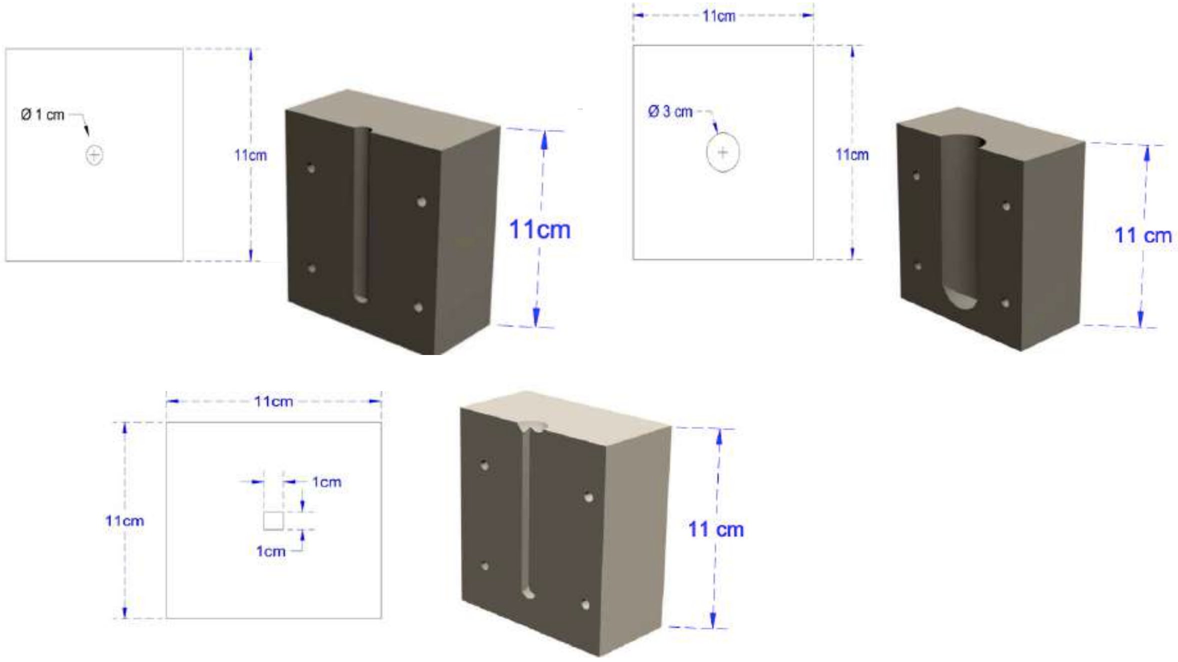


Figure 3.5 Different cast iron moulds.

3.3 Microstructure Examination

In the production of composites of particle reinforced, the homogeneous distribution of the reinforcement is the most significant component. Therefore, for examining the microstructures of Al6061-particles composites, a scanning electron microscope (SEM) and an optical microscope were employed. The microstructure samples were grinded using abrasive silicon carbide paper with grit sizes of 800, 1000, 2000, and 2500. The grinding was done in steps on each abrasive paper. It was decided to clean and dry the samples before being polished with velvet cloths. To reveal the grain boundaries, with Keller's reagent (ASTM E407 standard), which is a solution mixture of 95% of distilled water, 2.5% of nitric acid (HNO_3), 1.5% of hydrochloric acid (HCl), and 1% of hydrofluoric acid (HF) the samples were etched for about 10 seconds before their microstructural examination (Soliman, Ramadan and Yagoob, 2021).

3.4 Mechanical and Physical Characterization

3.4.1 Density and Porosity

(Agarwal and Broutman, 1992 cited in Kumar, 2015) proposed a mixing rule to calculate the composites theoretical density regarding the weight fraction as presented in Equation 3.1:

$$\rho_t = \frac{1}{\frac{W_p}{\rho_p} + \frac{W_m}{\rho_m}} \qquad (3.1)$$

where, ρ_t is theoretical density (*g/mm*^{3}), The weight fraction and density are represented by W and ρ correspondingly. Particulate, and matrix material are represented by the suffixes p, and m, respectively.

Equation 3.2 determine the composite's actual density:

$$\rho_a = \frac{W_c}{V_c} \qquad (3.2)$$

Where, ρ_a is the actual density (*g/mm*^{3}), W_c and V_c are the total mass and volume of the composite sample.

The porosity volume content was determined through analyzing the densities obtained from the measured weights with the theoretical densities derived using the Rule of Mixtures. Equation 3.3 is used to determine the composites' void content.

$$Void\ content = \frac{\rho_t - \rho_a}{\rho_t} \times 100 \qquad (3.3)$$

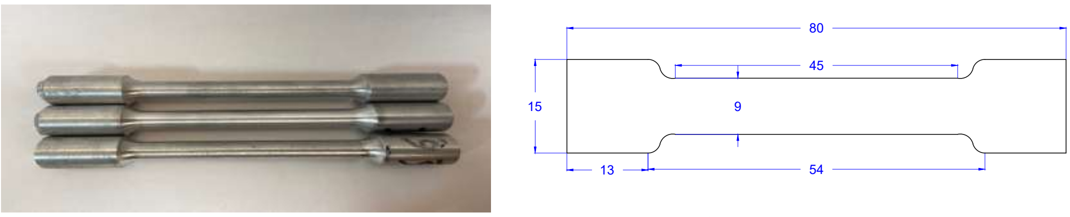
Where, ρ_t, ρ_a represents theoretical and actual values of densities.

In this example the theoretical (ρ_t) and actual density (ρ_a) of Al6061-5% SiC were calculated:

- $\rho_t = \rho_{Al} + \rho_{SiC} + \rho_{Mg}$
- $\rho_{Al} = \frac{665}{707}(2.7 * 10^{-3}) = 2.5396 * 10^{-3} \; g/mm^3$
- $\rho_{SiC} = \frac{35}{707}(3.21 * 10^{-3}) = 1.5 * 10^{-4} \; g/mm^3$
- $\rho_{Mg} = \frac{7}{707}(1.738 * 10^{-3}) = 1.72 * 10^{-5} \; g/mm^3$
- $\rho_t = 2.71 * \; 10^{-3} \; g/mm^3$
- $\rho_a = \frac{W_c}{V_c}$ $, which\ the\ weight\ of\ the\ sample = \; 5.4323 \; g$
- $V_c = L * W * H$
- $V_c = (19.95 * 9.77 * \; 10.37) = \; 2021.232255 \; mm^3$
- $\rho_a = \frac{5.4323}{2021.232255} = \; 0.002687618 \; g/mm^3$

3.4.2 Tensile Test

To examine the tensile behaviour of the Al6061-particles composite, the tensile test was conducted in accordance with ASTM standards and using a universal testing machine. The tensile test is carried out on XHG-50 ring stiffness universal testing machine at a cross head speed of 5 *mm/min* and a strain rate of 0.00166 *mm/min/s*. The tensile samples were manufactured from the fabricated composites using a lathe machine, based on the ASTM E8 standard. For the tensile test, the gauge's length, diameter, and length were evaluated 45 *mm*, 9 *mm,* and 80 *mm* respectively. Figure 3.6 shows a photograph and a schematic of the tensile sample. The tensile strength values presented are an average of three for each weight percentage of Al6061-reinforcements particles.



(a)

(b) dimensions are in mm

Figure 3.6 A photograph and a schematic of the tensile specimen.

3.4.3 Hardness Test

In this work, for measuring the hardness of Al6061-particles composites, a Vickers hardness testing machine (Type: HV, Serial No.: GT-20211206) was utilized according to the ASTM E384-10 standard. The tests were conducted for a specific time of 15 *s* by applying a constant load of 5 *Kg*. Prior to the hardness tests, the samples were grinded and polished to remove surface deposits or level uneven surfaces. For this purpose, a disc grinding machine was used with various emery papers (800, 1000, 2000, and 2500). On a disc polishing machine, the samples were then polished to achieve a fine finish. The experiment was run at room temperature, later the hardness was assessed at an average of five distinct places for preventing the impact of the resting of indenter on the particles of hard reinforcement.

3.4.4 Wear Test

A tribometer pin-on-disc machine type TQ-Plint TE91/1 at room temperature was used to examine the Al6061-particles composite's wear resistance. Based on the ASTM G99-04 standard, wear test specimens were manufactured from the fabricated composites utilizing a lathe machine. The dimensions of the wear specimens and the pin on disc tribometer have been illustrated in Figure 3.7 and Figure 3.8, respectively. The counterpart disc, with a 2 *mm* thickness and a 50 *mm* outside diameter, was manufactured utilizing duplex stainless steel (SAF 2205). Using Vickers hardness machine, the disc hardness was assessed. The disc hardness is 293 *HV*, indicating a greater hardness that of AMCs. The hardness values presented are an average of five measurements. The chemical composition and physical properties of SAF 2205 have been illustrated in Table 3.2 and

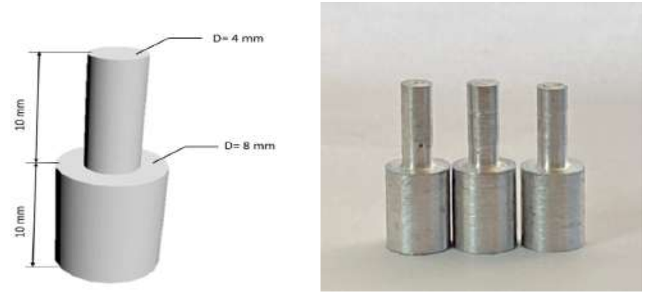
Table 3.3 (Mohammed, Gardi and Ramadan, 2020). Both the specimens and the discs were mechanically polished to remove scratches and machining marks, and they were maintained in a dry atmosphere while not in use to avoid surface corrosion.

Table 3.2 Chemical Composition of SAF2205 (Duplex Stainless Steel)

Elements	C	Si	Mn	P	S	Cr	Ni	Mo	N	Fe
Weight %	0.03	1	2	0.03	0.015	22	5	3.2	0.18	Bal.

Table 3.3 Physical Properties of SAF2205 (Duplex Stainless Steel) (Mohammed, Gardi and Ramadan, 2020).

Properties	Yield strength (*MPa*)	Ultimate strength (*MPa*)	Hardness (HV)	Modulus of elasticity (*GPa*)	Melting Range (℃)
SAF2205	450	655	293	200	1410-1450



(a) (b)

Figure 3.7 A schematic and a photograph of the wear specimen.

Figure 3.8 Pin on disc device.

A pin-on-disc tribometer machine was used to conduct dry sliding wear testing for the reinforced composites at room temperature. Before each experiment, the pin sliding surfaces were polished with 1000-grit emery paper and then cleaned with acetone to remove any remaining residue. The experiments were performed by applying a constant normal load of 20 *N*, a constant sliding velocity of 0.240855 *m/s*, constant time of 15 *min*, and a constant sliding distance. The weight of the pins was measured before and after each test using an electronic balance with an accuracy of 0.0001 *g*. Each experiment was performed three times to confirm that the measurement data was repeatable, and an average was calculated.

Wear amounts can be calculated by using Equation (3.4):

$$\Delta \mathrm{W} = \mathrm{W}_1 - \mathrm{W}_2 \quad (\mathrm{g}) \qquad (3.4)$$

Where W_1 and W_2 are the weight of the pin before and after testing.

Equation (3.5) shows how the wear rate is calculated.

$$W_r = \frac{\Delta W}{\rho} (mm^3) \qquad (3.5)$$

Where W_r is wear rate and ρ is the density of the AMCs.

3.5 Conclusion

This chapter has described the materials used in this investigation and provided details on how the composites were manufactured and the experiments that were conducted. The findings of this study would be presented in the following chapter.

CHAPTER FOUR

RESULTS AND DISCUSSION

This chapter presents the experimental findings that have been carried out and discusses the experimental findings from mechanical and tribological tests. This chapter will also look at how the parameters of each test affected the results. Additionally, we compared the impact of adding reinforcement to the matrix and the results of the current study with previous findings.

4.1 Experimental Procedure

As described in Chapter Three, to enhance the mechanical properties and tribological characteristics of Al606, different reinforcement particles were used. To fabricate the samples, the technique of stir-casting was utilized. The following parts explain the microstructural, tensile, hardness, and wear study findings.

4.2 SEM Analysis

As mentioned in Chapter Three, to investigate the microstructural characterization of the fabricated samples SEM was employed. The SEM results of the cast Al6061-reinforcements composites with various weight percentages of the particles are illustrated in Figure 4.1 to Figure 4.5. Images captured by a SEM show that the particles are evenly distributed over the matrix alloy. Furthermore, the images do not show any typical defects of cracks, or shrinkage. The rest of the SEM images are presented in the Appendix.

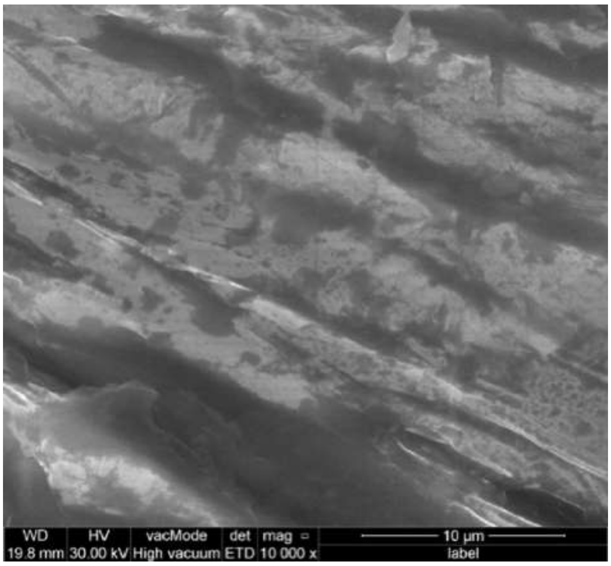
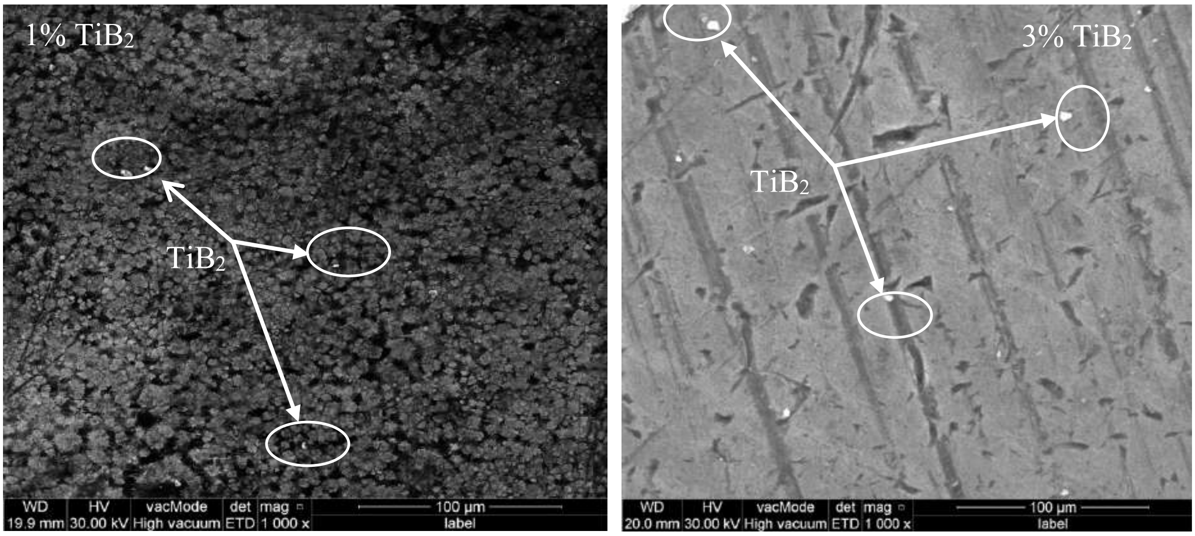


Figure 4.1 SEM images of Al6061.



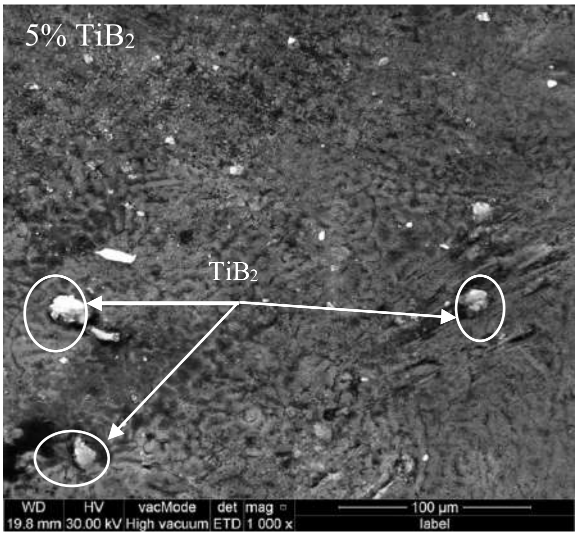


Figure 4.2 SEM images of Al6061–TiB_2 composites.

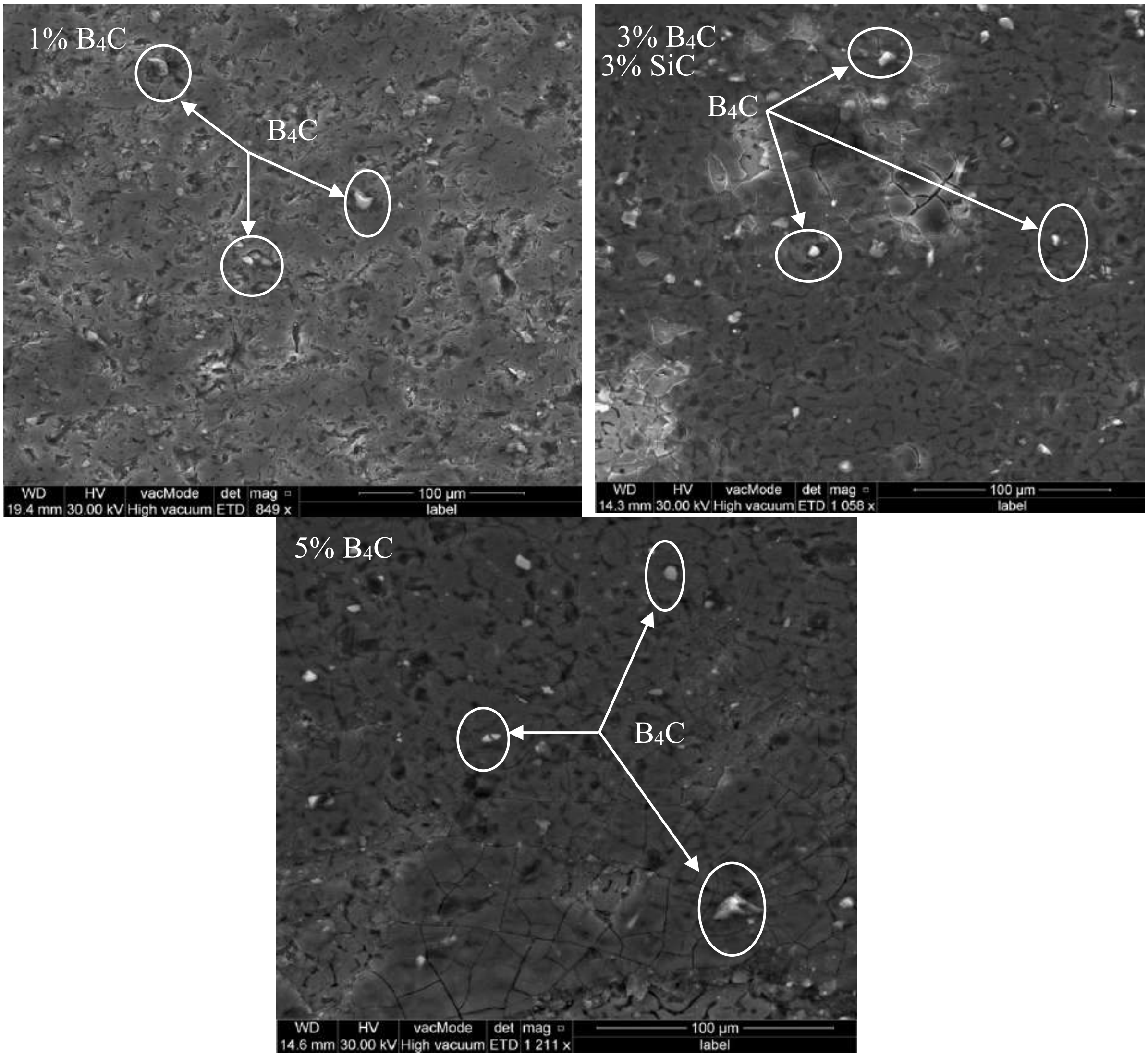


Figure 4.3 SEM images of Al6061–B_4C composites.

