

DEVELOPMENT OF COMPOSITE USING ALUMINIUM, CERAMIC AND INDUSTRIAL WASTE

**A Thesis Submitted
in Partial Fulfillment of the Requirements
for the Degree of**

DOCTOR OF PHILOSOPHY

In

MECHANICAL ENGINEERING

BY

ROHIT SAHU

(Roll Number 2K20/PHDME/506)

Under the Supervision of

Dr. Krovvidi Srinivas

Associate Professor, MED

DTU, Delhi

Dr. Atul Kumar Agrawal

Professor, MED

DTU, Delhi



Department of Mechanical Engineering

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Shahbad Daulatpur, Main Bawana Road, Delhi-110042, India

June, 2026

DECLARATION

I declared that the work which is being presented in this thesis entitled "**Development of Composite using Aluminium, Ceramic and Industrial Waste**" in the partial fulfilment of the requirement for the award of the degree of Doctorate in Philosophy submitted in the Department of Mechanical Engineering at Delhi Technological University, is an authentic record of my own work under the supervision of **Dr. Krovvidi Srinivas** and **Prof. (Dr.) A.K. Agarwal**, Department of Mechanical Engineering, Delhi Technological University, Delhi. The matter presented in this thesis has not been submitted to any other University/Institute for the award of any degree or diploma.

(ROHIT SAHU)

(Roll Number 2K20/PHDME/506)
Department of Mechanical Engineering
Delhi Technological University, Delhi

Date: 23-06-2026

Place: New Delhi

CERTIFICATE

This is to certify that the thesis entitled "**Development of Composite using Aluminium, Ceramic and Industrial Waste**" submitted to the Delhi Technological University, Delhi -110042, is the fulfilment of the requirements for the award of the degree of Doctorate in Philosophy in Mechanical Engineering embodies the original research work carried out by **Mr. ROHIT SAHU**, Enrollment No: 2K20/PHDME/506 under our supervision. This work has not been submitted in part or full for any other degree or diploma of this or any other University.

23-06-2026

Dr. Krovvidi Srinivas

Associate Professor

Department of Mechanical Engineering
Delhi Technological University, Delhi

Dr. Atul Kumar Agrawal

Professor

Department of Mechanical Engineering
Delhi Technological University, Delhi

Dedicated to
Almighty
My Mentors
Dr. Krovvidi Srinivas
Prof. (Dr.) A.K. Agarwal
My father
Shri Prem Kumar Sahu
My Mother's
Late Shrimati Sarla Sahu
&
Shrimati Sunita Sahu
for
making me be who I am and my wife, my brothers, my son and
my daughter for supporting me all the way

ACKNOWLEDGMENT

*I would like to express my special appreciation and thanks to my supervisor(s) **Dr. Krovvidi Srinivas & Prof. (Dr.) A.K. Agarwal** you have been a tremendous mentor for me. Perseverance, exuberance, positive approaches are just some of the traits he has imprinted on my personality. These lines dedicated to my guides:*

**“गुरुब्रह्मा गुरुर्विष्णु गुरुर्देवो महेश्वरः
गुरु साक्षात् परब्रह्मा तस्मै श्रीगुरवे नमः”**

He steered me through this journey with his invaluable advice, positive criticism, stimulating discussions and consistent encouragement. If I will stand proud of my achievements, then undeniably he is the main creditor. It is my privilege to be under his tutelage. I would like to thank you for encouraging my research and for allowing me to grow as a research scientist. Your advice on both research as well as on my career have been priceless.

It gives me privilege to sincerely thank Prof. (Dr.) Prateek Sharma, the Vice Chancellor, DTU, for providing Institute lab facilities to carry out my research work.

I would also like to thank my HOD Prof. (Dr.) B.B. Arora, and I am thankful to all faculty members, technical staff of the department from DTU for continuous motivational support and encouragement throughout my journey, I am very thankful to Prof. R. C. Singh and Dr. Venkat Ramana for being members of my SRC committee. Professor Dr. Praveen Pachauri, for teaching me how to face difficulties of life with a smile, Dr. Maninder Singh and Mr. Avdhesh Tyagi for being a constant source of my moral support, Dr. H.S. Pali, for teaching me how to be dedicated towards my job.

I am very much thankful to Director of our Institute Dr. Manas Kumar Mishra and Head of the department Dr. V. R. Mishra of G. L. Bajaj Institute of Technology and Management (GLBITM) to support me during my Ph.D.

I would like to thank Dr. Ambuj Saxena, Dr. Nagendra Kumar Maurya Dr. Tarun Kumar Gupta, Dr. Abhishek Pandey, and Dr. Ranjeet Kr. Singh, Department of Mechanical Engineering GLBITM for their valuable information and assistance during this work and

for being available at all the time for help. I am also grateful to the staff of materials engineering department

Dr. Shashi Prakash Dwivedi and Dr. Rajkumar for their experienced and vertically specialized guidance to enable conduct of experiments and analysis of test samples.

I would also like to express my gratitude towards my senior Dr. Pawan Kumar Arora, Dr. Vinod Kumar Yadav and thank my friends especially Dr. Anant Bhardwaj, Mr. Venkat, Mr. Vipin Kumar and Mr. Dushiyant Reddi.

It adds more happiness in my boundless delight for revealing my gratitude towards my parents, the people who do everything just to make me win and remained with me in each pain and sorrow of my career and life, my siblings, Amit Sahu, Shivani Sahu, Swastik Sahu, Harsh Rathur, and Utkarsh Gupta for being a constant companion in my Ph. D journey.

With immense pleasure and delight I would like to thanks my wife Shikha Rathaur, my daughter Tvisha Sahu and Sons Amogh Sahu, Shiv Sahu for giving me mental and moral support in my highs and lows of this Ph. D. journey.

At the end I would also like to thank my friend Dr. Vijay Kr. Chaudhary for helping me in giving words to my emotions.

Rohit Sahu

Abstract

Aluminium matrix composites (AMCs) have been the subject of a lot of scholarly interest as a lightweight structural material for aerospace and advanced engineering applications, mainly because of their high strength-to-weight ratio, wear resistance and high thermal stability. Among aluminium alloys, AA2024 is generally used in aerospace structures due to its outstanding specific strength and fatigue strength. In spite of this, its relatively low level of hardness and tribological performance restricts its range of applications to highly abrasive environments. Accordingly, the present study attempts to develop and characterize a hybrid aluminium matrix composite based on AA2024 reinforced with titanium diboride (TiB₂), waste glass powder (WGP) and nano-copper oxide (Nano-CuO) particles.

The main aim of this study is to developed AA2024-based hybrid composites using stir-casting method and systematically understand the mechanical, tribological, microstructural and thermal characteristics of the composites using both experimental and computational methods. Composite samples were generated in 8 different formulations by varying amounts of TiB₂ substitution of waste glass powder and keeping the nano-CuO as the reinforcement same at 0.25 wt.%.

Mechanical characterization revealed a considerable improvement in strength and hardness with the addition of hybrid reinforcements. The optimum composition consisting of 5 wt.% TiB₂, 2.5 wt.% WGP, and 0.25 wt.% nano-CuO exhibited the highest ultimate tensile strength of 580.37 MPa and yield strength of 431.39 MPa compared with 495 MPa and 375 MPa for the base alloy. Similarly, flexural strength increased from 640 MPa to

803.37 MPa, while hardness improved from 137 HV to approximately 170 HV. However, a gradual reduction in ductility from 14% to 6% and a slight decrease in impact energy from 2.09 J to 1.91 J were observed, indicating a typical strength–toughness trade-off associated with ceramic particle reinforcement.

Microstructural analysis using scanning electron microscopy and energy dispersive spectroscopy confirmed fairly particle distribution, grain refinement, and good interfacial bonding between the matrix and reinforcements. Fractographic studies found a mixed ductile-brittle type failure. Subsequent true stress-strain examinations supported the fact that the hybrid composites possess enhanced strain-hardening behaviour. Finite-element simulations based on the constitutive model of Hollomon showed good agreement with experimental data with the predictive discrepancy limited to 4%-5% thus verifying the reliability of the computational model.

The tribological performance of the composites was investigated by assessing the influence of reinforcement content and process parameters, such as normal load, sliding velocity and sliding distance on the wear phenomenon. An optimization study using the Taguchi L16 orthogonal array showed high improvements in wear resistance and hardness due to the synergy of TiB₂, WGP and nano-CuO addition. The minimum coefficient of friction obtained was 0.262 while the optimised wear rate, as checked by confirmatory tests, was 4.133×10^{-3} g/m. Thermal expansion measurements also showed an increase in dimensional stability with the coefficient of thermal expansion reduced from $23.4 \times 10^{-6} \text{ K}^{-1}$ for the unreinforced alloy to around 21.8 to $22.4 \times 10^{-6} \text{ K}^{-1}$ in the reinforced composites.

Overall, the fabricated hybrid AA2024 composites displayed enhanced mechanical strength, superior wear resistance and increased thermal stability which reveals their promising applicability to the advanced aerospace and high-performance engineering environment.

Table of Contents

TOPICS	Page No.
DECLARATION	<i>i</i>
CERTIFICATE	<i>ii</i>
ACKNOWLEDGEMENT	<i>iv</i>
ABSTRACT	<i>vi</i>
TABLE OF CONTENT	<i>ix</i>
LIST OF FIGURES	<i>xii</i>
LIST OF TABLES	<i>xiv</i>
NOMENCLATURE AND SYMBOLS	<i>xv</i>
1 Introduction	1
1.1 Need of Light Weight Material in Engineering Application	1
1.2 Motivation	4
1.3 Chronological sequence of Composite material	5
1.4 Composite Material	6
1.4.1 Polymer - Matrix Composites (PMCs)	7
1.4.2 Ceramic-Matrix Composites (CMCs)	7
1.4.3 Carbon-Carbon Composite (CCCs)	7
1.4.4 Metal Matrix Composites (MMCs)	8
1.5 Material	9
1.6 Reinforcements	10
1.7 Fabrication process of AMCs	12
1.8 Stir casting	13
1.9 Characterization	16
1.9.1 Characterization of Composite Materials	16
1.9.2 Mechanical Characterization	17
1.10 Microstructural analysis	17
1.11 Wear Behaviour Evaluation	18
1.12 Thermal Characterization	18
1.13 Process Optimization	19
1.14 Recent applications of AMCs	20
1.15 Problem Statement	20
1.16 Thesis Organization	22
2 Literature Review	25
2.1 Overview	25
2.2 Circular Economy Approaches in Aluminium Alloy	28
2.3 Rationale for Aluminium Matrix Composites (AMCs)	29
2.4 Aluminium Matrix Composites (AMCs)	31
2.5 Reinforcement Materials in Aluminium MMCs.	32
2.5.1 Ceramic Reinforcement	33
2.5.2 Industrial Waste as a reinforcement	36

	2.6	Mechanical Behaviour of AMCs	38
	2.7	Tribological Behaviour of AMCs	43
	2.8	Thermal Properties of Aluminium Matrix Composites (AMCs)	45
	2.9	Computational Analysis of Reinforced and Unreinforced Al-2024-Based Composites	48
	2.10	Historical Development of hybrid aluminium matrix composites (HAMCs)	54
	2.11	Stir Casting Technique for Aluminium Metal Matrix Composite	58
	2.12	Identified Research Gaps	63
	2.13	Research Objectives	63
3		Materials and Methods	64
	3.1	Matrix Material	64
	3.2	Reinforcements	65
	3.2.1	Titanium Diboride (TiB ₂)	65
	3.2.2	Copper Oxide (CuO)	66
	3.2.3	Waste Glass Powder	67
	3.3	Fabrication Method	69
	3.4	Experimental Procedure	71
	3.4.1	Tensile Testing	71
	3.4.2	Hardness Testing	72
	3.4.3	Impact Testing	73
	3.4.4	Flexural Strength	74
	3.5	Wear Testing	76
	3.6	Thermal Analysis	83
	3.7	Microstructural analysis	84
	3.7.1	Optical Microscope	84
	3.7.2	Instrument used for Microstructural Analysis	85
	3.8	Computational Analysis of Tensile Behavior	88
4		Result and Discussion	90
	4.1	Influence of weight %age of reinforcement on tensile properties	90
	4.2	Impact and Hardness behavior of developed composite material	96
	4.3	Influence of reinforcement particles on the flexural behavior of developed composite material compositions	98
	4.4	Microstructural Investigation	100
	4.5	Validation of Hollomon power law parameters for sample AA2024/waste Glass 2.5wt%/TiB ₂ 5.0 wt%/Nano CuO 0.25wt% (Sample 4)	102
	4.6	Tribological Behaviour	107
	4.6.1	Development of regression model for the wear loss	107
	4.6.2	Effect of process parameters on wear loss	109

	4.6.3	Effect of reinforcement percentage on frictional coefficient	111
	4.6.4	Effect of reinforcement percentage on the wear rate	112
	4.6.5	Microstructural examination of composite material	114
	4.6.6	EDS elemental mapping of the composite material	115
	4.6.7	FESEM analysis of worn-out surface	117
	4.6.8	Confirmation test	118
	4.7	Effect of Reinforcement Particles on CTE	119
5.0		Conclusions, Future Scope and Social Impact	121
	5.1	Conclusions	121
	5.2	Future Scope	124
	5.3	Social and Industrial Impact	125
		References	127