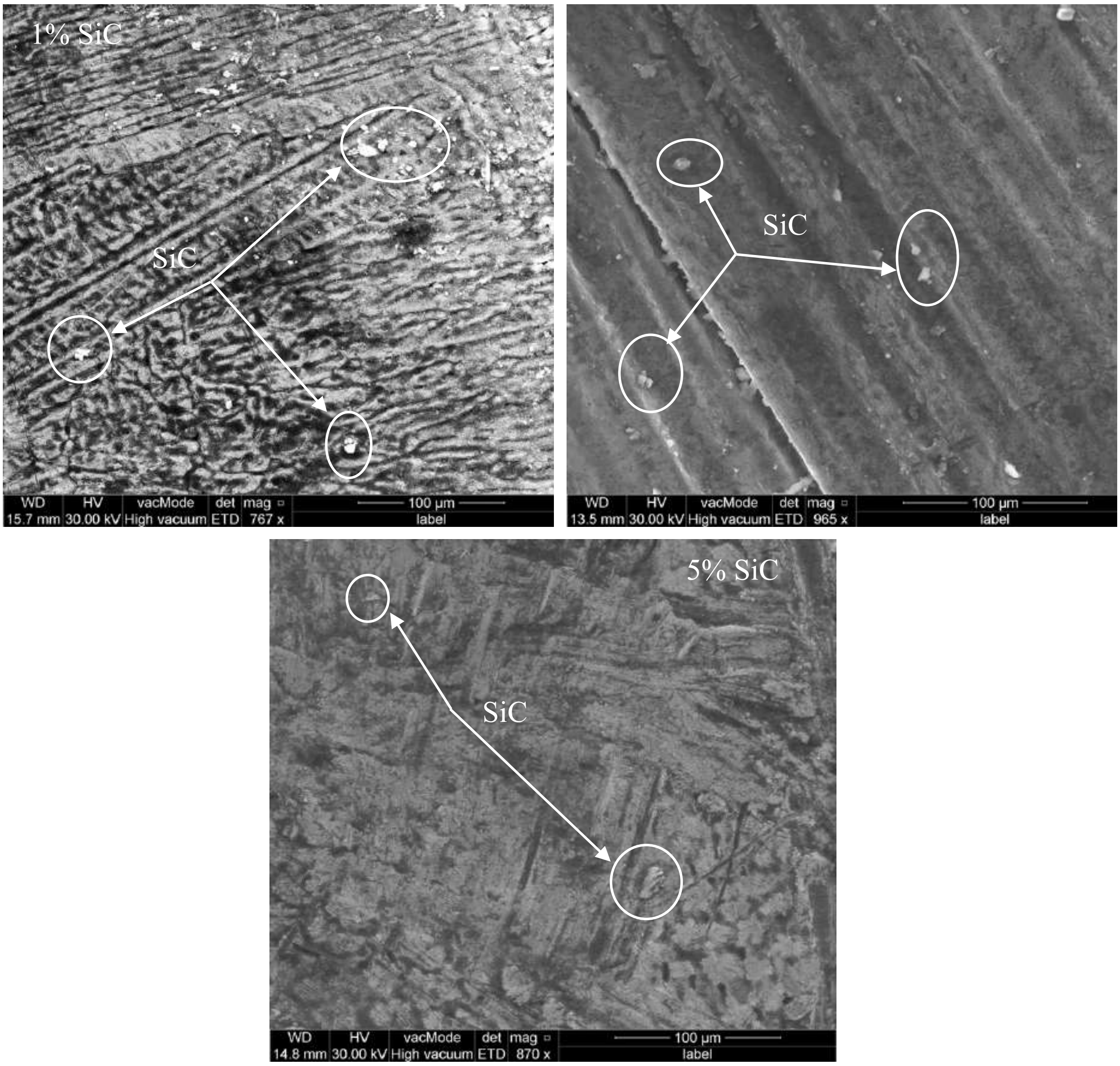
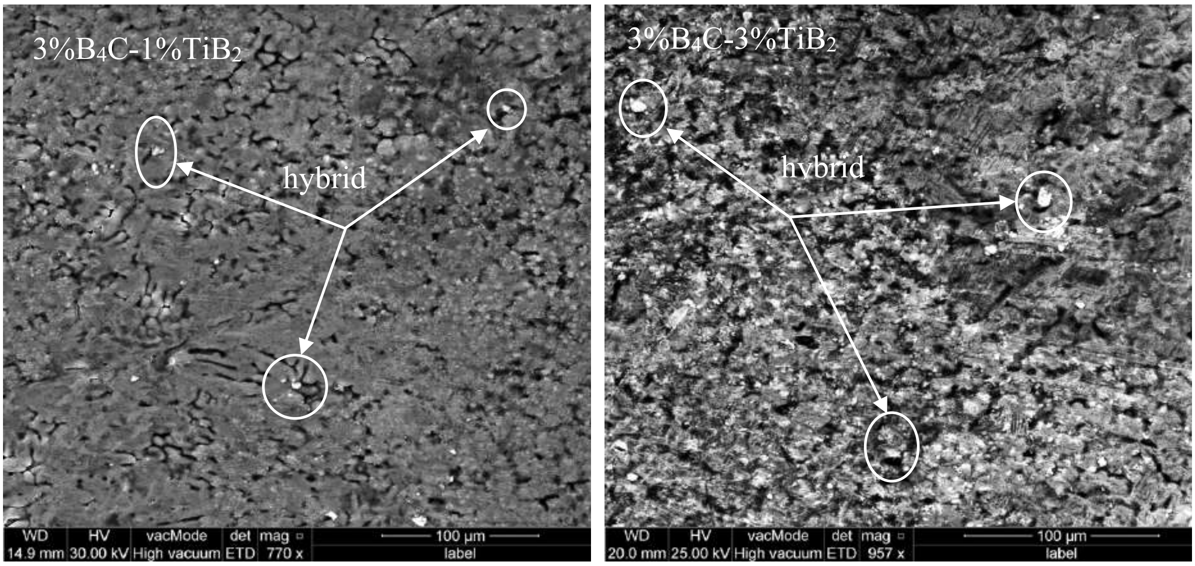


Figure 4.4 SEM images of Al6061–%SiC composites.



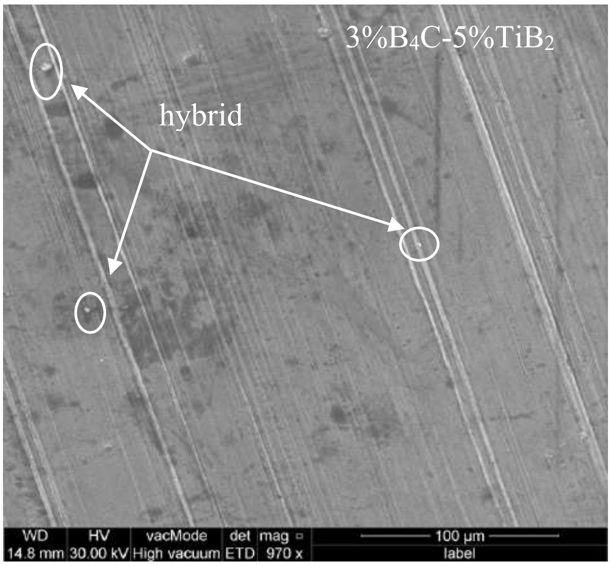
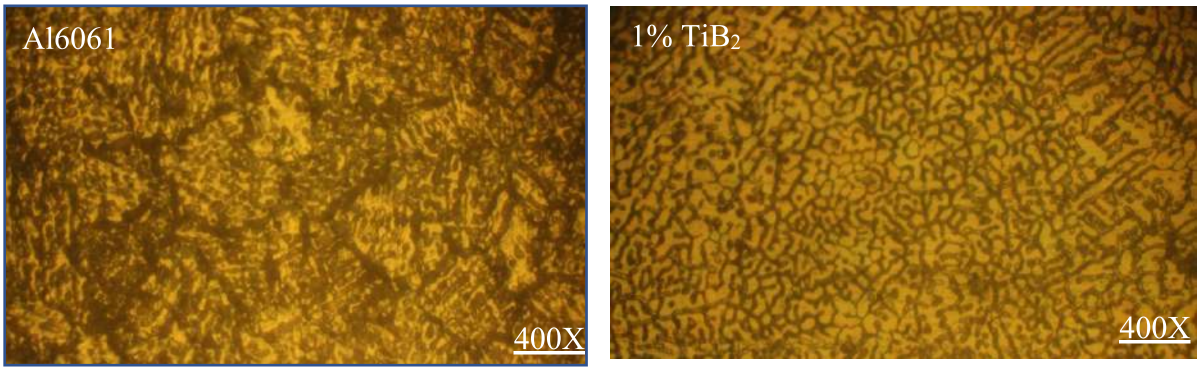
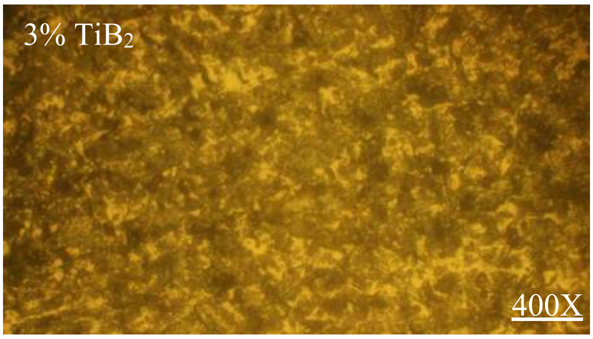
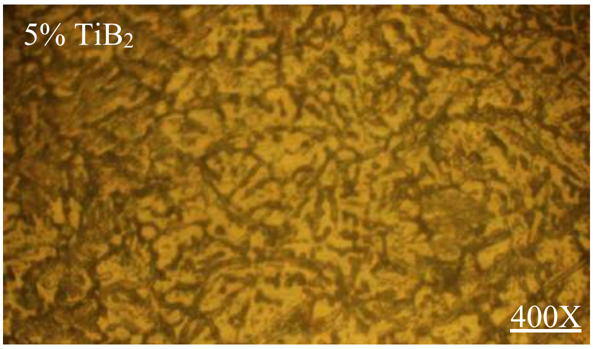


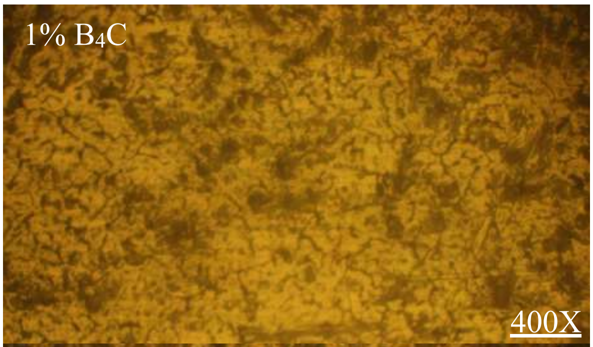
Figure 4.5 SEM images of Al6061-hybrid composites.

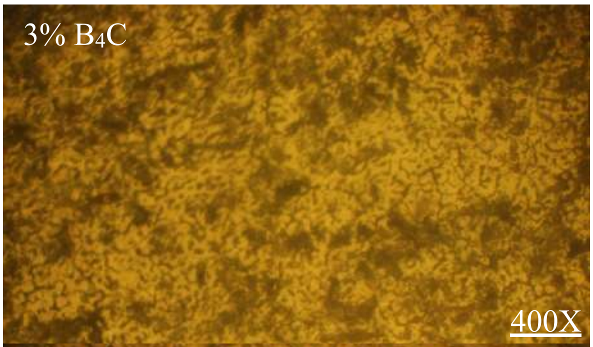
Figure 4.6 illustrated the optical photomicrographs of the manufactured AMCs. The microstructure findings show that the reinforcement particles are distributed equally in the matrix at all weight percentages. This is due to different factors such as the wettability agent (Mg), the application of optimal process parameters and the efficient stirring action, which cause the particles to neither float nor settle in the mixture. To increase the AMCs mechanical properties, the particles homogenous distribution is required.

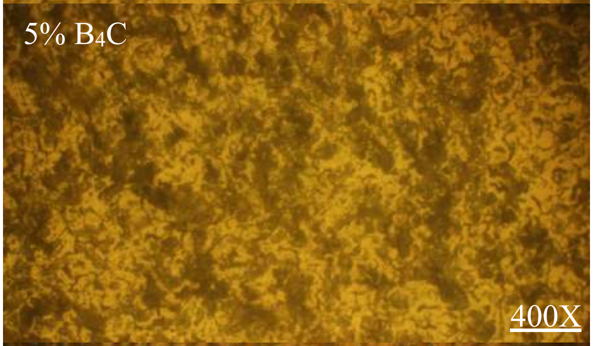


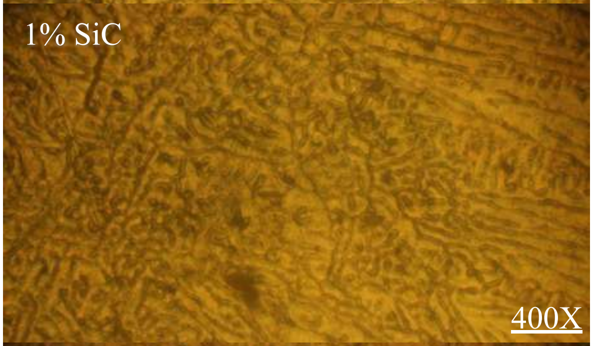

3% TiB_2
400X


5% TiB_2
400X


1% B_4C
400X

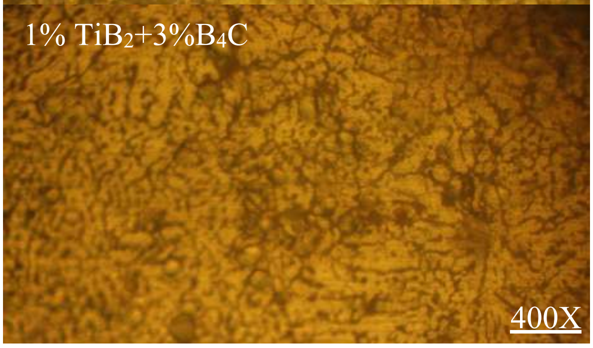

3% B_4C
400X

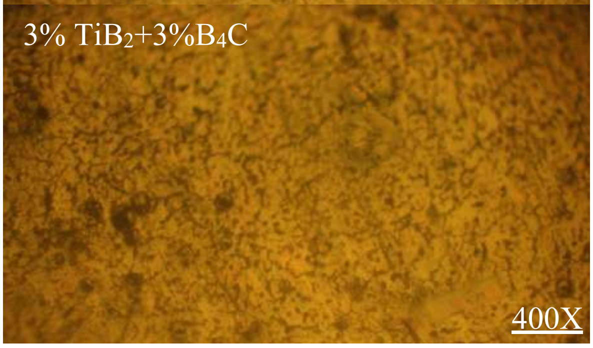

5% B_4C
400X


1% SiC
400X


3% SiC
400X


5% SiC
400X


1% TiB_2+3%B_4C
400X


3% TiB_2+3%B_4C
400X

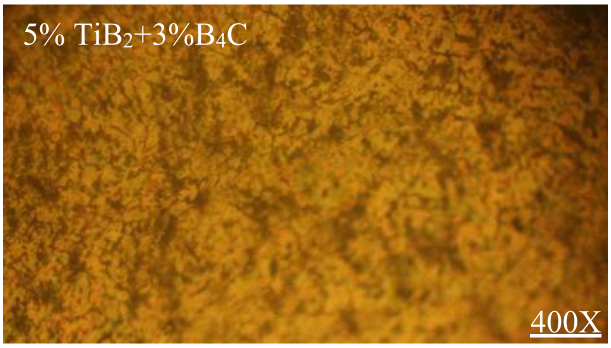


Figure 4.6 Microstructure of Al6061-reinforcements composites.

4.3 Density and Porosity

At room temperature, the void content and density of titanium diboride, boron carbide, silicon carbide, and hybrid reinforced aluminium matrix composites were analyzed for determining the amount of porosity in the composite. The theoretical density is measured by the volume and weight of the samples. The measured practical density was compared to the theoretical densities according to the mixture rule and determined the volume content of porosity.

4.3.1 Density of Al6061-TiB_2 Composites

Figure 4.7 and Figure 4.8 show the relationship between the percentage of titanium diboride particles in Al6061-TiB_2 composites and the changes in density and porosity, respectively. As seen in Figure 4.7, the theoretical and experimental densities of Al6061-TiB_2 composites have resemble patterns and are quite close. The density increase implys that particle breaking might not significantly affect the manufactured composites. Because TiB_2 particles are spread out evenly, and the matrix-reinforcement bonds are getting stronger. Density measurements of the Al6061-1% TiB_2 composite show a discrepancy with theory, perhaps attributable to particle clustering of the TiB_2 or the development of porosity.

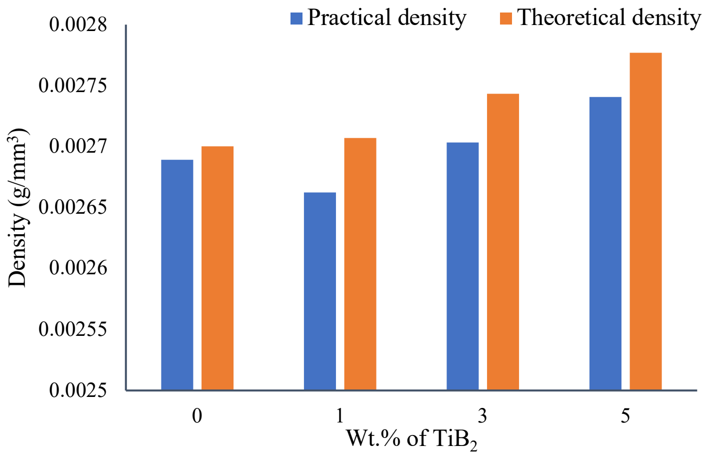


Figure 4.7 Density of Al6061-TiB_2 composites.