List of Figures

Fig. No.	Figure caption	Page no.
1.1.	a) Fuel Efficiency Standards Across Major Countries for Passenger Vehicles b) Light Vehicle Production Volumes (Million Units) in Leading Markets	3
1.2.	Chronological sequence of developments of MMCs	6
1.3.	Classification of Composite Material	7
1.4.	Broad Classification of Composite Material based on Matrix	8
1.5.	Percentage of Matrix Material	10
1.6.	Different type of reinforcement employed for AMCs	11
1.7.	Classification of AMC on the basis of type of Particles	12
1.8.	Current manufacturing approaches for AMCs are driven	14
1.9.	Procedure for the development of composite material by using Stir Casting Process	16
1.10.	Applications of AMCs in Different Field	21
2.1.	Various process variables impact the MMCs Performance	28
2.2.	Technological Readiness and Impact Potential of Sustainability Measures in Structural Alloys	30
2.3.	Aluminium alloys Series	32
2.4.	Line diagram of a conventional stir-casting set-up	59
3.1.	a) Matrix Material AA2024 b) SEM Image of AA2024 and c) EDS Result of the Matrix Material	64
3.2.	SEM and EDS micrograph for TiB ₂ reinforcement particles	66
3.3.	SEM and EDS micrograph for CuO reinforcement particles	67
3.4.	SEM and EDS micrograph for Glass Powder reinforcement particles	68
3.5.	Schematic Diagram of Stir-Casting Process set-up	70
3.6.	a to e Step-by-step process of fabrication of composite material	70
3.7.	a) Universal testing machine, (b) Line diagram of Tensile test specimen c) Prepared samples along with scale	72
3.8.	(a) Hardness Testing machine, (b) Schematic diagram of Hardness test specimen c) Prepared samples	73
3.9.	(a) Impact testing machine, (b) Schematic diagram of impact test specimen c) Prepared samples along with scale.	74
3.10.	(a) Schematic diagram of 3-point bending test specimen b) Prepared samples along with scale c) Bending Specimen	75
3.11.	(a) 2D dimension of the sample (b) prepared sample of composite material of wear test. (c) pin on disc tribometer (d) pin on disc holder with pin (e) Prepared samples along with scale (f) Samples as per the orthogonal array L16.	78
3.12.	Muffle Furnace and (b) Sample for Thermal Expansion with Scale	84
3.13.	Chroma India Metallurgical Microscope (MVG2005)	85

3.14.	a) Carl Zeiss EVO 50 b) Nova Nano SEM 450	87
3.15.	Validation of Hardening (Power-Law) Model	88
3.16.	Loding and Boundary Condition of Specimen	89
4.1.	The mechanical properties of developed composite material,	
	(a) Engineering stress vs. Engineering strain	92
	(b) True stress vs. True plastic strain	92
	(c) Yield and ultimate tensile strength	93
	(d) Percentage elongation vs. sample number	93
	(e) n, K vs. sample number	93
	(f) Strain hardening rate vs. True plastic strain	93
4.2.	The hardness and impact properties of the developed composite material	97
4.3.	(a) Flexural strength vs. Flexural strain, (b) Flexural strength vs sample number	99
4.4.	SEM micrograph of sample AA2024/waste Glass 2.5wt%/TiB ₂ 5.0 wt%/Nano CuO 0.25wt% (Sample 4) at a	100
4.5.	EDS mapping of sample AA2024/waste Glass 2.5wt%/TiB 5.0 wt%/Nano CuO 0.25wt% (Sample 4)	103
4.6.	(a) Tensile test specimen CAD model, (b) Boundary and Load conditions, (c) Meshing	104
4.7.	Von-mises stress contours up to necking AA2024/waste Glass 2.5wt%/TiB ₂ 5.0 wt%/Nano CuO 0.25wt% at different step time	105
4.8.	Equivalent Plastic Strain FEA results up to necking AA2024/waste Glass 2.5wt%/TiB ₂ 5.0 wt%/Nano CuO 0.25wt% at different step time and Fractured Tensile test sample after testing	106
4.9.	Experimental vs. FEA result for AA2024/waste Glass 2.5wt%/TiB 2 4.6 5.0 wt%/Nano CuO 0.25wt% specimen	107
4.10.	(a) Main effect plot of means for wear rate (b) Main effect plot for SN ratios	110
4.11.	(a) Normal probability plot of wear rate (b) residual vs fitted value (c) frequency vs residual (d) residual vs observation order	111
4.12.	Effect of reinforcement on frictional coefficient	112
4.13.	Effect of reinforcement percentage on wear rate	113
4.14.	(a) No1 100 X (b) No.2 100 X (c) No1 200 X (d) No2 200 X	114
4.15.	EDS spectrum of the fabricated composite material	115
4.16.	EDS Analysis of developed composite material	116-117
4.17.	FESEM analysis of worn-out surface (a)500x (b)1000x (c) 5000x(d) 200x	118
4.18.	Coefficient of Thermal Expansion	120

List of Table

Table. No.	Table caption	Page no.
3.1	Chemical composition of AA2024 is as follows	64
3.2	Chemical composition of TiB ₂ is as follows	66
3.3.	Chemical composition of CuO is as follows	67
3.4.	Chemical composition of Glass Powder is as follows:	68
3.5.	Composition of Fabricated Samples	71
3.6.	Process parameters and their level	81
3.7.	Orthogonal array L16	82
4.1.	Analysis of Variance for the response variable wear rate	108
4.2.	Response table for means	108
4.3	Confirmation test	119

Nomenclature and Symbols

Abbreviation/Symbols	Definitions with units
PMCs	Polymer matrix composites
CMCs	Ceramic matrix composites
CCCs	Carbon - carbon composites
MMCs	Metal matrix composites
AMCs	Aluminium Matrix Composite
CTE	Coefficient of thermal expansion
TiB ₂	Titanium Diboride
WGP	Waste Glass Powder
CuO	Copper Oxide
HAMCs	Hybrid aluminium matrix composites
AA2024	Aluminium Alloy 2024
AMMCs	Aluminium Metal Matrix Composite
EDS	Energy Dispersive Spectroscopy
SEM	Scanning Electron Microscopy
FE-SEM	Field Emission Scanning Electron Microscopy
Al	Aluminium
S/N	Signal to noise
ANOVA	Analysis of variance
SiC	Silicon Carbide
Al ₂ O ₃	Aluminium Oxide
B ₄ C	Boron Carbide
TiC	Titanium Carbide
CNT	Carbon Nano Tube
Al-Li	Aluminum-lithium
UTS	ultimate tensile strength
wt%	Weight Percentage
%	Percentage
NbC	Niobium Carbide
SiO ₂	Silica

Fe_2O_3	Iron Oxide
CaO	Calcium oxide
MgO	Magnesium oxide
TiO_2	Titanium oxide
RHA	Rice husk ash
CSA	Coconut shell ash
LM6	Aluminium-Silicon Casting Alloy
FA	Fly ash
COF	Coefficient of friction
Gr	Graphite
MWCNTs	Multi-walled carbon nanotubes
kgf	Kilogram force
E	Young's modulus
W/L	Load
y	Distance from the neutral axis
M	Bending Moment
I	Moment of Inertia
b	Width
h	Height
ASMT	American Society for Testing and Materials
ρ	Density (kg/ m^3 or g/cm^3)
W_a	Developed composite weight in air
W_w	Developed composite weight in water
ρ_w	pure water density
T	Time (s)
V	Sliding velocity (m/s)
S	Sliding distance (m)
Δm	Weight Loss (Kg or g)
ΔV	Volume loss (m^3)
W_i	Initial Weight (gm)
W_f	Final Weight (gm)
σ	True stress, MPa
ε_T	True strain

ε	True plastic strain
k	Specific Wear Rate ($\text{m}^3/\text{N}\cdot\text{m}$)
μ	Coefficient of friction (COF)
F_f	Friction Force (N)
α	Coefficient of thermal Expansion,
ΔL	Change in Length
Δt	Change in temperature

Chapter 1

Introduction

1.1 Need of Light Weight Material in Engineering Application

Competition within the automobile and aerospace industry to develop more fuel-efficient vehicles with lower CO₂ emissions has worsened in recent years. Governments all over the world are at present actively promoting the design and development of such vehicles. In actual fact, the transportation sector is responsible for carbon dioxide emissions energy production and use of 13.5 % of the country's emissions. Ninety percent of energy spent by road transport alone comes from the same mode of transport. Decarbonization provides the serious co-benefits of cleaner air and better public health; so, this means that India is compelled to set concrete targets in order to meet their comprehensive climate pledges. The combined benefit of decreased emissions and improved health living conditions is why the decarbonisation of India needs to be prioritized as part of the national strategy. Without concrete targets, the co-benefits are not achieved and gains in public health are unlikely to be realized. To get a better picture as to what this would mean for the road transport sector of India, Prior to the advent of Covid-19 pandemic, it was projected that the number of vehicles on the roads in India will rise to more than 200 million by 2030. Such forecasts were based on macro-economic growth assumptions and historical growth rates for the vehicles, the rapid expansion of road transport. In the modern era, most of the energy used in road transport comes from petroleum-based sources, most of which are imported. This dependence on fossil fuels imported is bringing massive implications with it, in terms of energy security and economic vulnerability. India's Nationally

Determined Contribution (NDC) under the Paris Agreement commits the country to cut the carbon intensity of GDP at that level and reduce it by 33 to 35 percent below 2005 levels by 2030. Which is reflective of a quantitative frame of reference for national decarbonisation targets. Although the government has stipulated economy extensive emission reduction aims, these are largely unavailable for and at high emitting sectors such as transportation and manufacturing industries. The absence of sector specific targets is an obstacle to the implementation of national pledges into concrete policy measures. Fuel-efficiency regulations differ from country to country and many countries have stricter standards than India. Nevertheless, all nations share the goals of reducing CO₂ emissions and ensuring better fuel efficiency [1-4]. Manufacturing industries have been experimenting and finding different solutions, including making vehicles lighter, which can fulfil the customer needs and improve fuel-economy standards. The size of the vehicle can be reduced or use lighter materials. Reducing size can compromise passenger safety and comfort and therefore the usual goal is to reduce weight with lighter materials whilst maintaining performance. Reports show that 10 per cent reduction in automobile weight promotes for an increase of fuel economy around 8 per cent to 10 per cent and 100 kg of weight reduction results in 12.5 g/km reduction of CO₂ emission. Aluminium alloys are still pivotal in the automotive industry, and emerging trends are determining the future of this vital substance [5-8]. The high-performance lightweight vehicles without compromising safety features intensify the need of composite materials. The substitution of aluminium in place of epoxy reinforced products that's makes the Boeing 787 more efficient than conventional aircraft [9-11]. As a result, fuel consumption and emission are reduced however at the same time payload capacity is

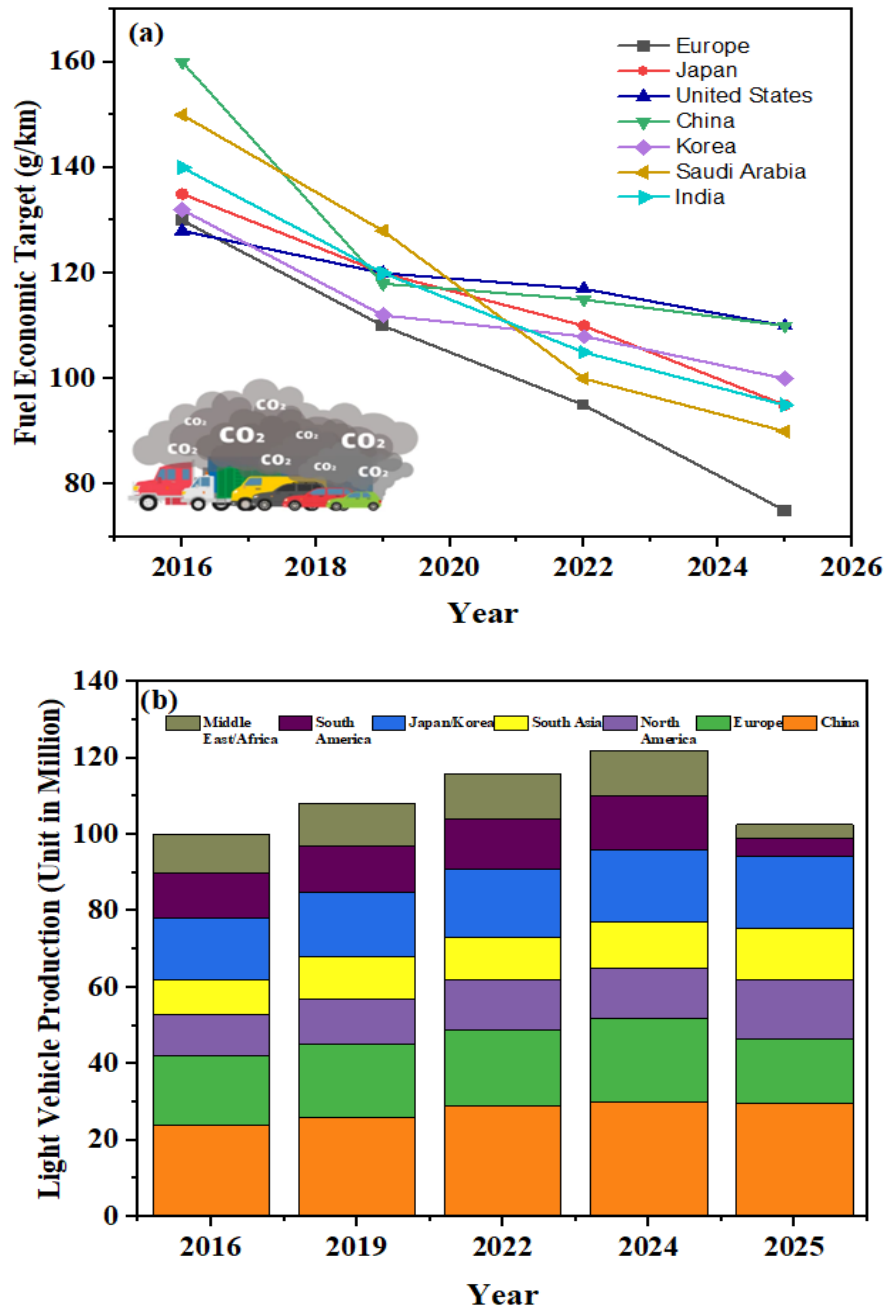


Figure 1.1. a) Fuel Efficiency Standards Across Major Countries for Passenger Vehicles b) Light Vehicle Production Volumes (Million Units) in Leading Markets [13]

increased. In aerospace and other transport sectors that deal with CO₂ emission and fuel efficiency, the manufacture of high-performance, lightweight high strength materials is critical. Meeting fuel-efficiency goals is dependent on the production of such light vehicles [12-13], which are depicted in Figure 1.1.