As shown in Figure 4.8, the produced composites have higher porosity values than the matrix alloy. Adding reinforcement to molten Al6061 alloy increases the contact surface area, which is the primary cause of a rise in Al6061-TiB_2 composites porosity. The casting method used in AMC manufacturing also affects porosity. During the stir casting process, gases might get trapped in the composite of molten increasing the content of porosity. The porosity of Al6061-TiB_2 composites increased from 0.4% at 0% TiB_2 to 1.66% at 1% TiB_2, but then slightly decreased compared to 1% TiB_2. These results reflect those of Dey *et al.* (2020), who also found that adding the hard particles of TiB_2 increased matrix density and porosity (Dey, Bhowmik and Biswas, 2020).

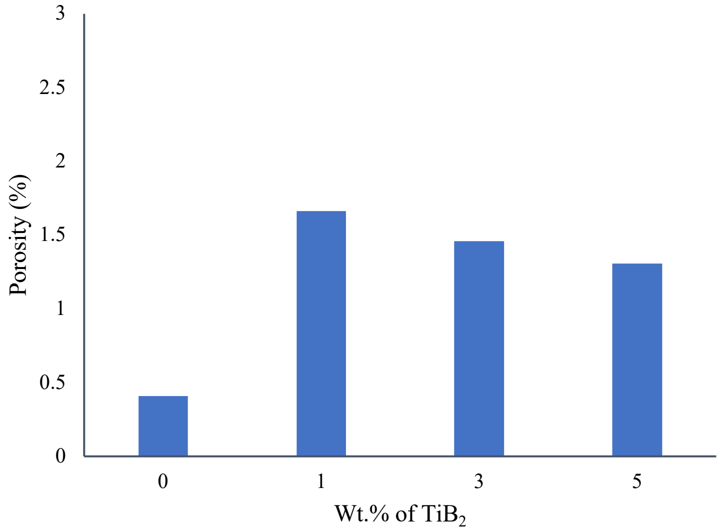


Figure 4.8 Porosity of Al6061-TiB_2 composites.

4.3.2 Density of Al6061-B_4C Composites

Figure 4.9 shows the sample densities obtained after casting the composite material. The experiments' findings reveal that the composite samples' density gradually increases when hard B_4C particles are added as reinforcement. The percentage of porosity for each Al6061-B_4C combination is shown in Figure 4.10. The results show that porosity increased when adding 1%, 3% and 5% of the reinforcement, maybe due to the casting defects or adding reinforcement. These results agree with those obtained by (Hashim, Looney and Hashmi, 1999), who discovered that reducing porosity was related to the casting parameters.

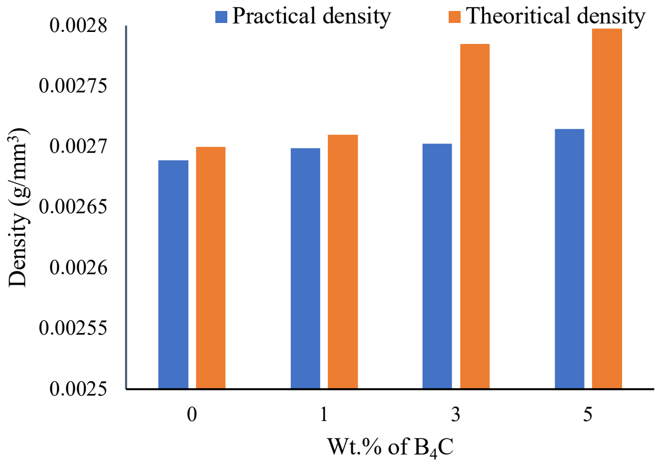


Figure 4.9 Density of Al6061-B_4C composites.

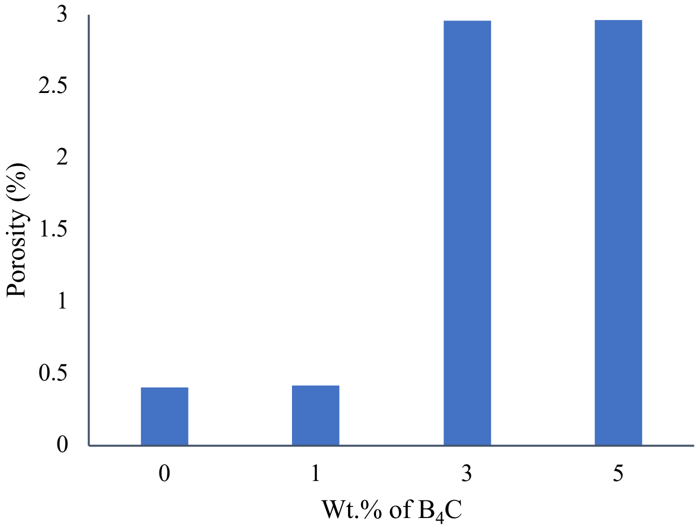


Figure 4.10 Porosity of Al6061-B_4C composites.

4.3.3 Density of Al6061-SiC Composites

Figure 4.11 illustrates the discrepancy between the measured and calculated composite material densities. By adding 1% wt. of SiC, theoretical density is decreased compared to base alloy due to the fact that using 400 *g* weight at the beginning test instead of 700 *g* weight. The findings for porosity in the composites are shown in Figure 4.12. The findings indicate that adding the particles to the matrix increases porosity and voids within the composite due to the poor casting process that causes porosity and voids within the composite.

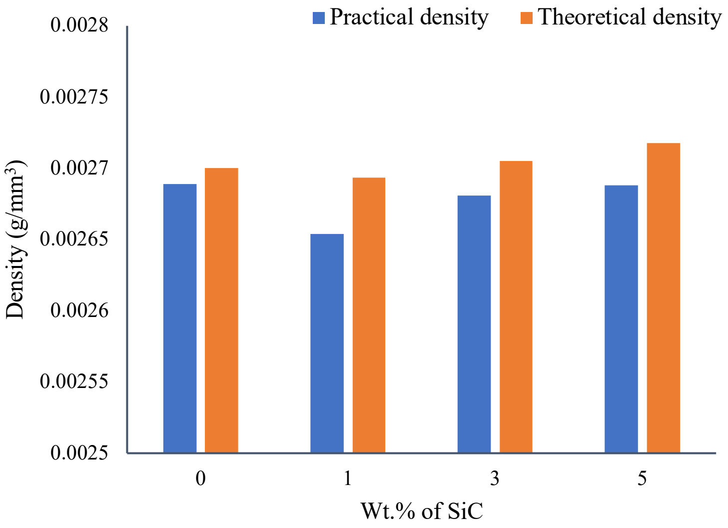


Figure 4.11 Density of Al6061-SiC composites.

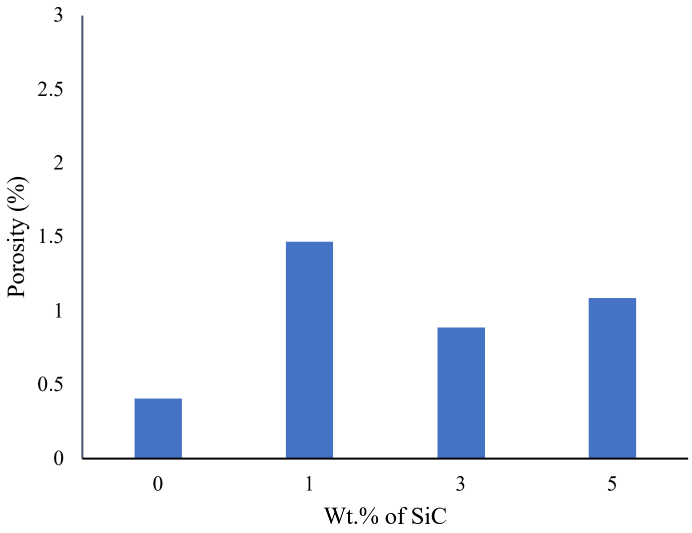


Figure 4.12 Porosity of Al6061-SiC composites.

4.3.4 Density of Al6061-Hybrid Composites

The Al6061-Hybrid composite density has been measured and analysed theoretically and experimentally. Figure 4.13 shows the densities range. Due to the higher density of TiB_2 (4.52 *g/cm*^{3}) and B_4C (2.52 *g/cm*^{3}) particles when compared to aluminium alloy, the density rises as the weight percent of TiB_2 and B_4C increases (Prince *et al.*, 2022). Different hybrid composites have different porosity levels, as shown in Figure 4.14. The graph demonstrates that the proportion of porosity rises with the percentage of secondary hard particles of TiB_2. This occurrence results from certain unavoidable minor clustered zones forming around the secondary hard TiB_2 particles separated from the base Al6061 matrix alloy with the initial reinforcement of B_4C particles. This finding is consistent with that of Hillary *et al.* (2020), who discovered that increasing the amount of hard additives in metal matrix composites increased porosity (Hillary, Ramamoorthi and Chelladurai, 2020).

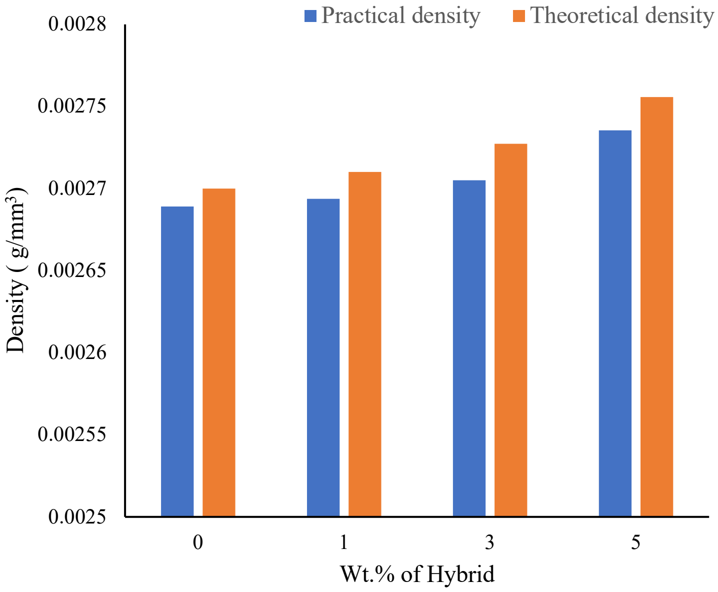


Figure 4.13 Density of Al6061-Hybrid composites.

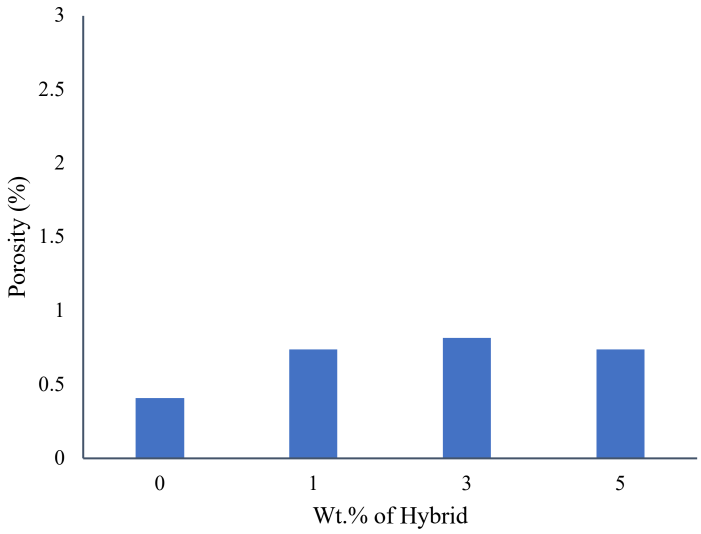


Figure 4.14 Porosity of Al6061-Hybrid composites.

4.4 Tensile Test Results

Based on ASTM.E8 standards and utilizing a computerized testing machine of universal tensile, tensile tests were performed to examine the composites' tensile behaviour.

4.4.1 Tensile Test Results of Al6061-TiB_2 Composites

The tensile results are presented in Figure 4.15. The average of three readings is used for each result. Results demonstrated an improvement in composite tensile strength from 126.26 *MPa* (0%TiB_2) to 290 *MPa* (5% TiB_2). As can be observed, the cast Al6061 has a lower strength and a larger elongation than Al6061-TiB_2 composites. The AMCs has the highest ultimate strength, as a result of its homogeneous dispersion and strong bonding properties. These results corroborate the ideas of (Suresh and Moorthi, 2013; Suresh, Moorthi, *et al.*, 2014; Banoth and Bt NaiK, 2020) who proposed that using additional TiB_2 reinforcing particles during the composite fabrication process would increase the material's tensile strength. The ultimate tensile strength at various amounts of TiB_2 particles is illustrated in Figure 4.16 and the error bars represent the standard deviation. In summary, according to these findings, when the reinforcing amount is increased, tensile strength rises while ductility decreases. The larger value of the tensile strength of 5% TiB_2 which approximentally 290 *MPa*.

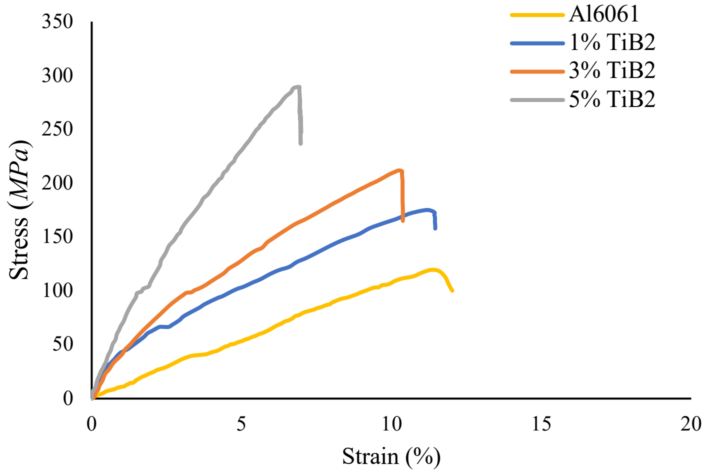


Figure 4.15 Stress-Strain curves of Al6061-TiB_2 composites.

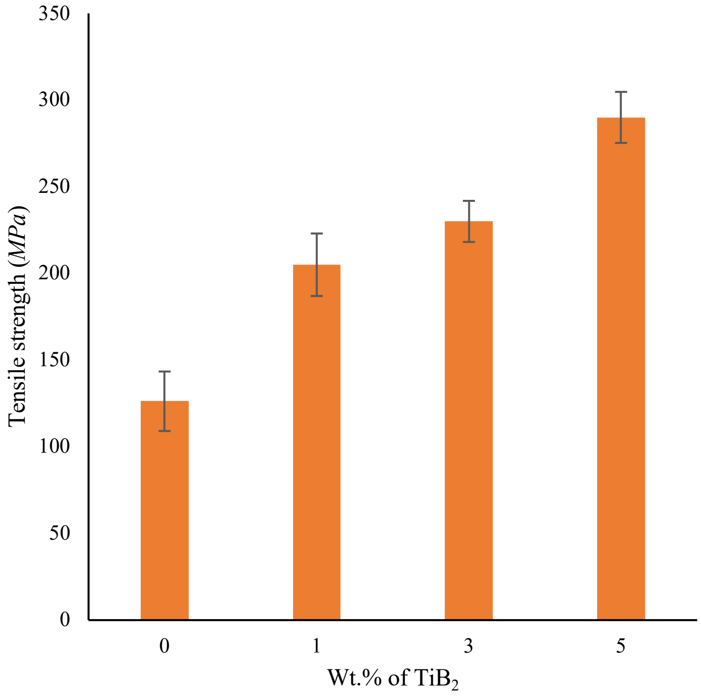


Figure 4.16 Differentiation in ultimate tensile strength with wt.% of TiB_2.

4.4.2 Tensile Test Results of Al6061-B_4C Composites

Tensile test results from experiments are shown in Figure 4.17. Results are presented as the mean of three measurements. After being treated with B_4C particles, the composites tensile strength was enhanced from 126 *MPa* to 225 *MPa*, indicating that these particles are effective. The Al6061-5% B_4C composite has the highest ultimate tensile strength, while the cast Al6061 has less strength and greater elongation than the Al6061-B_4C composites because of its uniform distribution and strong bonding characteristics. Figure 4.18 demonstrates that adding more B_4C particles improves the material's ultimate tensile strength and the error bars show the standard deviation. These results corroborate the ideas of Kalaiselvan *et al.* (2011), who suggested that the tensile strength of fabricated composites was raised by adding more B_4C reinforcing particles (Kalaiselvan, Murugan and Parameswaran, 2011).

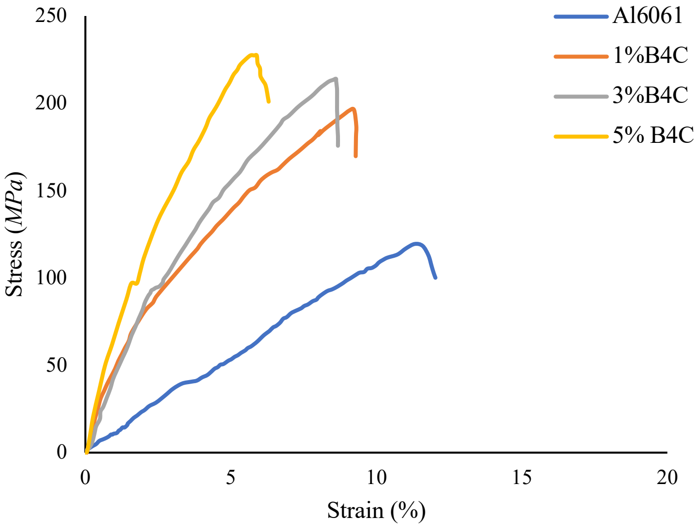


Figure 4.17 Stress-Strain curves of Al6061-B_4C composites.

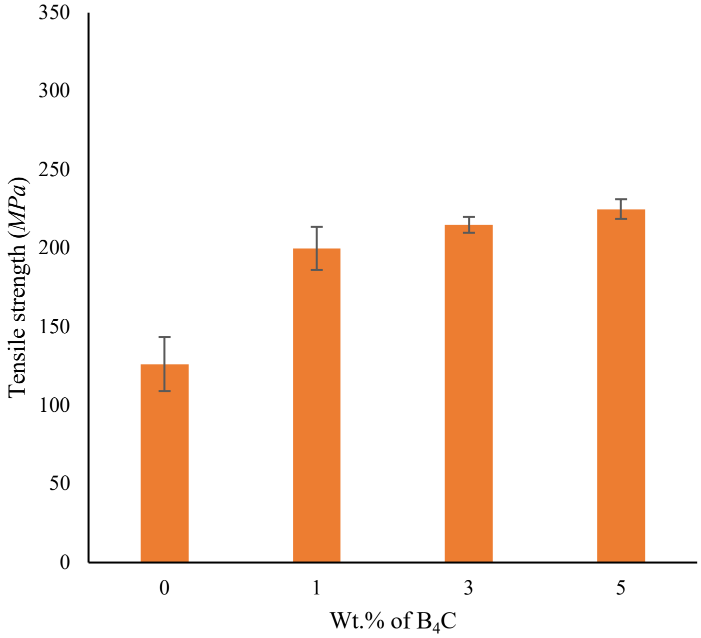


Figure 4.18 Differentiation in ultimate tensile strength with wt.% of B_4C.