1.2 Motivation

The overlap of tough vehicle emission regulations (BS-VI and future CAFE-III), international regulatory regimes (Euro7, U.S. EPA Tier regulations and China 6/7) and the multi-faceted net-zero target of India, as defined in the NITI Aayog, provides the urgency around the use of emission-reduction policies beyond traditional powertrain-enhancements. Although the importance of electrification and cleaner fuels cannot be overstated, the introduction of vehicle structural light weighting has become one of the major supplemental solutions to the realization of significant fuel consumption, CO₂, and total environment impact reductions, especially in light vehicle segment. NITI Aayog must underline that vehicle efficiency, materials replacement, and mass reduction could be the key to achieving the national emission and energy-efficiency goals. The direct consequence of structural weight reduction is the diminished energy requirement per kilometre, which applies to internal combustion engine vehicles that must meet BS-VI and CAFE standards, and at the same time, improves battery range in electric vehicles as well as battery pack size requirements. Such policy course is rather consistent with international trends, where real-life emissions and life-cycle efficiency is getting more and more important.

A number of Government of India programs, as the National Electric Mobility Mission Plan (NEMMP), Faster Adoption and Manufacturing of Electric Vehicles in India Phase (FAME-II / FAME-III), Make in India, the Production-Linked Incentive (PLI) Scheme and Atmanirbhar Bharat, have a powerful push in respect of research in the field of lightweight aluminium-based composite materials. Moreover, the National Resource Efficiency Policy and circular economy work towards ensuring that the

industrial waste is used as value-added engineering materials, to both attain resource efficiency and environmental sustainability.

The current study invents the creation of the aluminium-based composites that are reinforced with ceramic and industrial waste, thus, present a two-fold benefit of avoiding weight and sustaining. Via plastic reinforcement, ceramic reinforcement increases the mechanical performance, resistance to wear and thermal stability whereas the use of industrial waste minimizes the use of raw materials and environmental impact. Outside the automotive use, these lightweight composites are of paramount significant to the aerospace industry, as the reduction of weight directly correlates with the fuel usage, passenger capacity and emissions.

Therefore, this study is both technically applicable, greener, and policy-consistent, targeting national priorities and global issues and working towards the progress of lightweight composites in seamless use in both automobile and aerospace industry.

1.3 Chronological sequence of Composite material

Chronological sequence of developments of MMCs is shown in Figure 1.2. It has been observed from the categorization that the first-generation composites did not significantly contribute to improvement of the metal matrix. However, they have better properties than steel. Therefore, composite materials are applied in various domains such as consumer goods industries, automotive, aerospace, aviation, medical, marine and sporting etc [14-16].

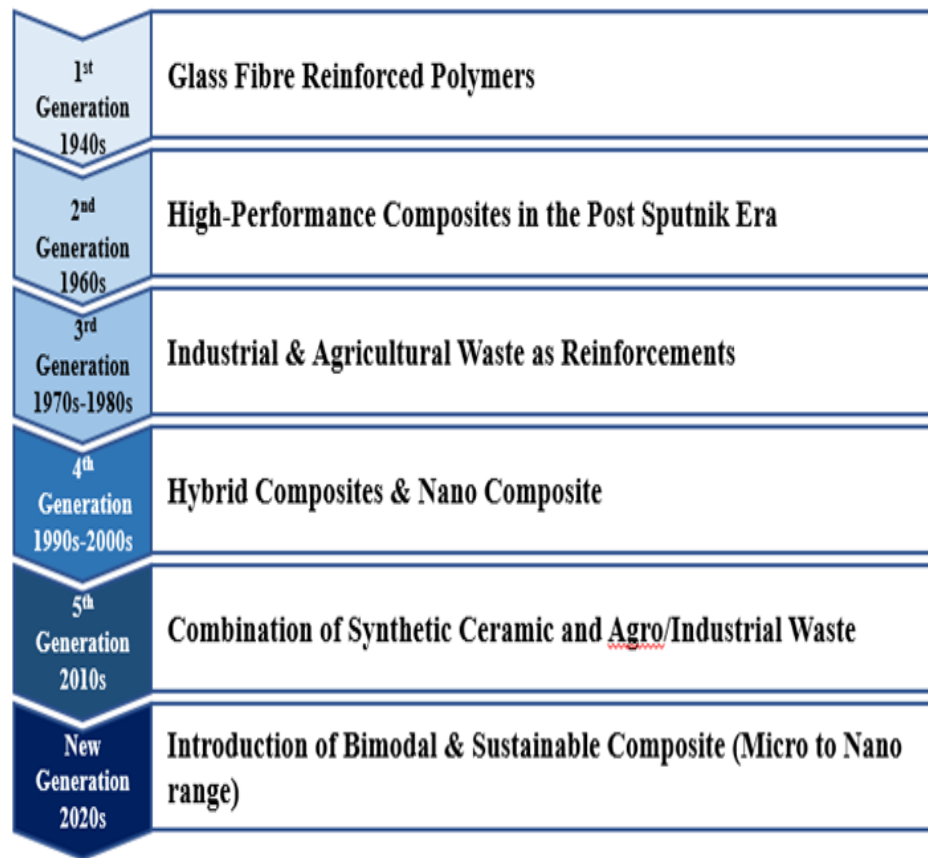


Figure 1.2 Chronological sequence of developments of MMCs

1.4 Composite Material

The composites are developed by mixing two or more chemically and physically distinct phases of materials, in which a certain proportion of one phase is dispersed in the second phase to improve the existing properties of composites. Over a last decades the demand of composite material has been on the raised globally. Figure 1.3 shows that composites are grouped into four types of matrixes: polymer matrix composites (PMCs), ceramic matrix composites (CMCs), carbon - carbon composites (CCCs) and metal matrix composites (MMCs). MMCs have a number of benefits for contemporary

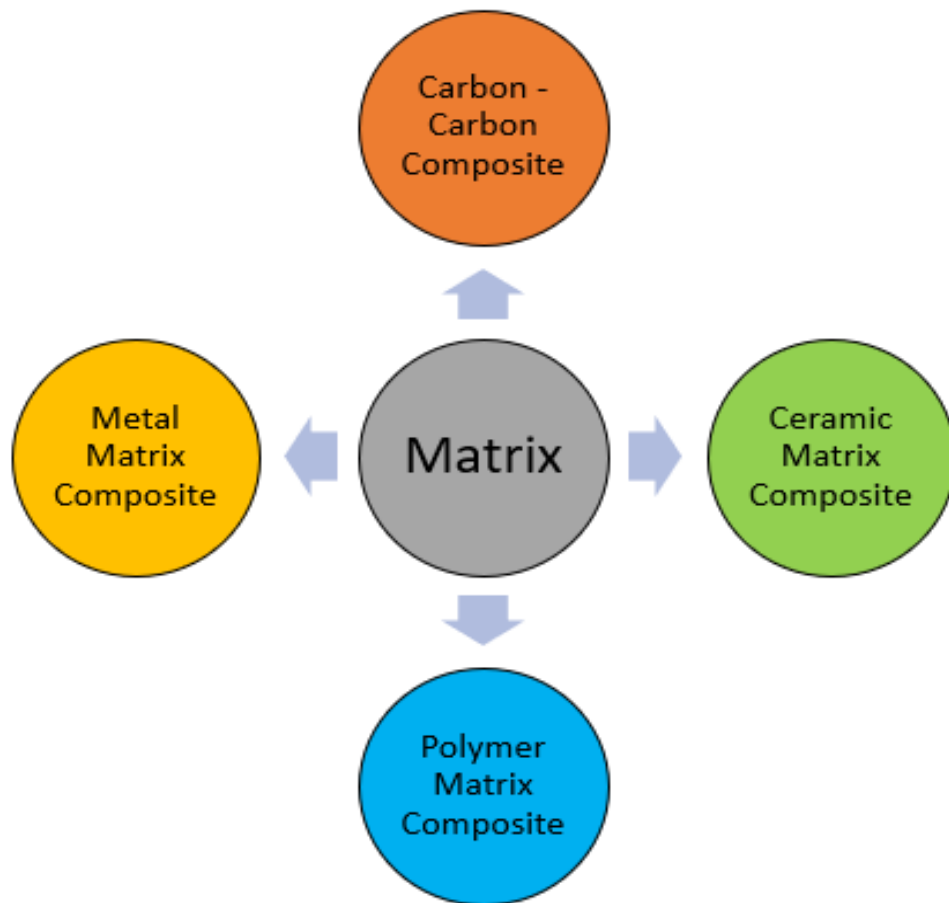


Figure 1.3 Classification of Composite Material

engineering applications over other composites and conventional monolithic metals and alloys [14].

1.4.1 Polymer - Matrix Composites (PMCs): PMCs are light, resistant to corrosion and are utilized in the interior of aerospace, automobile parts, and in sporting equipment.

1.4.2 Ceramic-Matrix Composites (CMCs): CMCs are characterized by extremely high-stability in terms of temperatures and find use in turbine blades, braking systems, and heat shields

1.4.3 Carbon-Carbon Composite (CCCs): is an advanced high temperature structural material, and the composite is made of carbon fibres reinforcement which is embedded in a carbon matrix. As both constituents are made from carbon, the

composite maintains a significant degree of strength in exactly the zone where conventional materials are prone to failure.

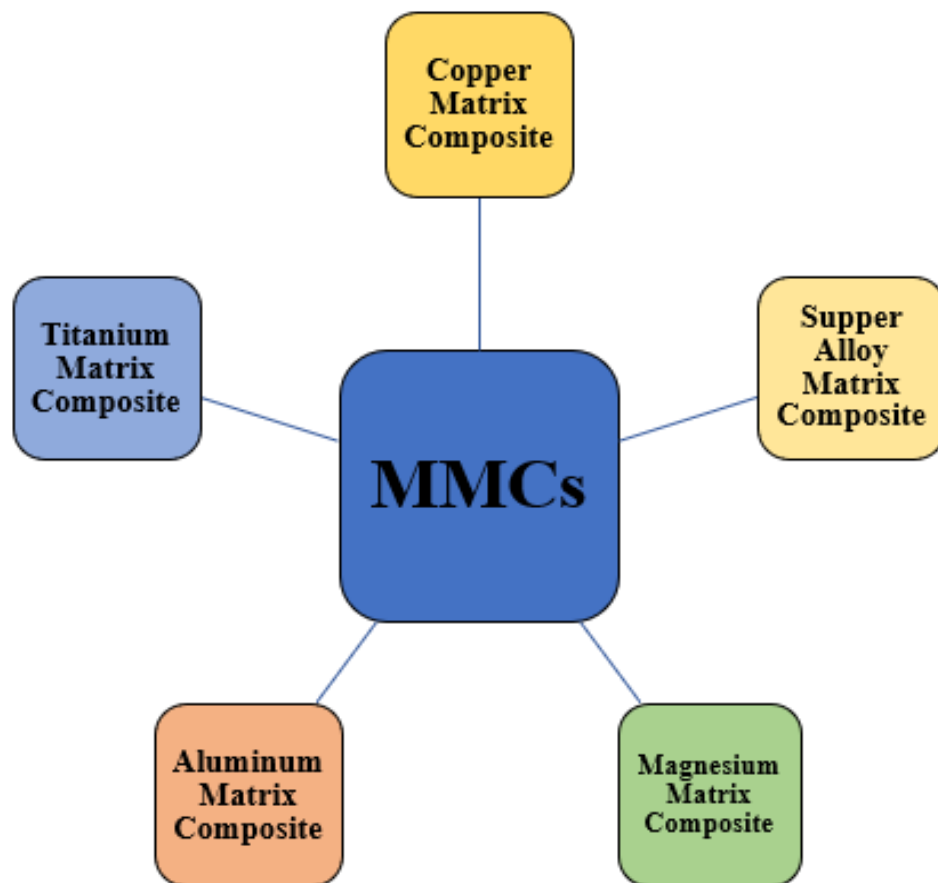


Figure 1.4 Broad Classification of Composite Material based on Matrix

1.4.4 Metal Matrix Composites (MMCs): Metal matrix Composites (MMCs) is a composite that incorporates metal matrix and ceramic/metallic reinforcements hence, outperforming the traditional alloys. The MMCs have high specific strengths, excellent wear resistance as well as improved stiffness making them useful when subjected to high loading and when working under extreme conditions. Compared to monolithic metals and alloys, MMCs are very challenging materials and are used in large numbers as functional and structural parts. The resultant composites have better

properties than the individual components. Figure 1.4 illustrates that the matrix in MMCs is usually made of materials such as Al, Mg, Cu, Ti and super alloy as well as alloys of these material.

1.5 Material

Matrix materials have a profound influence in the evolution of composite materials for particular engineering applications. Numerous matrix materials are available in the market however, each of the material has certain constraints. The most common matrix material used for Aluminium matrix composites (AMCs) is aluminium alloy itself, as shown in Figure, 1.5 [14]. When used without a substantial increase of weight, aluminium alloys offer higher mechanical properties, thermal conductivity, electrical conductivity and wear resistance in different industrial sectors and applications. Aluminium alloys are used as major alternatives to cast iron and cast steels, since they are about 35% lighter than cast iron. In more recent years, the use of aluminium alloys has been made in the place of cast iron in the production of engine blocks and cylinder heads, thus lowering the weight of the entire vehicle. The increased demand in the aerospace and automotive industries predicts the maintaining of growth in aluminium usage over the next few decades [17-24].

Aluminium 2024 is one of the 2xxx series of heat-treatable alloys where copper is used as a primary strengthening alloy. The alloy has gained high specific strength and great fatigue resistance making it one of the most sought materials in the aerospace structure like fuselage skin, frame and wing elements. However, its state of tribology is limited by a relatively low hardness, which predetermines the adhesive and abrasive wear. The addition of ceramic and oxide particles to AA2024 generates significant improvements

in wear resistance, dimensional consistency and hardness as well as does not alter the more light-weight character of the alloy