Compared to other efforts, it is clear that the present research produces superior outcomes. Kalaiselvan *et al.* (2011) showed that adding 12% of B_4C, enhanced tensile strength to 215 *MPa* (Kalaiselvan, Murugan and Parameswaran, 2011). In a research carried out by Ravi *et al.* (2015), it was shown that when 10% B_4C added to the matrix the tensile strength enhanced 23.9% comparing with the base alloy (Ravi, Balu Naik and Udaya Prakash, 2015). In another major study, Karabulut *et al.* (2016) found that by adding 20 wt.% of B_4C to the base alloy tensile strength decrease from 200 to 189 *MPa* (Karabulut, Karakoç and Çıtak, 2016). The results of this investigation show that the tensile results increased 78.2% when 5% of B_4C added to Al6061.

4.4.3 Tensile Test Results of Al6061-SiC Composites

Figure 4.19 illustrated the tensile strength changes for SiC reinforced composites, and aluminium 6061 alloys. As it could be observed from Figure 4.20, tensile strength varies with silicon carbide particle content and the error bars show the standard deviation. A rise in tensile strength from 126.26 *MPa* to 165 *MPa* was seen after adding 1 wt.% particles of silicon carbide to Al6061. One unanticipated finding was that by adding 1% of SiC, elongation also increase maybe due to poor interfacial boding between matrix and reinforcement. Tensile strength of 3 wt.% SiC decreased to 115 *MPa*. Because there are pieces that are broken in the structure, this is because not enough strength is being put into the connection between the matrix and the particulars. When 5 wt.% SiC particles added into the alloy, UTS was shown to increase slightly. This finding was also reported by Ozben *et al.* (2008), by adding 15 wt.% of SiC particles, final tensile strength decreased (Ozben, Kilickap and Çakir, 2008).

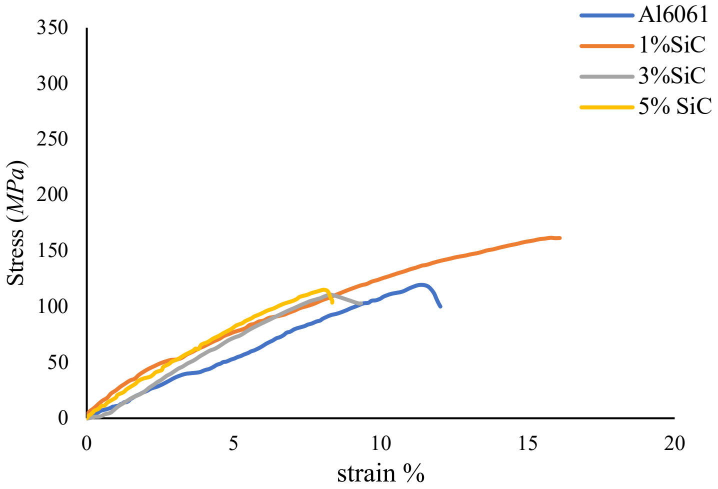


Figure 4.19 Stress-strain curve of Al6061-SiC composites.

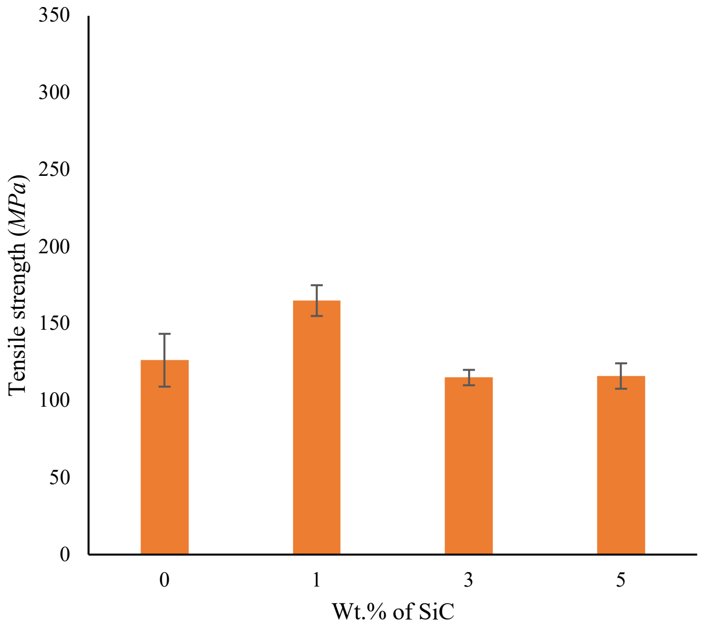


Figure 4.20 Differentiation in ultimate tensile strength with wt.% of SiC.

4.4.4 Tensile Test Results of Al6061-Hybrid Composites

Figure 4.21 displays the stress-strain relationships for Al6061-B_4C-TiB_2 hybrid composites. In increasing the ultimate tensile strength of AMCs, titanium diboride (TiB_2) and boron carbide (B_4C) particles are superior because of their excellent bonding nature.

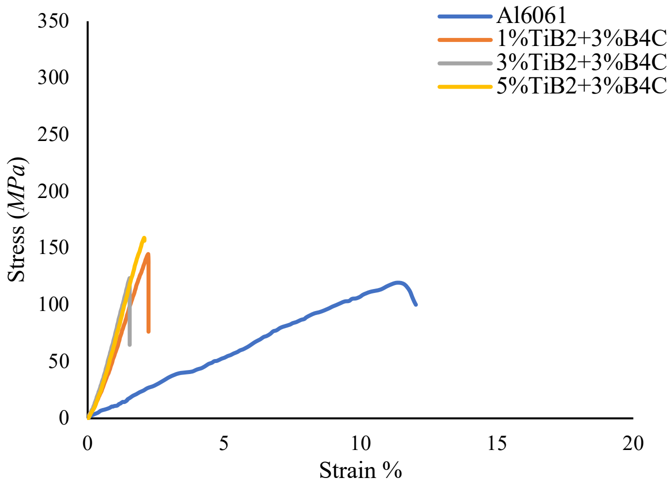


Figure 4.21 Stress-strain curve of Al6061-Hybrid.

Figure 4.22 displays the ultimate tensile strength of aluminium matrix composites. Adding 5 wt% TiB_2–3 wt% B_4C of hybrid reinforcement improved the ultimate tensile strength and the error bars on the experimental lines show how much the data deviated from the average. The tensile strength of hybrid composites increases by 25%, compared to the base alloy. The findings of this investigation suggest that the composites had maximum ultimate tensile strength when TiB_2 was added as a reinforcement.

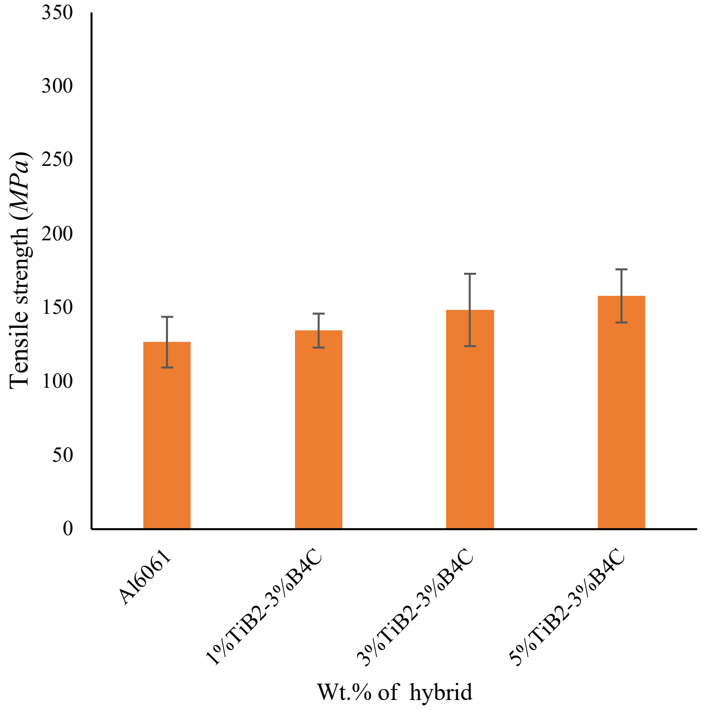


Figure 4.22 Differentiation in ultimate tensile strength with wt.% of hybrid.

Overall, these results indicate that adding TiB_2 particles to the Al6061 have higher tensile strengths than other reinforcements as shown in Figure 4.23.

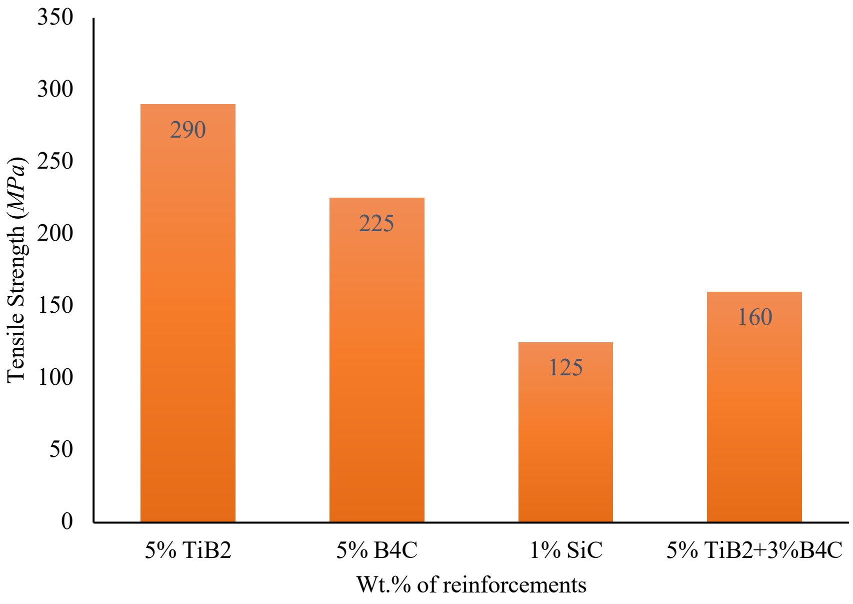


Figure 4.23 Tensile variation of Al6061 with weight percentages of reinforcements.

4.5 Hardness Test Results

Vickers hardness measurements were taken for both the matrix alloy and the composite to determine how the reinforcement affects the aluminium. As mentioned in Chapter Three, for avoiding the influence of the indenter pressing on the particles of hard reinforcement, the hardness was measured at an average of five different locations.

4.5.1 Hardness Test Results of Al6061-TiB_2 Composites

Figure 4.24 depicts the correlation between the amount of the Vickers hardness and TiB_2. The error bars on the experimental lines show how much the data deviated from the average. The findings show that with enhancing the weight percentages of the TiB_2 particles the hardness enhanced because of the good bonding interface and structure of the composite. Comparison of the results with those of other studies confirms that by increasing the reinforcements, the hardness of the composite also increases. These results reflect those of (Suresh and Moorthi, 2013) who found that adding TiB_2 to Al alloy increased the materials hardness. The most surprising aspect of the hardness data is the comparison of the findings with those of other studies. Suresh *et al.* (2013) succeeded in increasing the hardness of Al6061 by 10.57% when a 12% weight percentage of TiB_2 was added (Suresh and Moorthi, 2013). While Suresh *et al.* (2014) added 10% of TiB_2 to the matrix Al6061, they increased the hardness by only 16% (Suresh, Moorthi, *et al.*, 2014). While in the current study, by adding only 5% of TiB_2 particles, the hardness increased by 40.2% compared to base alloys. These findings are probably connected to the uniform distribution and uniform stirring action.

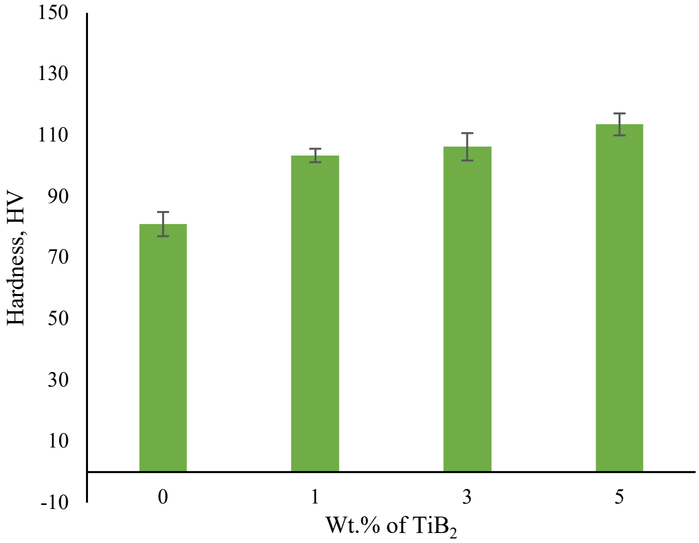


Figure 4.24 Variation of hardness with weight percentage of TiB_2.

4.5.2 Hardness Test Results of Al6061-B_4C Composites

As shown in Figure 4.25, the findings demonstrate that the hardness increased as the B_4C particle weight percentages increased. The experimental lines' error bars indicate how much the data varied from the average. Compering the findings with those of other studies confirms current works have better results than other. In 2011, Kalaiselvan and co-workers added 12% of the particles, and the hardness enhanced from 51.3 to 80.8 *HV* (Kalaiselvan, Murugan and Parameswaran, 2011). A study on B_4C's effect on hardness characteristics was conducted by

Ravi *et al.* (2015). They reported that by adding 10% of the particle, hardness enhanced from 62 to 68 *HV* (Ravi, Balu Naik and Udaya Prakash, 2015). In a recent cross-sectional study, Karabulut *et al.* (2016) investigated when 20% of the reinforcement added to Al6061, hardness increased from 56 to 70 *HV* (Karabulut, Karakoç and Çıtak, 2016). In the current study, adding 5% of B_4C particles increased the hardness from 81 to 100.2 *HV* compared to base alloys.

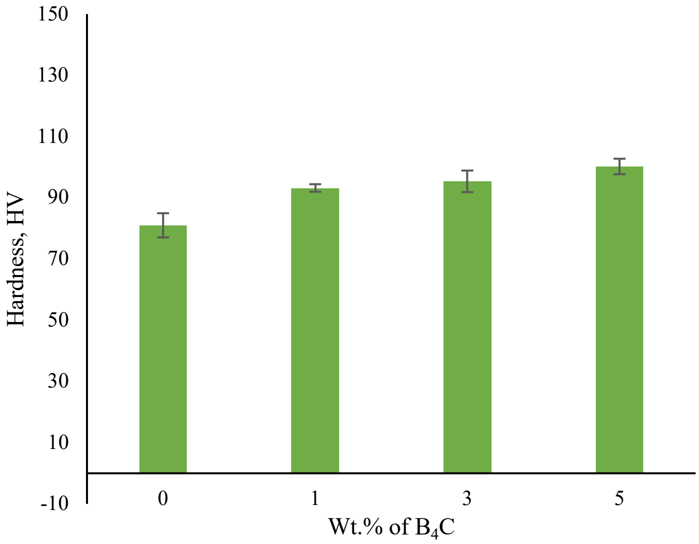


Figure 4.25 Variation of hardness with weight percentage of B_4C.

4.5.3 Hardness Test Results of Al6061-SiC Composites

The material's hardness was significantly increased by introducing SiC particles into the aluminium matrix, as seen from the data in Figure 4.26. Experimental lines' error bars represent data deviations from the average. Adding 1wt.% of SiC particles increased hardness slightly from 81*HV* to 83.175*HV*. The Al6061 alloy hardness was enhanced from 81 to 91.62 *HV* by adding 3 wt.% SiC particles. Al6061-5% SiC was found to have the hardness with the highest value 92.74 *HV*. These results reflect those of Vanam *et al.* (2018), who discovered that adding reinforcement enhanced the composite's hardness (Vanam *et al.*, 2018). Sivananthan *et al.* (2020), in their research showed that addition of 4 wt.% of SiC particles to Al6061, raised 25% the hardness comparing with the base alloy

(Sivananthan, Ravi and Samuel, 2020). In the same area, a research carried out by Veeresh Kumar *et al.* (2012) showed that through adding 6 wt.% SiC to the matrix, the hardness enhanced by 65% compared to base alloy (Veeresh Kumar, Rao and Selvaraj, 2012).

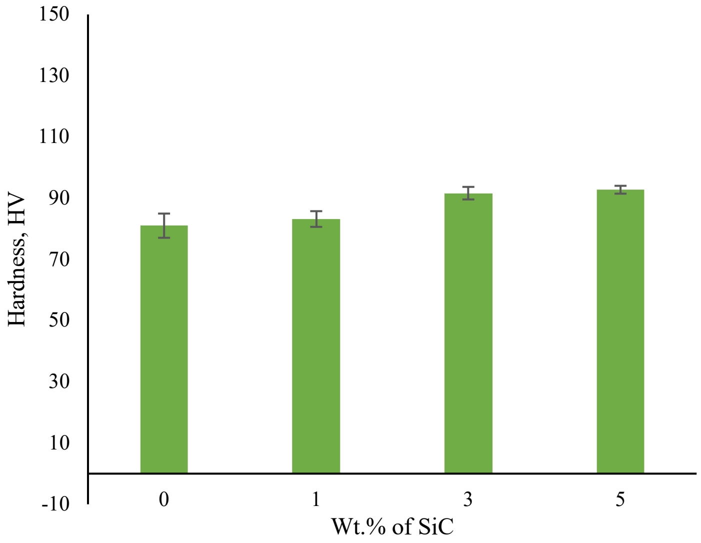


Figure 4.26 Variation of hardness with weight percentage of SiC.

4.5.4 Hardness Test Results of Al6061-Hybrid Composites

Figure 4.27 shows the variation of hardness in Vickers with the weight percentage of hybrid. The figure illustrates that when 1%, 5% TiB_2-3% B_4C as a hybrid reinforced with Al6061, and the error bars show the standard deviation. The hardness was increased dramatically by an amount of 81.5% and 81.48% compared to the base alloy, but when TiB_2 increased to 3% with constant B_4C, the hardness decreased slightly compared to 1%TiB_2. The great interfacial area between the soft and hard phases, might be the primary cause of this (Gupta *et al.*, 2018).

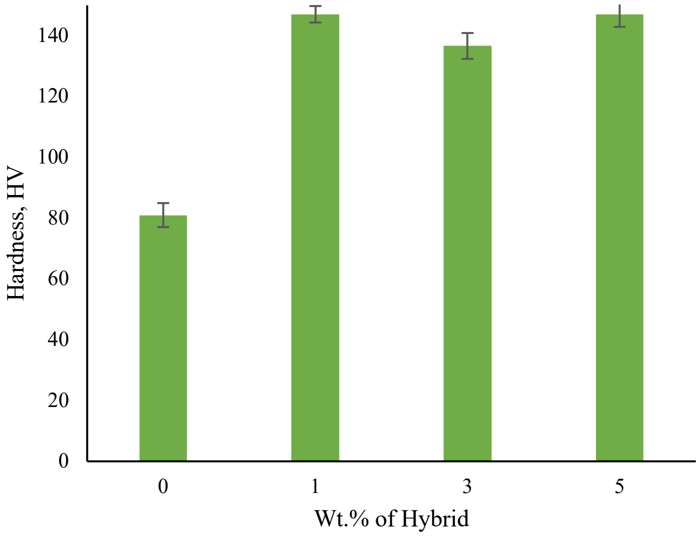


Figure 4.27 Variation of hardness with weight percentage of hybrid.