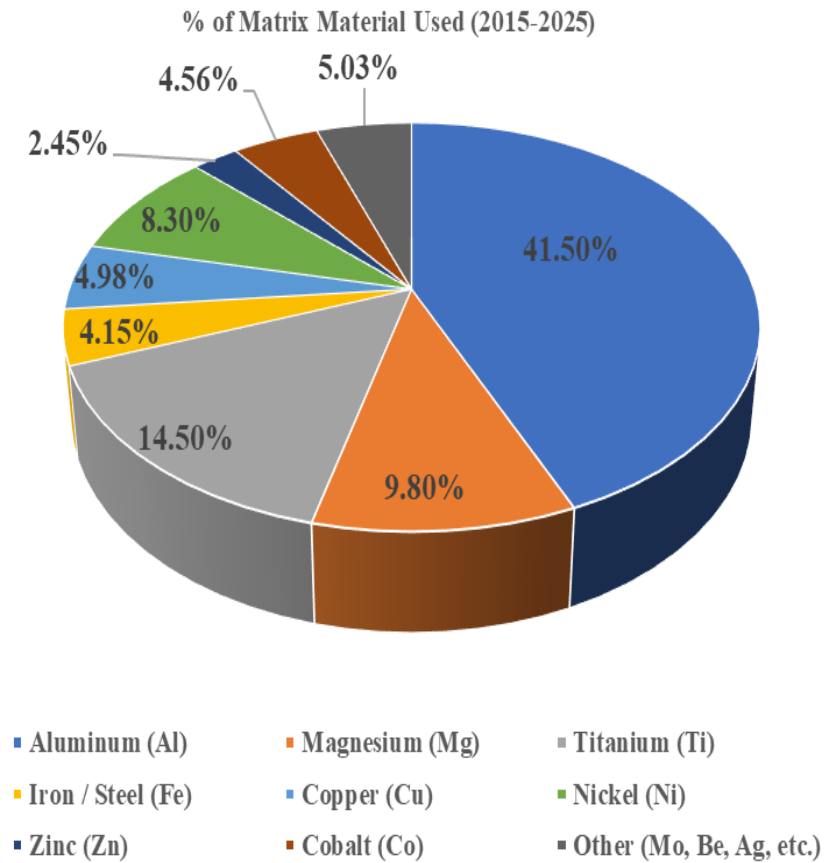


Figure 1.5 Percentage of Matrix Material

1.6 Reinforcements

The compatibility provided between the matrix and the reinforcement is very important for the characteristics of MMCs. The selection of reinforcement is based on the mechanical and thermal characteristics of the alloy including ultimate tensile strength, modulus of elastic, ductility, the coefficient of thermal expansion (CTE), the matrix material compatibility, and the cost [25]. Different MMCs has been used

to developed by reinforcing the different In organic and organic reinforcement in the recent decades, Figure 1.6 shows different reinforcement used for the development of the Aluminium Matrix Composite (AMCs).

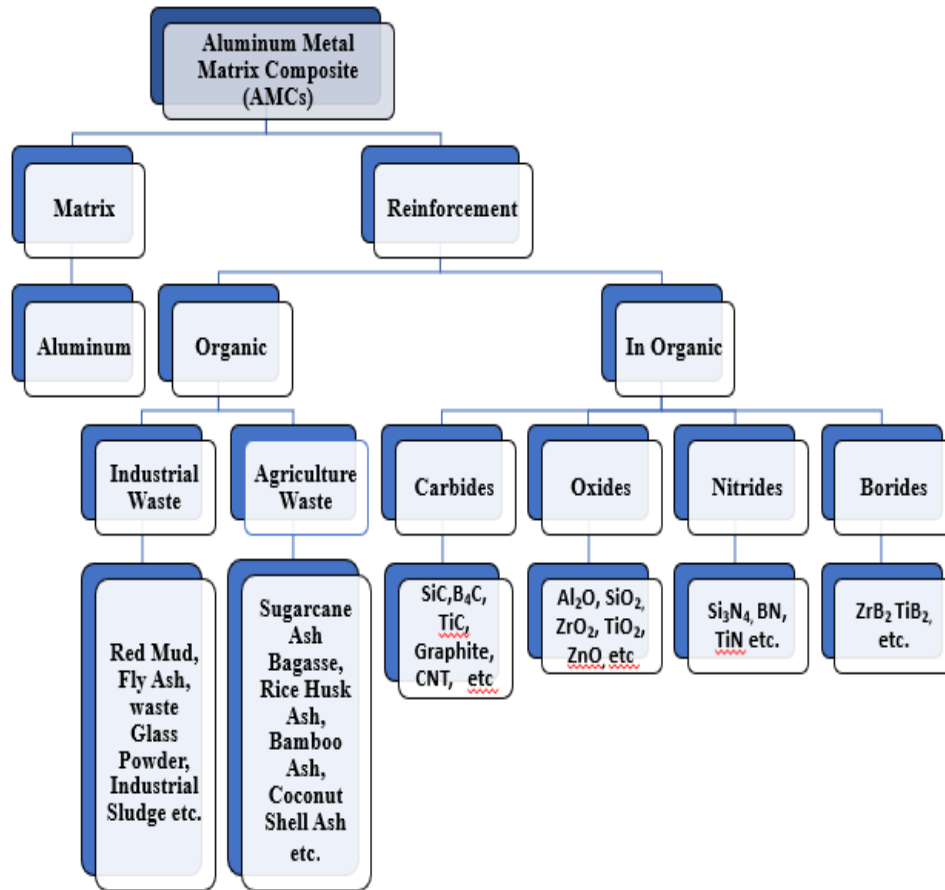


Figure 1.6 Different type of reinforcement employed for AMCs

As shown in Figure 1.7 On the basis of the reinforcements shape (particles, fibres, whisker and layers), AMCs can be further categorized into laminar, fiber-reinforced, filled, flake and particle reinforced. Particle reinforced composites are the primary focus of this study as they are more common, cheaper and fairly distribution throughout the matrix. Selection of reinforcement material depend upon the purpose and intended properties of a composite. In This research Titanium Diboride (TiB_2),

Industrial Waste Glass and Nano CuO has been considered for study is based on particle reinforced composite because they are abundant, cheap and also very easily distributed throughout the matrix. The choice of the reinforcement is dictated by the purpose and application of the composite. Reinforced lightweight metals allow a great weight reduction while this is an important goal in many domains [26,27].