Overall, these results indicate that by adding 5 wt.% of TiB_2, B_4C, SiC, and hybrid particles, the hardness increased by 40.2%, 23.7%, 14.49%, and 81.48%, respectively. As can be seen from Figure 4.28.

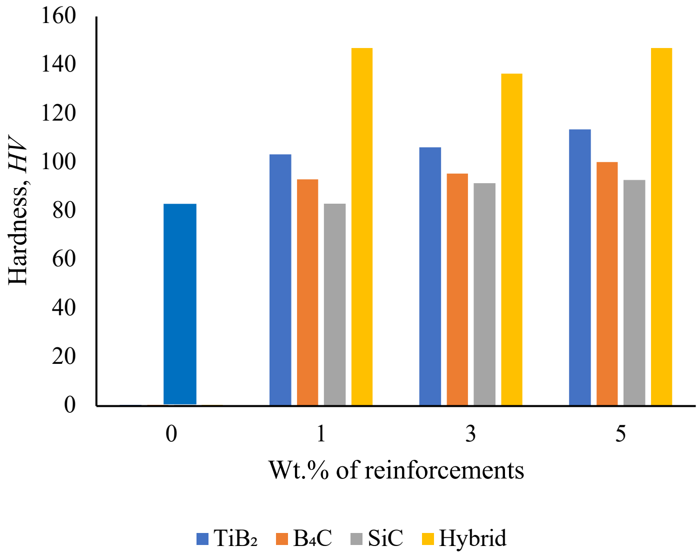


Figure 4.28 Hardness variation of Al6061 with weight percentages of reinforcements.

4.6 Wear Test Results

As described in Chapter Three, dry sliding wear tests on the composite specimens were carried out at room temperature utilizing a pin-on-disc tribometer machine to examine the wear of the manufactured AMCs. The wear results for each reinforcement particle are presented separately below.

4.6.1 Wear Test Results of Al6061-TiB_2 Composites

The findings of wear tests carried out on Al6061-TiB_2 are illustrated in Figure 4.29. The figure illustrates how the quantity of TiB_2 in the composites affects the wear rate for a constant load and sliding speed. The lower wear rate and thus the improvement in wear resistance of Al6061-TiB_2 composites can be clarified as follows: The dislocation and TiB_2 particle interactions during sliding wear prevent crack propagation. Strain fields are formed around the reinforcement particles during solidification as a result of the temperature mismatch between the TiB_2 particle and Al6061. Such strain fields impede the crack's propagation and subsequent material removal. The defect-free TiB_2 particles formed in situ maintain their integrity during sliding. TiB_2 particles are distributed homogeneously, providing Orowan strengthening (Zhang and Chen, 2008). The detachment of the TiB_2 particles from the aluminium matrix (Al6061) is delayed by good bonding and a clear interface. As a result, TiB_2 particles improve the AMCs' wear resistance. Another factor that may contribute to a decreased wear rate is the TiB_2 particles' ability to refine the grain. The lower wear rates and thus in composites containing 3% TiB_2 particles are due to the strong interfacial bonding in such in situ composites. This finding is consistent with that of Mandal *et al.* (2007), who found that wear rates do not decrease linearly with increasing quantities of TiB_2, which might be attributable to the complex processes that occur during composite wear (Mandal, Chakraborty and Murty, 2007).

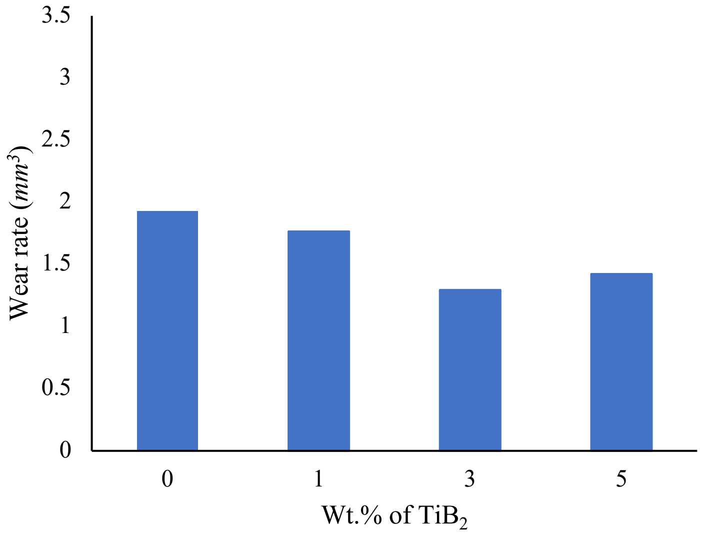


Figure 4.29 Wear rate of Al6061- wt.% of TiB_2.

4.6.2 Wear Test Results of Al6061-B_4C Composites

Figure 4.30 shows that different combinations of the Al6061-B_4C composites made have different rates of wear at constant applied load and constant sliding distances. The decreased wear rate, and hence improved wear resistance, of Al6061-B_4C composites may be explained as follows: During sliding wear, dislocation and B_4C particle interactions inhibit crack growth. As a consequence of the temperature difference between the B_4C particle and the Al6061, strain fields arise around the reinforcing particles during solidification. Such strain fields limit the growth of the crack and subsequent material removal. During sliding, the defect-free B_4C particles generated in situ preserve their integrity. B4C particles are dispersed uniformly, resulting in Orowan strengthening (Zhang and Chen, 2008). Good bonding and a clean interface delay the detachment of the B4C particles from the aluminium matrix (Al6061). As a consequence, B_4C particles increase the wear resistance of AMCs. Another element that may contribute to a lower wear rate is the capacity of the B_4C particles to refine the grain. Strong bonding between the surfaces of these in-situ composites is why composites with 1% B_4C particles show a lower wear rate. Another possible explanation for the low wear rate at 1% B_4C is due to the porosity of the samples, where the porosity is low compared to the other weight percentages (see Figure 4.18). This result agrees with Mandal *et al.* (2007), who showed that the rate of wear declines with increasing particles but that this relationship is not linear (Mandal, Chakraborty and Murty, 2007). It may be because of the complexity of the mechanisms at play during composite wear.

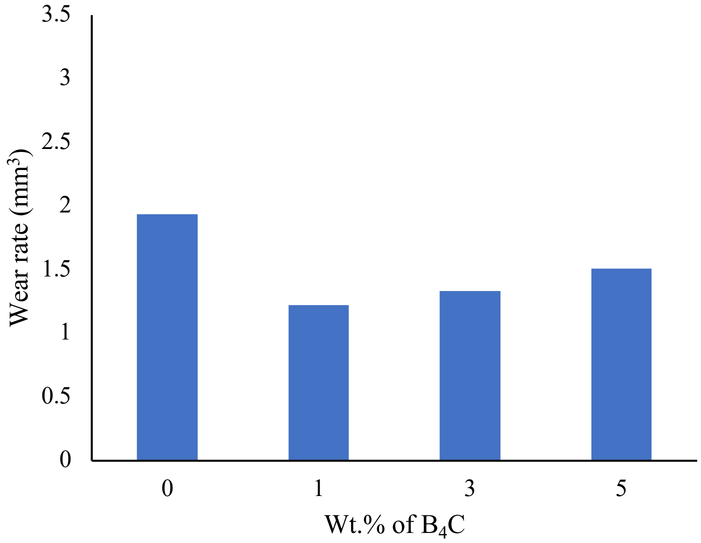


Figure 4.30 Wear rate of Al6061- wt.% of B_4C.

4.6.3 Wear Test Results of Al6061-SiC Composites

As shown by the data in Figure 4.31, adding 1% of SiC increased the rate of wear compared with the base alloy because the rate of wear increased by increasing the porosity of the sample. Then by adding 3, 5% of SiC wear rate decrease compared to base alloy.

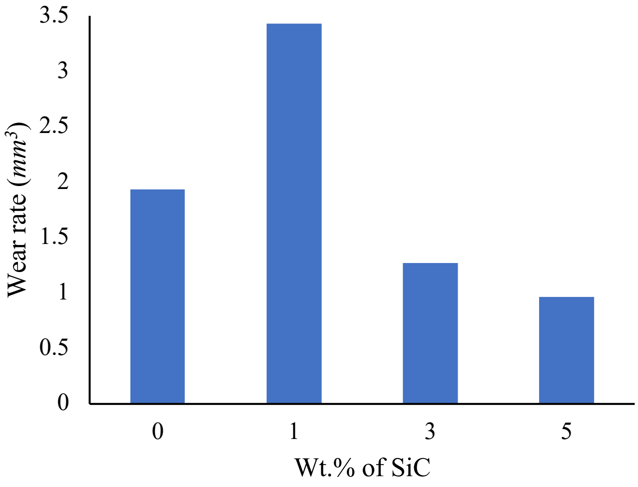


Figure 4.31 Wear rate of Al6061- wt.% of SiC.

4.6.4 Wear Test Results of Al6061-Hybrid Composites

Figure 4.32 shows the rate of wear in the Al6061-B_4C-TiB_2 composites. It was discovered that the Al6061-1% B_4C composite had a much lower rate of wear compared to the base alloy. When 1% wt. of the particles added to the matrix, wear rate significantly increased but when 3 and 5% wt. of B_4C added the wear rate increased compared to 1% wt. of the particles due to the sample's porosity. Wear rate is greatly affected by porosity.

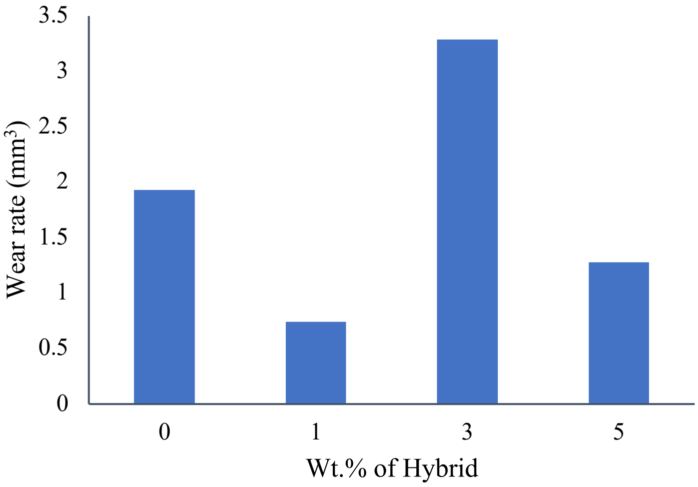


Figure 4.32 Wear rate of Al6061- wt.% of Hybrid.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

This chapter is divided into two sections; The results of the current work are highlighted in the first section. The second section presents some suggestions for future work.

5.1 Conclusions

The specific results of the experiment on particulate-filled composites of metal matrix are provided in the section below. To manufacture AMCs, the technique of stir casting was used using different reinforce particles including SiC, TiB_2, and B_4C with different weight percentages. Wear, hardness and tensile tests were carried out for the AMCs. SEM were performed for the samples as well. The following conclusion can be drawn from the present study.

5.1.1 Al6061-TiB_2 Composite

- Compared to the composite with the least amount of particles, the experimental densities of Al6061-5% TiB_2 composites were found to rise by an average of 1.9%.
- The composites' porosity rises from 0.4% to 1.66%, then slightly decreases.
- Tensile strength and hardness are increased when TiB_2 particles are incorporated into Al6061.
- The tensile strength improved by 79.54% at 5% of TiB_2, when compared to the base alloy.
- The addition of TiB_2 particles in Al6061 increases the wear resistance of the material by about 50%. In addition, the wear results reveal also that the

relationship between the wear rate and the quantity of TiB_2 is not linear, due to the bonding between the particles and casting defects.

5.1.2 Al6061-B_4C Composite

- By adding the particles into the matrix, the density of the composite materials enhanced. The experimental density results are lower than the theoretical density. 1% wt. of the B_4C exhibits lower porosity than adding 3, and 5% wt..
- Comparing with the base alloy, the tensile strength of composites has been enhanced by 78% because of particle reinforcement.
- The addition of 5% wt. B_4C resulted in the most significant increase in hardness which is 100.22 *HV*.
- Wear tests with fixed parameters demonstrate that when the amount of boron carbide particles enhances, the wear rate decreases and then slowly increases. Wear resistance is inversely proportional to wear rate. 1% wt. of boron carbide shows good wear resistance.

5.1.3 Al6061-SiC Composite

- The results of adding SiC particles to Al6061 show that theoretical density is more significant than experimental density. The minimum practical density of 0.002654 g/mm^3 was observed for Al6061-1%SiC due to its higher porosity and using 400 *g* of overall weight instead of 700 *g*. Adding 5 % wt. of SiC increased practical density to 0.002688 g/mm^3.
- Adding 1% of SiC porosity increased from 0.4% to 1.46%. Then, adding 3,5% wt. of SiC to the matrix porosity decreased compared to adding 1% wt. of SiC. All of the composite samples were found to have a porosity level of less than 5%, indicating that there were no casting faults in the composites.

- This study has shown that adding 5% wt. of silicon carbide to the Al6061 improved hardness from 81 *HV* to 92.74 *HV*.
- The research has also shown that adding 1 wt.% of SiC to the matrix tensile strength increased by 30.68% compared to the base alloy, but adding 3,5% wt. ultimate tensile strength decreased by 30%, and 29.6% compared to Al6061-1% wt. SiC.
- It was discovered that adding 1% SiC enhanced the wear rate owing to porosity. Then the wear rate decreased when SiC was added compared to the basic alloy.
- Aluminium composites with SiC reinforcing particles have improved wear resistance. Adding 3,5% wt. of SiC can increase wear resistance through forming a protective layer between the counter and pin face disc.

5.1.4 Al6061-Hybrid Composite

- Compared to the base alloy, the experimental density amounts of Al6061-B_4C-TiB_2 hybrid composites were enhanced by an average net increase of 1.72% due to the incorporation of TiB_2 (4.52 g/cm^3) and B_4C (2.52 g/cm^3) particles with a micrometer-sized size.
- As the weight percentage of secondary reinforcement of hard TiB_2 particles is raised from 1 to 5, the porosity of the composites rises from 0.407% to 0.736%.
- These experiments confirmed that by adding the hybrid particles ultimate tensile strength increases and elongation decreased.
- The investigation's findings revealed that adding more reinforcement increased the hardness. What is surprising is that by adding 5%TiB_2-3%B_4C, the hardness increased by 81.48% compared to the base alloy.
- Al6061-B_4C-TiB_2 composites have a higher wear rate of 3.29 mm^3 when 3% of second reinforcement is added. But when 5% of the TiB_2 was added wear rate decreased to 1.279 mm^3.

- When 1%TiB_2-3%B_4C is added to the Al6061, it has a higher wear resistance of 1.346 mm^{-3} compared to the 3 and 5 % of TiB_2.

The experimental results showed that adding TiB_2 and B_4C particles affected the wear rate. There is an obvious decrease in the wear rate when the base material is reinforced within 1, 3, and 5% compared to the base alloy. The results also show that adding particles affected decreasing wear rate except for 5% wt., which may be due to the sample's porosity because it didn't give an exact result. In reality, adding particles to the matrix decreases the wear rate.

5.2 Recommendations for Future Work

Results from the experimental approach presented here suggest a need for further research.

- More wear tests need to be conducted to gather more conclusive data.
- The work study maybe applied for another type of aluminium alloys like Al6063, Al2024, and Al7071.
- This investigation uses titanium diboride and boron carbide as hybrid reinforcement. A study maybe tries to investigate titanium diboride with silicon carbide.
- It is better to have one mould for all samples during the casting process because the effect of porosity is minimized.
- Specific research studies may be used with various reinforced material weight fractions.
- Changing the mixing process, rotational speed, and time of stirring.
- Additional mechanical behaviour detection for composite materials, including damping and compressive testing.

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List of Publication

Hassan, K.H., Ramadan, D.O. Experimental Investigation of the Mechanical Properties and Tribological Behaviour of Al6061 Enhanced by TiB_2 Particles. Trans Indian Inst Met (2023). https://doi.org/10.1007/s12666-023-02874-9

Hassan, K. H. and Ramadan, D. O. (2022) ‘Influence of SiC Particles on Microstructure, Hardness, Tensile and Wear of Al6061’, *Computer Integrated Manufacturing Systems*, 28(12), pp. 1091–1106. doi: 10.24297/j.cims.2022.12.74.

APPENDIX

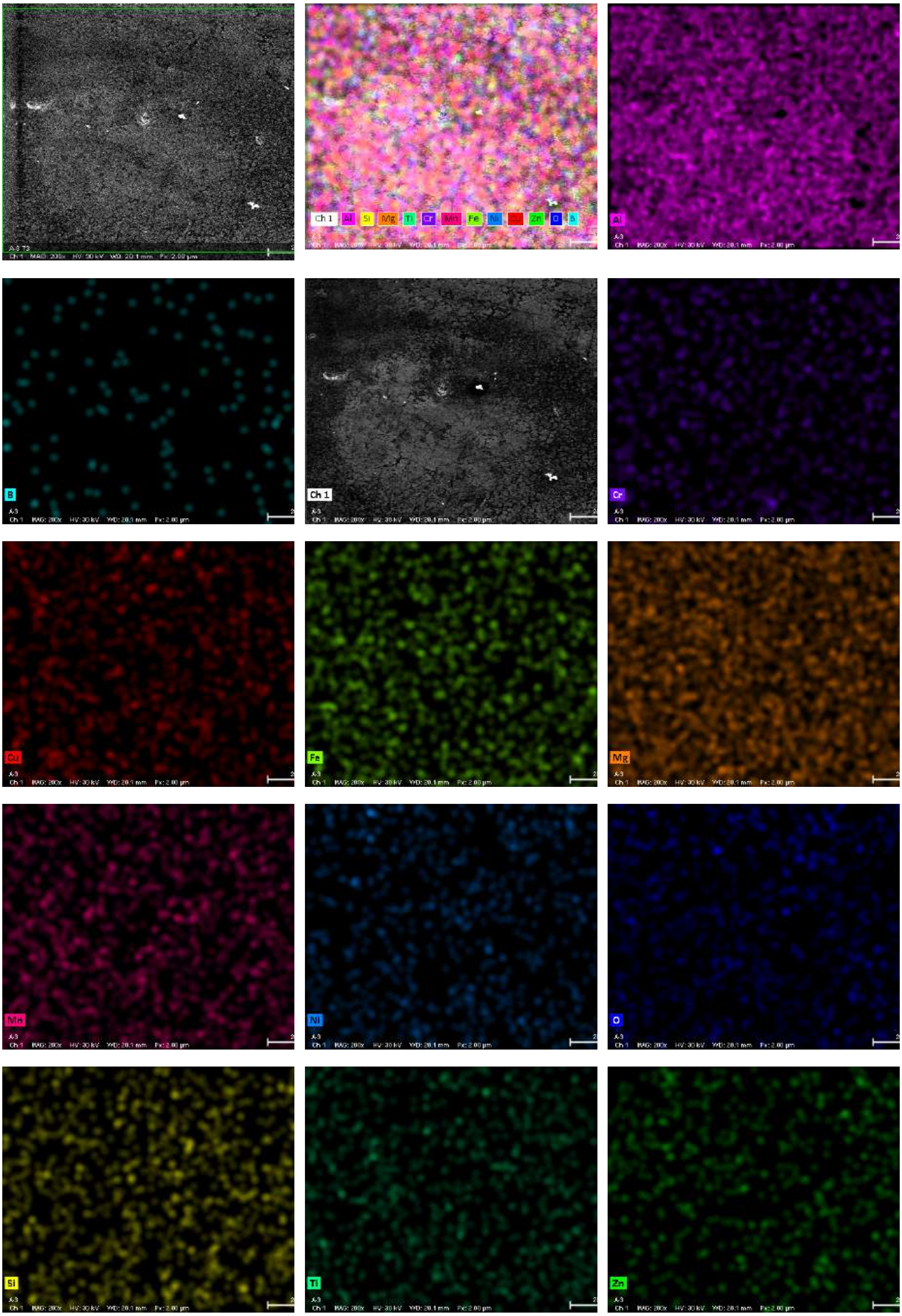

Figure A.1 Mapping of cast Al6061.

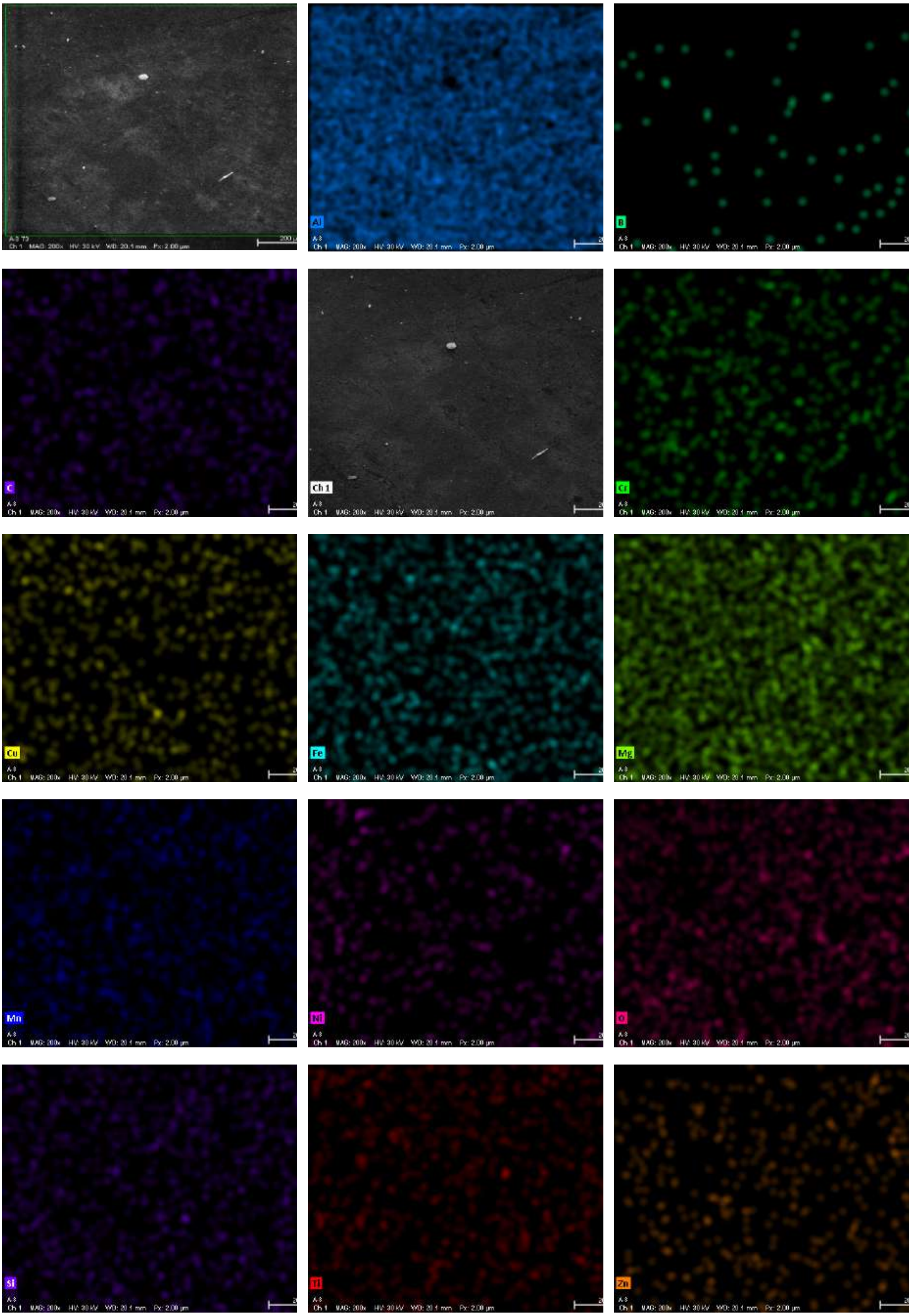

Figure A.2 Mapping of Al6061-1% TiB_2 composites.

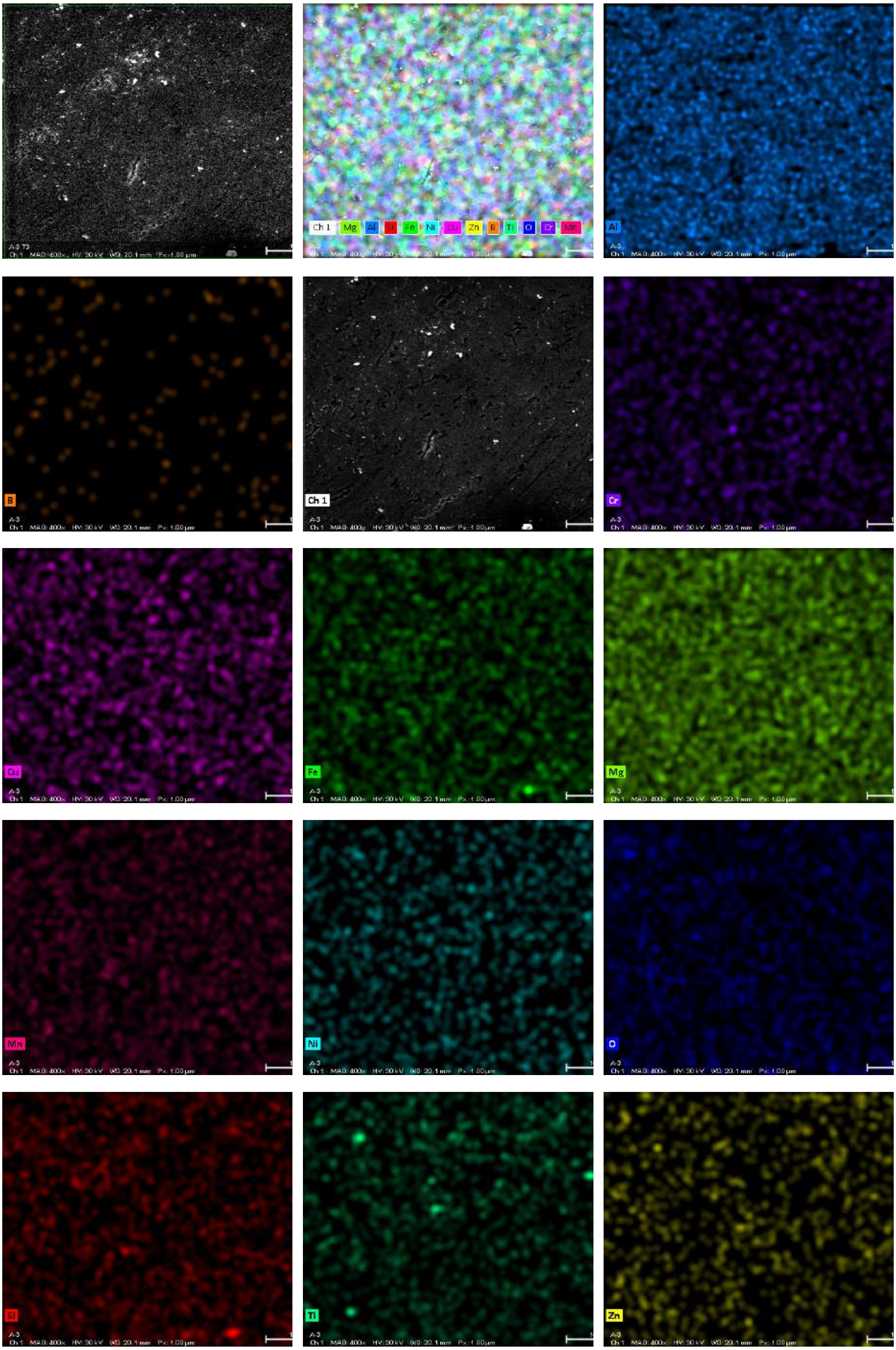

Figure A.3 Mapping of Al6061-3% TiB_2 composites.

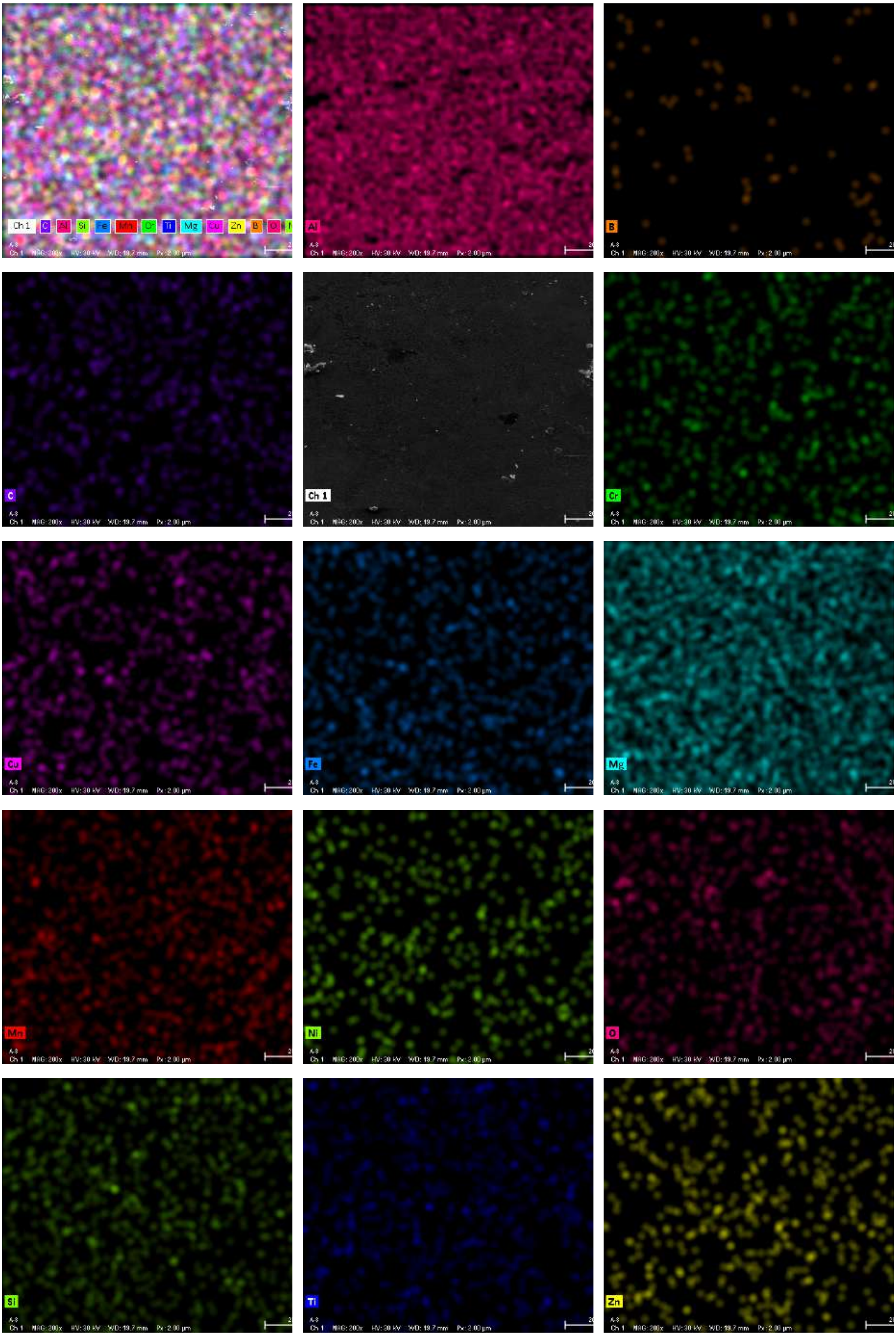

Figure A.4 Mapping of Al6061-5% TiB_2 composites.

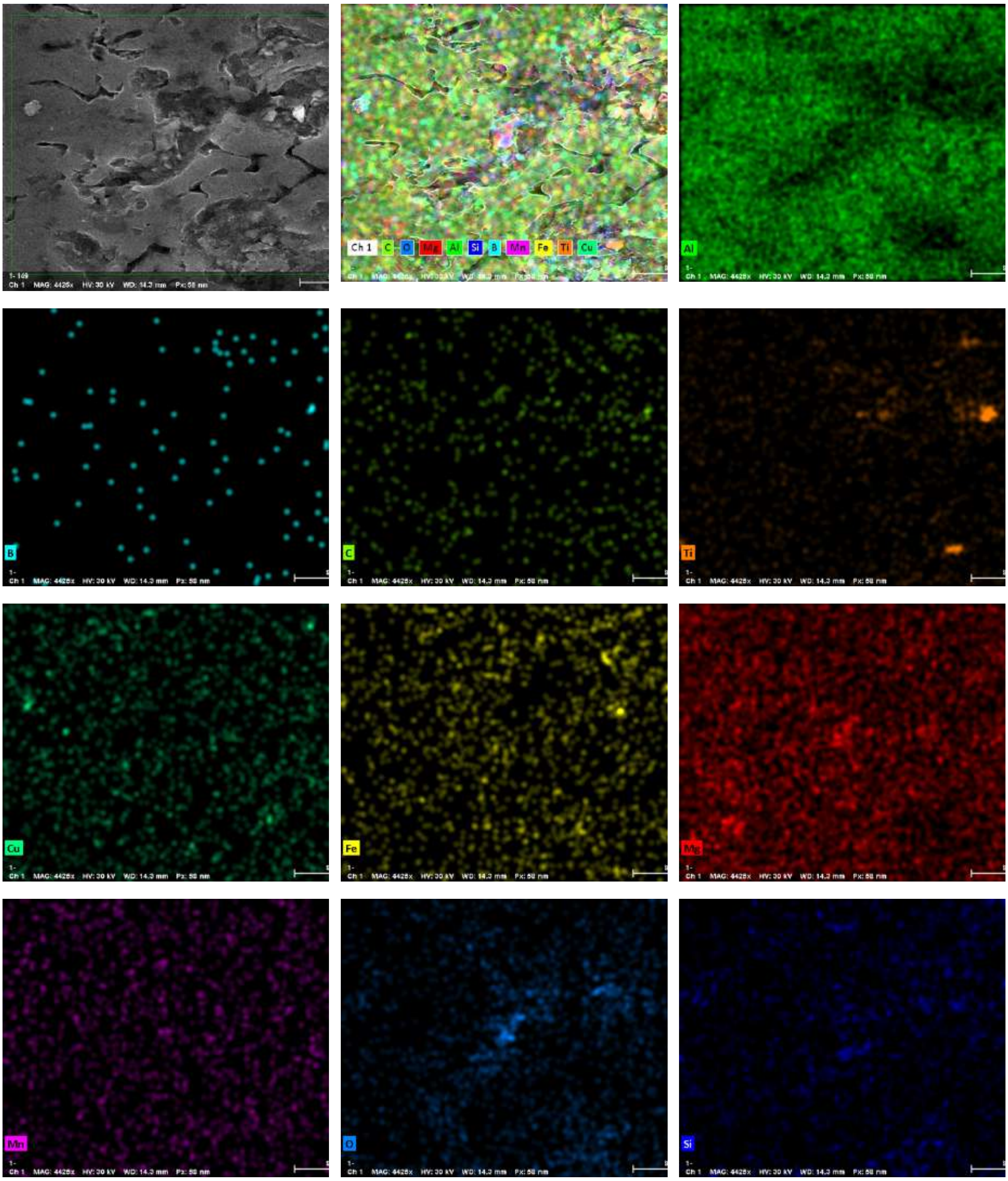

Figure A.5 Mapping of Al6061-1% B_4C composites.

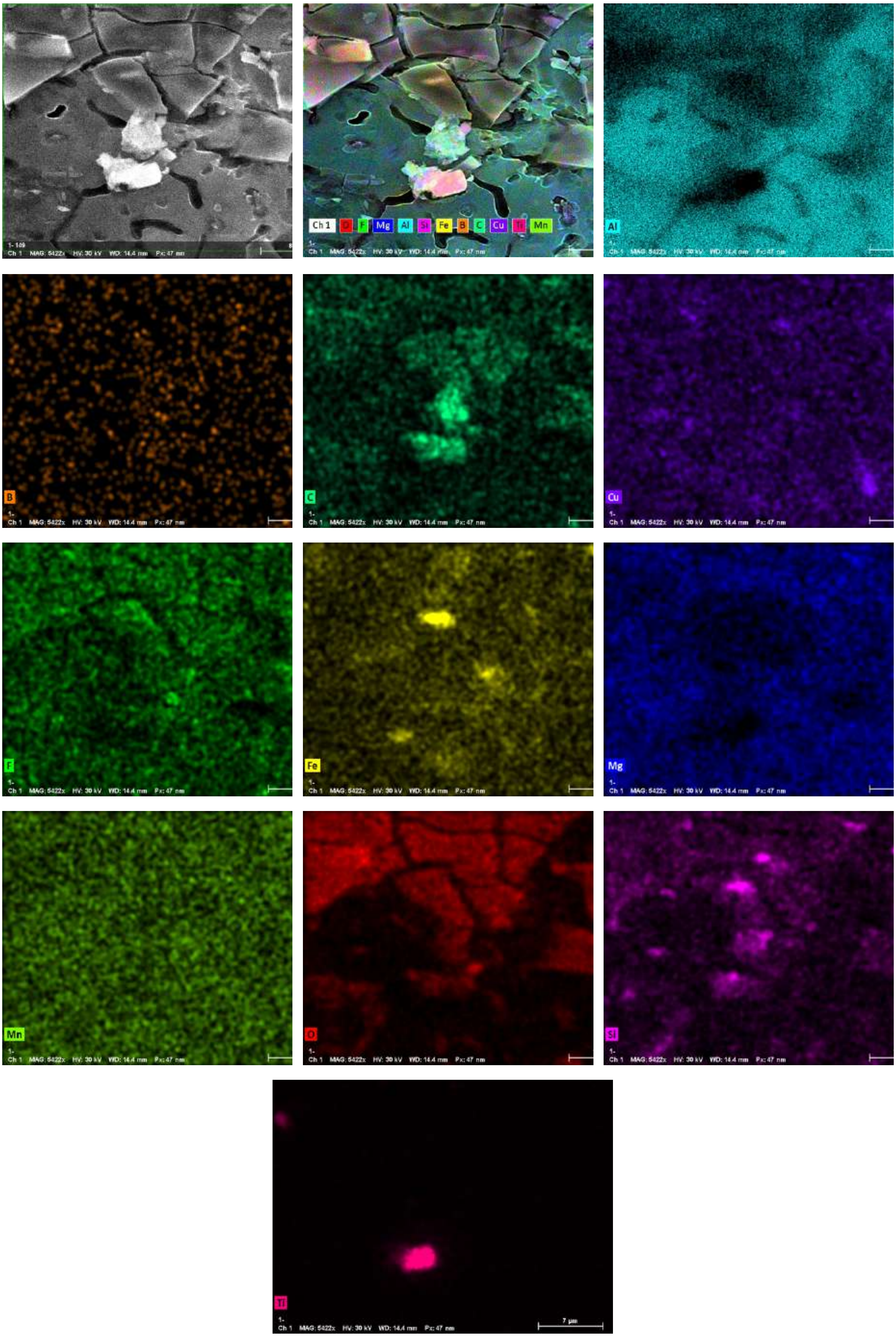

Figure A.6 Mapping of Al6061-3% B_4C composites.

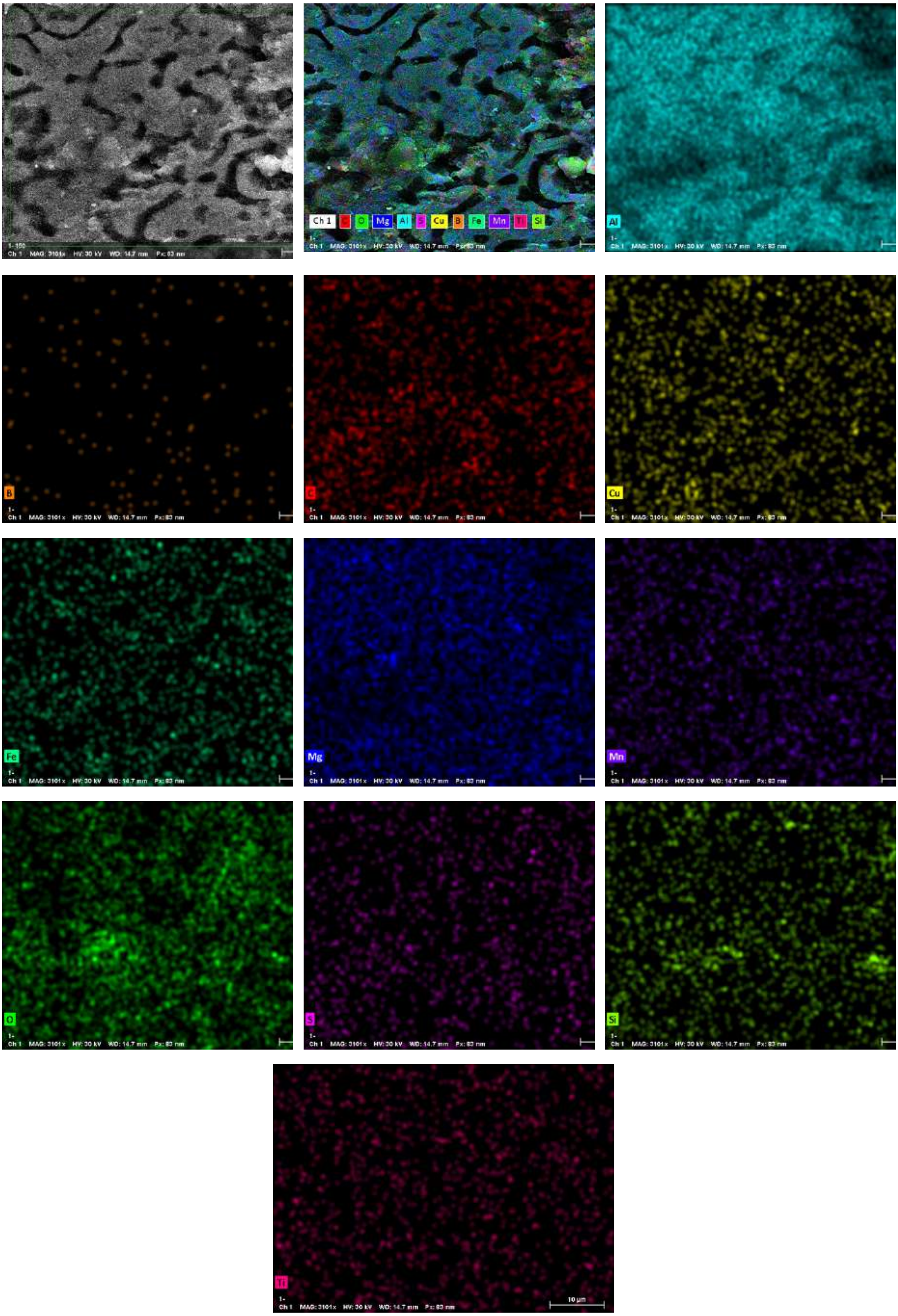

Figure A.7 Mapping of Al6061-5% B_4C composites.

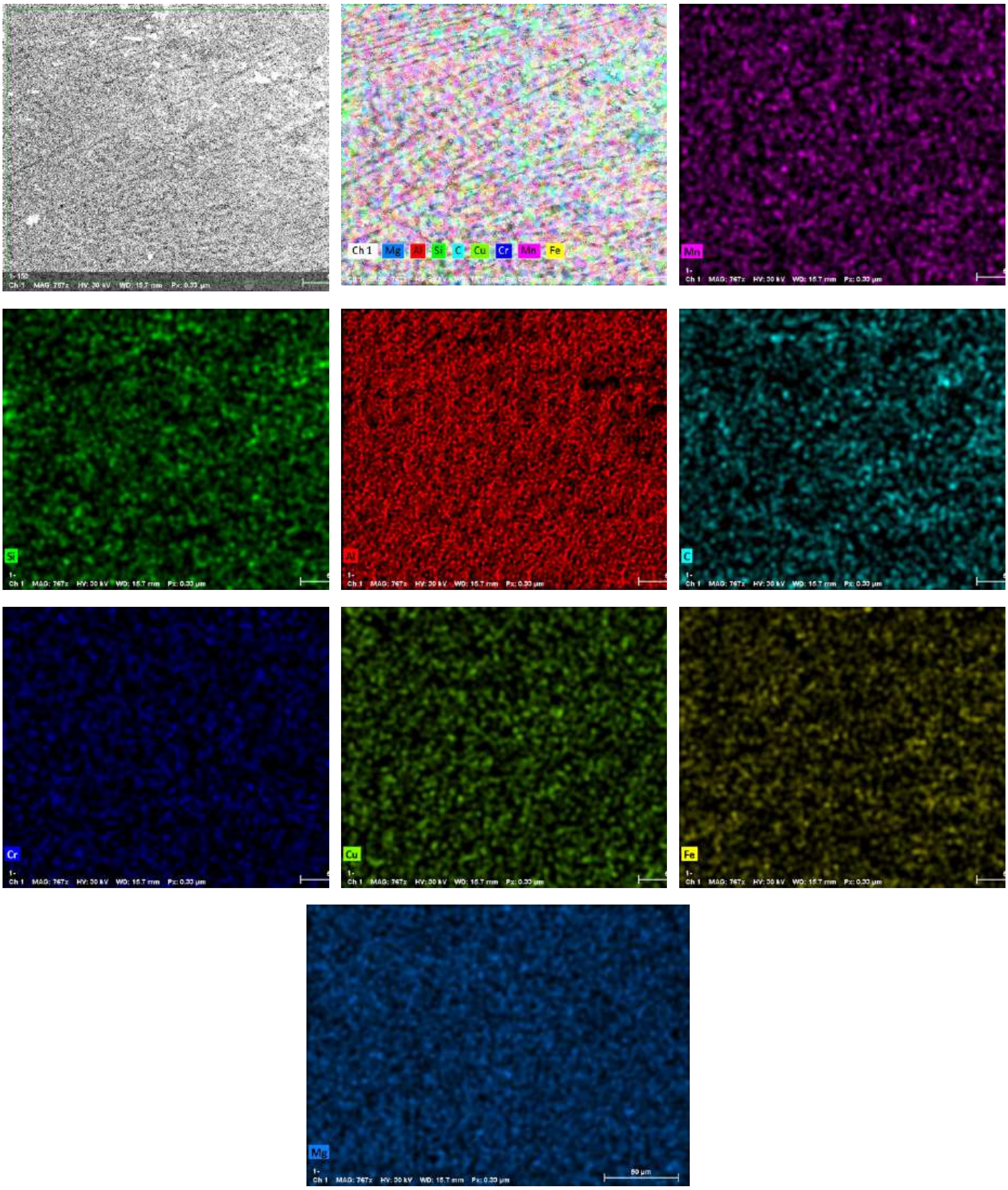

Figure A.8 Mapping of Al6061-1% SiC composites.

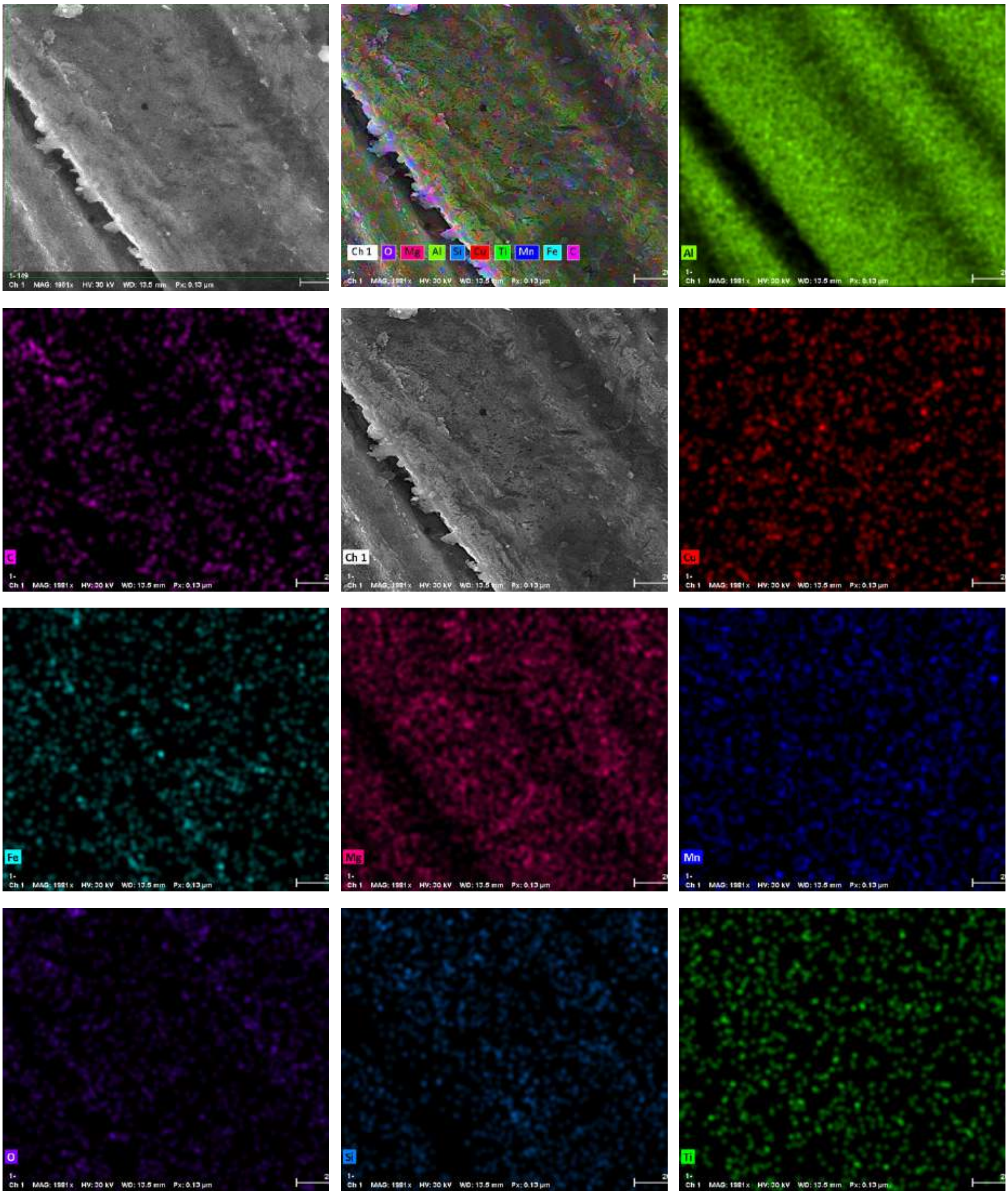

Figure A.9 Mapping of Al6061-3% SiC composites.

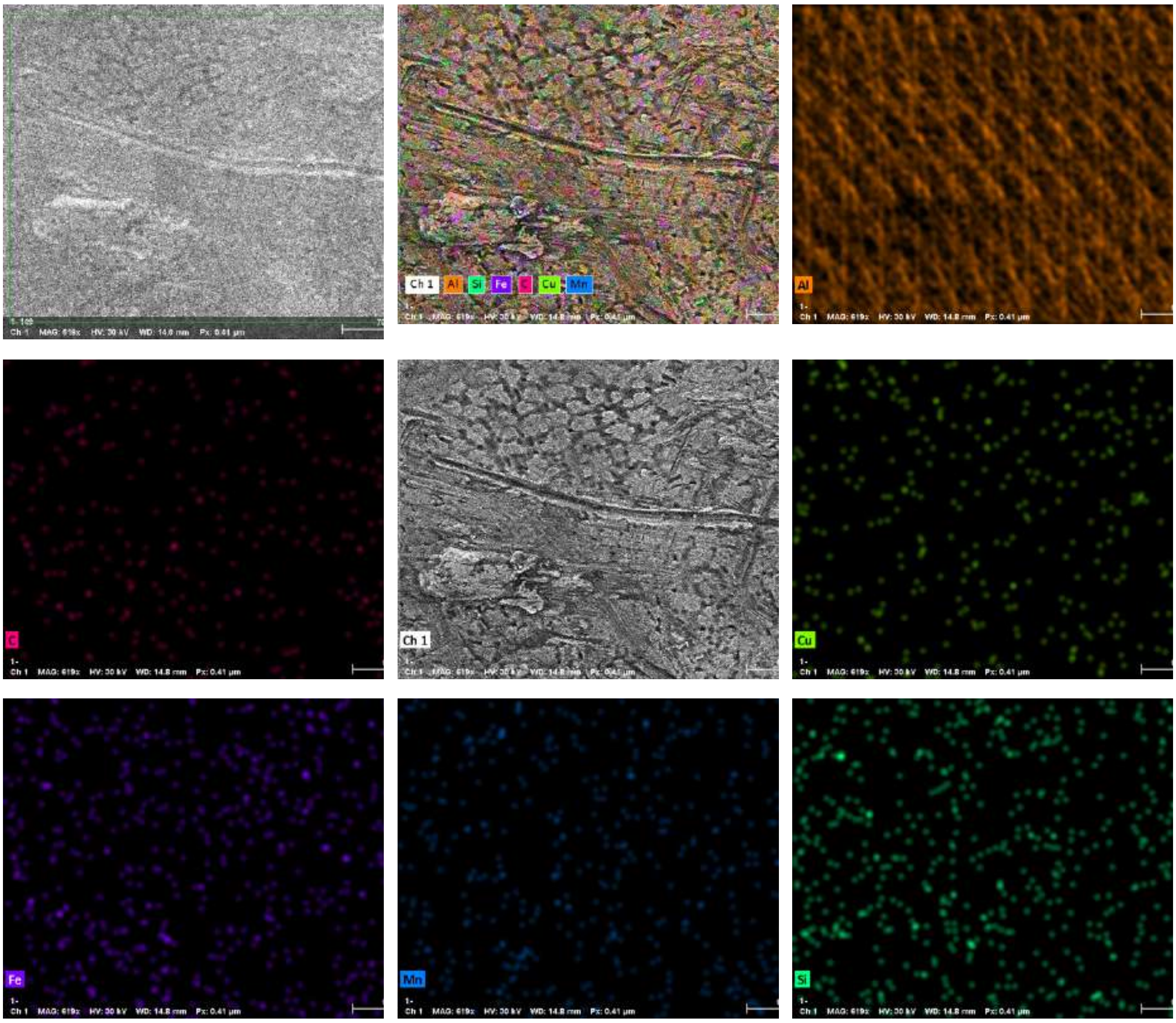

Figure A.10 Mapping of Al6061-3% SiC composites.

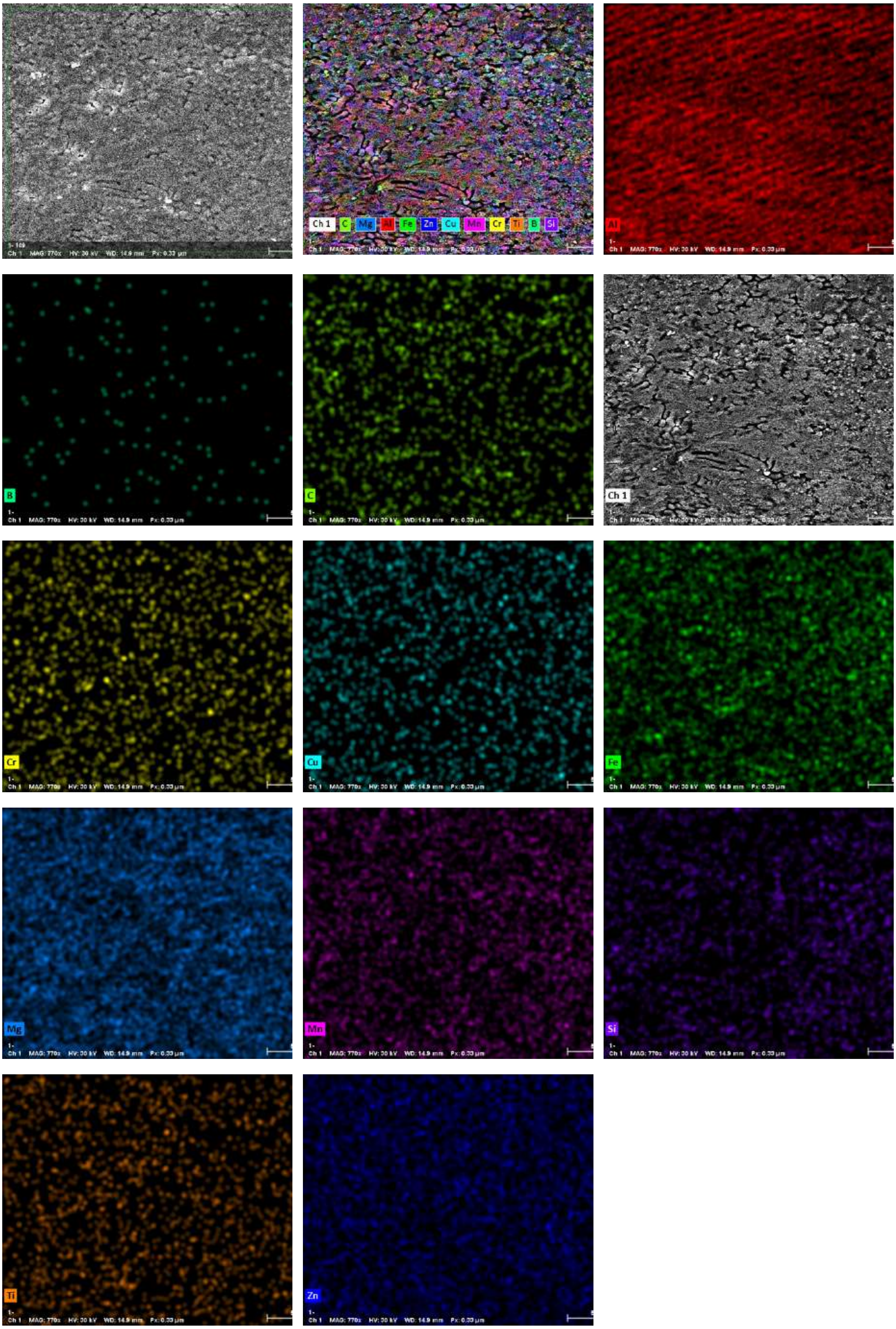

Figure A.11 Mapping of Al6061-1% hybrid composites.

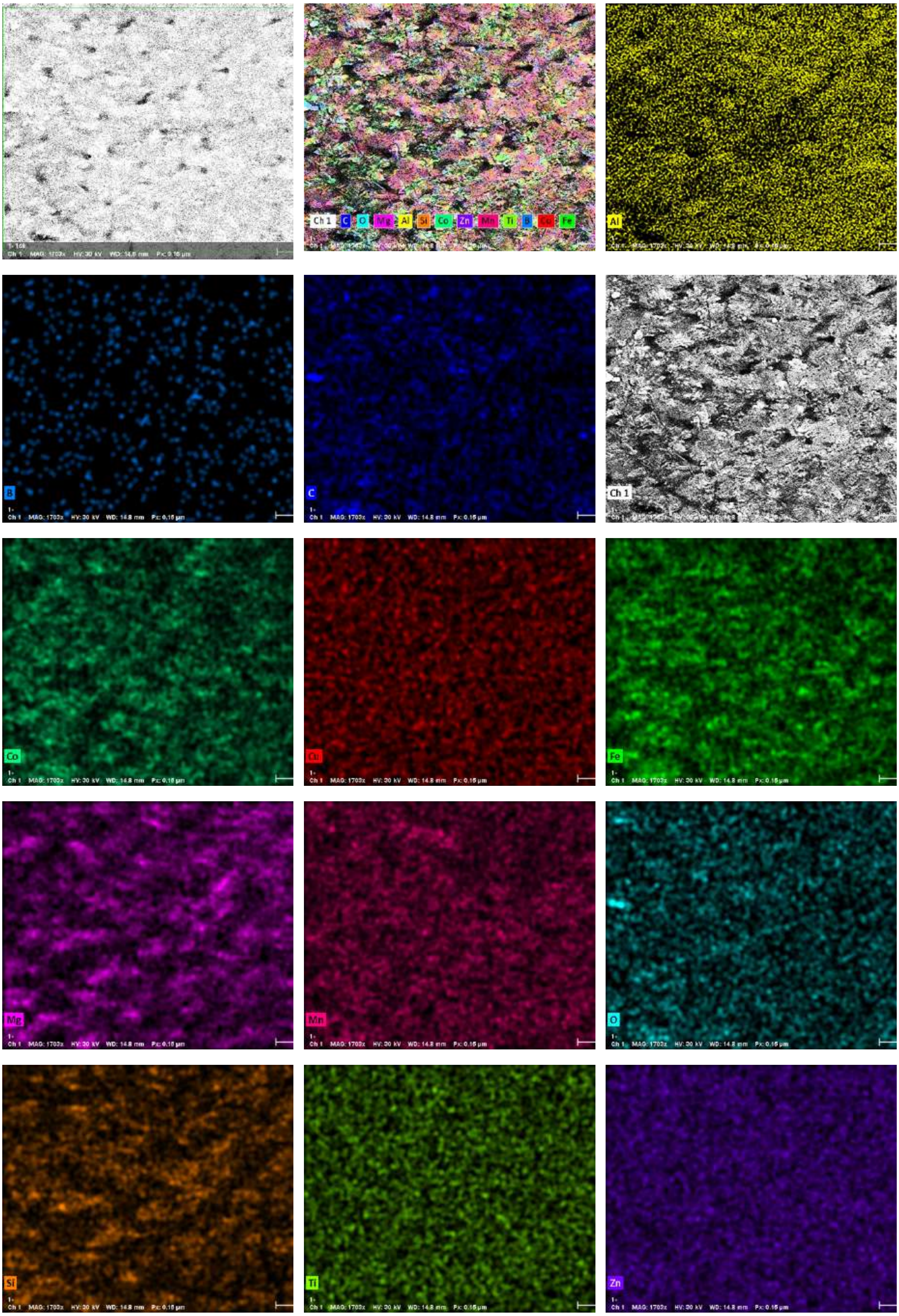

Figure A.12 Mapping of Al6061-3% hybrid composites.

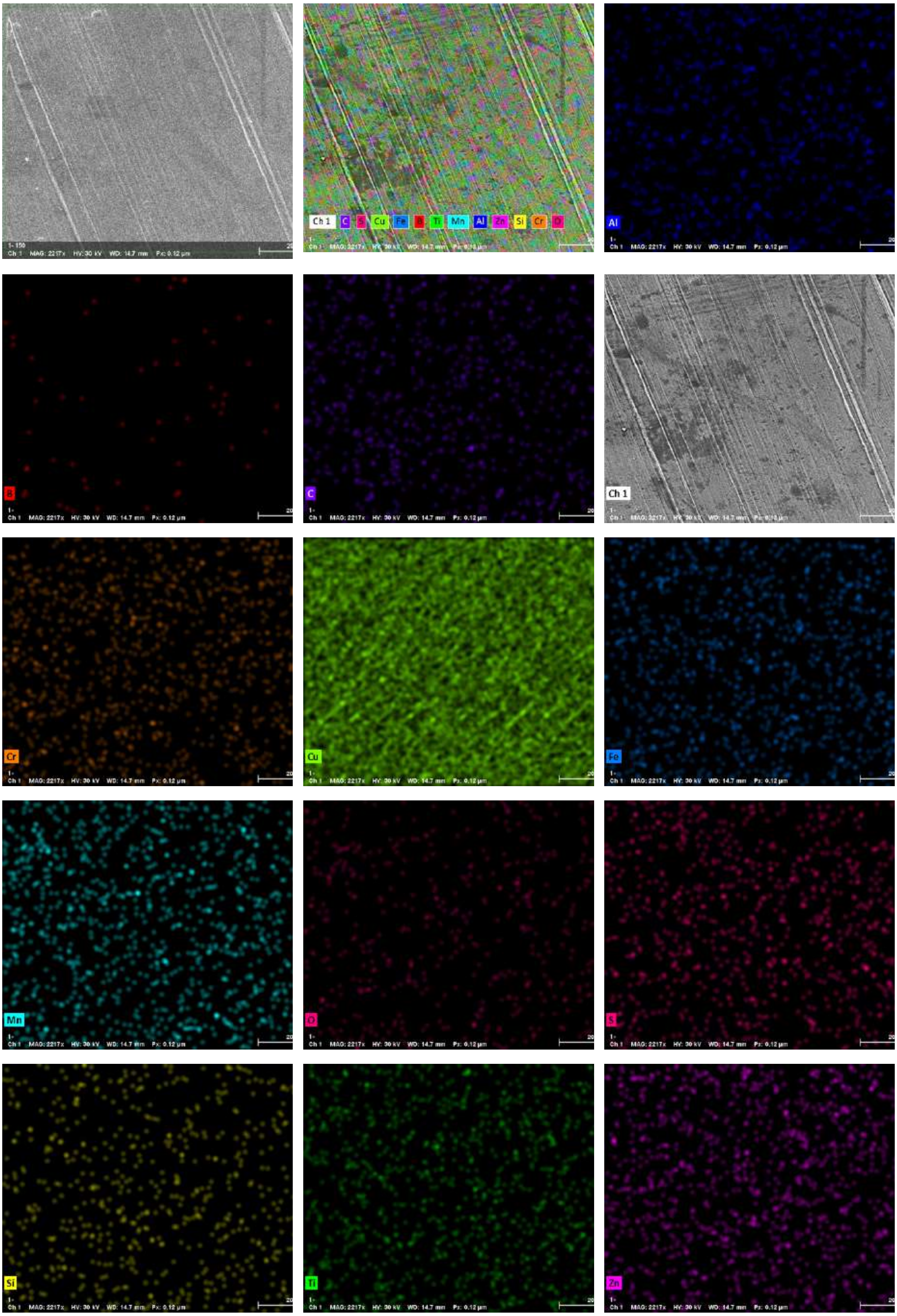

Figure A.13 Mapping of Al6061-5% hybrid composites.

Trans Indian Inst Met
https://doi.org/10.1007/s12666-023-02874-9

ORIGINAL ARTICLE

Experimental Investigation of the Mechanical Properties and Tribological Behaviour of Al6061 Enhanced by TiB_2 Particles

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Received: 9 October 2022 / Accepted: 4 January 2023

Abstract Metal matrix composites are becoming more common in industrial applications due to their superior tribological and mechanical properties. In this work, titanium diboride (TiB_2) particles with different weight percentages (1, 3 and 5%) were added to Al6061 using a stir-casting process. The hardness, tensile strength, and wear of Al6061-TiB_2 composites were investigated. Each experiment was repeated three times to ensure repeatability, and an average was taken. In addition, an optical microscope and a scanning electron microscope were used to characterize the Al6061-TiB_2 composites. The SEM examination shows that the TiB_2 particles are distributed evenly throughout the Al6061 matrix. The results show that the hardness, strength, and wear resistance of Al6061-TiB_2 composites increase as the weight percentage of TiB_2 is increased. The most interesting thing to come out of the data is that adding a small amount of TiB_2 particles increases the hardness of the composites much more than previous research has shown.

Keywords AMCs · Al6061 · Stir-casting process · TiB_2 · Wear resistance

1 Introduction

Studies of materials show the importance that when the chemical and physical properties of the components are incompatible, a new substance is created that is different from the actual components [1]. Reinforcement is added to an alloy or metal matrix in the form of fibers, particles, whiskers or metal sheets to create metal matrix composite (MMC) materials [2, 3]. The MMCs are one of the most significant classes of materials for thermal, structural, transportation, wear, and electrical applications [4, 5]. The goal of creating metal matrix composite materials is to combine the advantages of both metals and reinforcements [6]. Due to the addition of micro-sized reinforcing particles in the matrix, MMCs hold the greatest promise for enhancing mechanical parameters like yield strength, ultimate tensile strength, Young's modulus, and hardness [7, 8]. Comparing MMC to monolithic commercial alloys reveals that it is more robust in terms of weight and cost per unit of strength [9, 10]. Tensile strength and hardness are critical in engineering applications such as transportation and construction, and Al6061-alloy is commonly used in aluminium matrix composite (AMC) [11]. Different ceramic particulates like aluminium nitride (AlN), alumina (Al_2O_3), magnesium oxide (MgO), boron nitride (BN), silicon carbide (SiC), silicon nitride (Si_3N_4), titanium nitride (TiN), titanium diboride (TiB_2), and graphite (Gr) are the primary particulate-reinforced materials [12, 13]. Although the ceramic particles improve the ultimate and yield strength of the parent alloy, they have a detrimental effect on its ductility [14]. TiB_2 has several desirable mechanical properties, also excellent corrosion and wear resistance [15–17]. Suresh et al. [18] examined the mechanical characteristics and wear process of Al6061 reinforced with (0, 2, 4, 6, 8 and 10%) TiB_2. The mechanical and tribological parameters of the samples, such as tensile strength, hardness, and resistance to wear, were improved by the addition of TiB_2. Significantly less wear is achieved with a composite containing 10% TiB_2. Additionally, the size of the debris has a significant impact

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Influence of SiC Particles on Microstructure, Hardness, Tensile and Wear of Al6061

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Abstract:
Aluminium matrix composites (AMCs) have significant opportunities for essential automotive, defense, aerospace, marine, agricultural, and nuclear engineering applications. Over other conventional alloys, particle-reinforced AMCs have higher mechanical characteristics and enhanced wear resistance. The present work presents experimental findings on the tribological and mechanical characteristics of Al6061-SiC composites. Stir casting has utilized to manufacture Al6061 composites with 1,3 and 5 wt.% SiC. The AMCs' homogeneous distribution of SiC particles has shown applying scanning electron micrographs. According to the experiments' results, the composites' density and hardness increase as the percentage of SiC enhances. Composites wear resistance with 5 wt. % SiC was superior compared to the matrix material.

Keywords: AMCs, Hardness, MMCs, SiC, Stir-casting process, Wear resistance
DOI: 10.24297/j.cims.2022.12.74

1. Introduction

Metal-metal composites (MMCs) are made of metals and other metals or non-metals, such as ceramics or organic substances [1], [2]. MMCs were designed to solve the requirement for materials with higher specific wear resistance, stiffness, and strength [3]. Aluminum-based MMCs (AMCs) are very important to developing composites because aluminium is the most used metal in the industry [4], [5]. AMCs are reinforced using a variety of materials. Popular reinforcing materials include SiC, TiB_2, B_4C, Al_2O_3, graphene, and fly ash [6], [7], [8]. Aluminum matrix composites may be fabricated using various of techniques such as stir casting, also called liquid state, powder metallurgy, and semisolid. Stir casting is the most common approach to produce AMCs in a liquid state [9], [10], [11]. Stojanovic *et al.* (2013) have studied tribological properties of hybrid composite with Al matrix, Al2219 reinforced with distinct percentages of SiC and graphite. Graphite's soft particles enhance lubrication and minimize friction and wear, while silicon carbide particles enhance the hardness and wear resistance. A tribometer of pin-on-disc was applied to conduct tribological testing under the ASTM G99-95 standard. The volumetric percentage of SiC in the investigated samples ranged from 5% to 15%, with a particle size of 25

زانكۆی پۆلیتەكنیكی هەولێر
ERBIL POLYTECHNIC UNIVERSITY

لێکۆڵینەوە لە تایبەتمەندییە میکانیکییەکان و بەرگری داخورانی پێکهاتەکانی Al6061 کە بە شێوازی تێکەڵاوکردن دروستکراون

ماستەر نامەکە

پێشکەشی ئەنجومەنی کۆلێژی ئەندازیاری تەکنیکی هەولێر کراوە لە زانکۆی پۆلیتەکنیکی هەولێر لە بەشێکی جێبەجێکردنی مەرجەکان بۆ بڕوانامەی ماستەر لە ئەندازیاری میکانیك و ووزە

لە لایەن

خۆشی همزە حسن

بەکالۆریۆس لە ئەندازیاری میکانیك و ووزە

بە سەرپەرشتاری

د. دلێر عوبێد ڕەمەزان

هەولێر-کوردستان

کانونی دوەم ۲۰۲۳

پوخته

پێکهاتەکانی ماتریکسی ئەلەمنیۆم (AMCs)، کە تایبەتمەندی ترایبۆلۆجی و میکانیکی باشتریان هەیە لە داڕشتە ئاساییەکانی تر، توانایەکی زۆریان هەیە بۆ بەکارهێنانی گرنگ لە پیشەسازییەکانی ئۆتۆمبێل، بەرگری، ئاسمانی، دەریایی، کشتوکاڵی و ئەندازیاری ئەتۆمی. لەم کارەدا، هەوڵ درا بۆ دروستکردنی AMC بەهێزکراو بە ڕێژەی سەدی کێشی جۆراوجۆری تەنۆلکە بەهێزکەرە جیاوازەکان، کە بریتین لە کاربایدی بۆرۆن (B_4C)، دوانەبۆریدی تیتانیۆم (TiB_2)، و کاربایدی سیلیکۆن (SiC)، بە مەبەستی باشترکردنی ڕەوشتی کێشکردن، ڕەقیی، و بەرگری پۆشین. تەنۆلکە بەهێزکراوەکان بە ڕێژەی کێشی جیاواز (1، 3، و 5%) زیادکران بۆAl6061 بە بەکارهێنانی تەکنیکی تێکەڵکردنی داڕشتن. ئەم کارە دەتوانرێت دابەش بکرێت بەسەر دوو بەشدا: لە بەشی یەکەمدا، تەنۆڵکە بەهێزکەرەکان بە جیا زیادکران (پێکهاتەی تاکە بەهێزکەر)، لەکاتێکدا لە بەشی دووەمی ئەم کارەدا، پێکهاتەی تێکەڵاو (بەهێزکراوی تێکەڵاو) دروستکرا. لێکۆڵینەوە کرا دەربارەی هێزی کێشکردن و ڕەقیی و لەبەرکردنی AMC. هەر تاقیکردنەوەیەک سێ جار دووبارەکرایەوە بۆ دڵنیابوون لە توانای دووبارەبوونەوە، و تێکڕایەکەی وەرگیرا. سەرەرای ئەوەش، مایکرۆسکۆپی بینایی و مایکرۆسکۆپی ئەلکترۆنی بەکارهێنرا بۆ دیاریکردنی تایبەتمەندکردنی AMC. پشکنینی مایکرۆسکۆپی ئەلکترۆنی دەریخست کە تەنۆڵکە بەهێزکەرەکان بە شێوەیەکی یەکسان دابەشبوون بەسەر ماتریکسی Al6061. ئەنجامی بەشی یەکەمی ئەم لێکۆڵینەوەیە دەریدەخات کە زیادکردنی بڕی جیاوازی TiB_2 و B_4C بەشێوەی جیا، واتە وەک پێکهاتەی تاکە بەهێزکەر، بووە هۆی هاندانی هێزی کێشکردنی ئەوپەڕی، ڕەقیی پێکهاتەکان و بەرگری پۆشین. سەرنجڕاکێشترین شت کە لە داتاکان دەرکەوێت ئەوەیە کە زیادکردنی بڕێکی کەم لە تەنۆلکەکانی TiB_2 بووە هۆی زیادبوونی ڕەقیی پێکهاتەکان زۆر زیاتر لەوەی کە لێکۆڵینەوەکانی پێشووتر دەریانخستووە. هەروەها ئەنجامەکان ئەوەیان دەرخست کە بە زیادکردنی ڕێژەی یەک لە سەدی کێش لە B_4C، و ڕێژەی سێ لە سەدی کێش لە TiB_2، پێکهاتەکان تێکرای پۆشینی کەمتر و بەرگری پۆشینی بەرزتریان هەبوو بە بەراورد بە داڕشتەی بنەڕەتی. هەروەها ئەنجامەکان دەریانخست کە بە زیادکردنی ڕێژەی پێنج لە سەدی کێش لە SiC، بەرگری پۆشێن و ڕەقیی زیادی کرد بە بەراورد لەگەڵ داڕشتەی بنەڕەتی. بەڵام ڕێژەی یەک لە سەدی کێش لە تەنۆلکەکان هێزی کێشکردنی ئەوپەڕی زیاترە.

لە بەشی دووەمی ئەم توێژینەوەیە، هەوڵ درا بۆ دروستکردنی پێکهاتەی ماتریکسی ئەلەمنیۆمی تێکەڵ ($Al6061/3\% B_4C+TiB_2$) بە ڕێژەی جیاوازی TiB_2 (١، ٣، ٥ ڕێژەی سەدی کێش). ئەنجامەکان دەریخست کە ($Al6061/3\%B_4C+5\%TiB_2$)ڕەقیی و هێزی کێشکردنی زیاتری هەیە. بەهۆی کونیلەیی ناو نمونەکانەوە، ($Al6061/3\%B_4C+1\%TiB_2$) تێکڕای پۆشینی کەمترە و بەرگری زیاتری هەیە بەرامبەر پۆشین. دیارترین

ئەنجامەکان کە لەم لێکۆڵینەوەیەدا دەربکەوێت ئەوەیە کە زیادکردنی تەنۆلکەکانی TiB_2 کە بە Al6061 بەهێزکراون وەک ماتریکس ئەنجامێکی زیاتری هەیە بە بەراورد بەو تەنۆلکانەی تر کە بەکارهاتوون.