1.7 Fabrication Process of AMCs

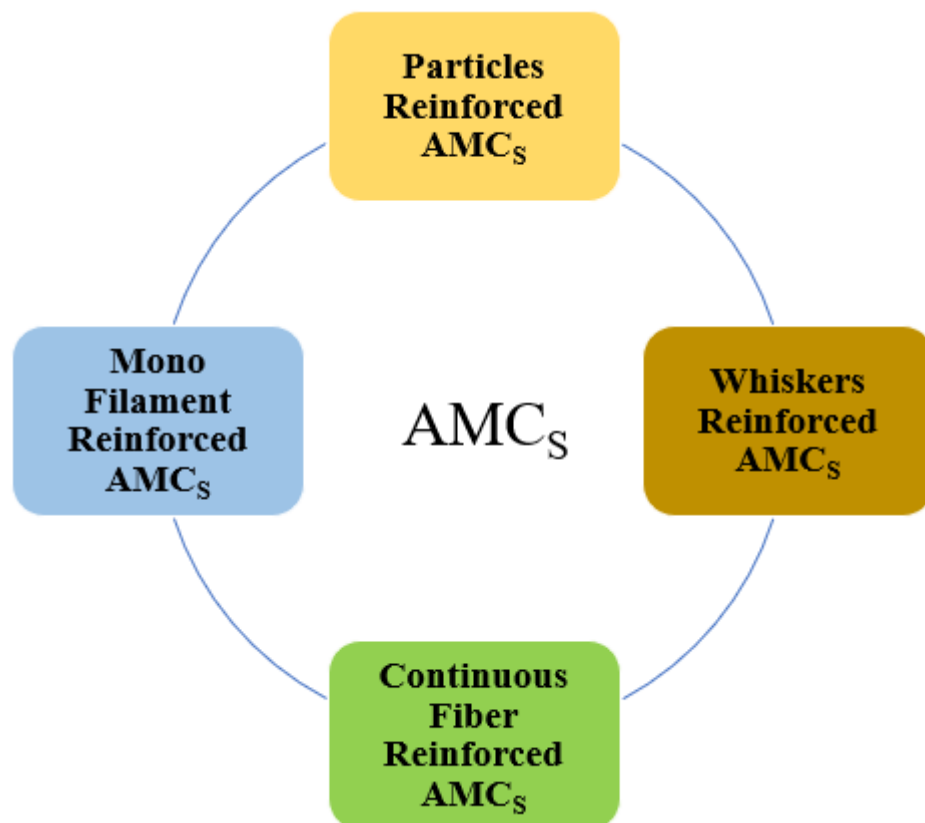


Figure 1.7 Classification of AMC on the basis of type of Particles

The reinforcement position in the aluminium matrix affects size, distribution and tribological behaviour of AMCs. By the choice of suitable reinforcing and synthesizing method HAMC properties can be adjusted. Hybrid aluminium matrix composites (HAMCs) are fabricated using various fabrication techniques, which include solid-

state, liquid-state, semi-solid and deposition techniques. The dominating manufacturing approaches for aluminium matrix composites (AMCs) are therefore dominated by these different processes are driven in Figure 1.8 and on the basis of archival literature. Determining best fabrication route requires knowledge of the material properties required: each route has its advantages and drawbacks. Researchers have been striving to make traditional synthesis processes more efficient. Stir casting, which stirs molten aluminium with the purpose of mixing reinforcement, is one of the leaders.

1.8 Stir casting

The attainment of successful casting of metal matrix composites (MMCs) depends on interfacial bonding and contact of the ceramic reinforcement particle phase with the molten matrix alloy. This physical involvement is normally done by using a mixture of ceramic dispersoids and molten alloys, pushing of molten alloys in preforms of the ceramic phase or swirl of the combination continuously in the melt. Since the vast majority of ceramics show low wettability, consolidation of the fiber and alloy is frequently achieved by artificially increasing the wetting capacity of the alloy, or exerting externally applied forces that defeat viscous drag and thermodynamically sorbed surface-energy barrier. Introduction and even dispersion of a discontinuous phase in a melt is most often done by the methods:

- implement by introducing particles to molten alloy in active agitation
- Melt injection cannon Injection of the discontinuous phase into the melt
- Spreading discontinuous phase briquettes or pellets.

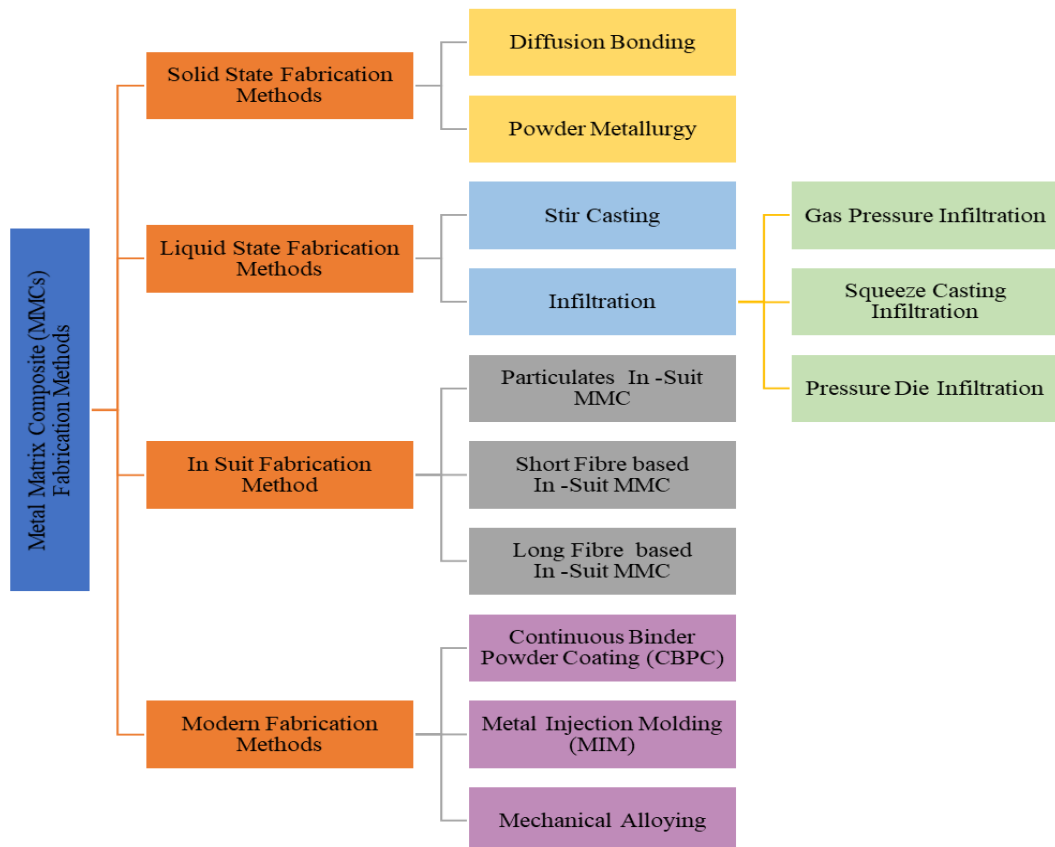


Figure 1.8 Current manufacturing approaches for AMCs are driven

These methods are all based on the presence of external force to add a non-wettable constituent of the melt and to obtain a homogeneous suspension of ceramic particles in the liquid metal.

The first step of settling of the loose-powdered particles and kinetics of the mobility of particles in the agitated liquid is what determines the uniformity of the dispersion of particles before they solidify. Centrifugal casting, gravity casting, or traditional foundry casting processes such as pressure-die and squeeze casting can be used to cast a melt-particle slurry, and processes such as squeeze casting can also be used. The casting method and the shape of the mould are also greatly influential on the quality of the composite, due to the displacement of the particles to some extent as the result

of the buoyant forces, the change of the particle position as the result of crystallization of the metal during its solidification, and the trapping of the particles, who is trapped in the solid mass, as a result. Specifically, ceramic particle orientation in casting has a severe bearing on the outcome composite and its mechanical and physical characteristics.

The resulting phase dispersal is dependent upon the superiority of component melt in the melt-particle slurry being cast, and on various important variables:

- The viscosity of the material solidifying, that controls the movement and interaction of the particles
- Particle size, shape and volumetric fraction, which determines the nature of interactions between the particles and the melt
- The specific gravities of the particle and the melt, which determine the effect of segregation and the effect of settling
- The thermal properties of the particles and the matrix alloy, which act on the heat transfer and the solidification kinetics.

In addition, the extent of interplay of the particles and the matrix is also important to know. According to solidification, ceramic particles can get entrap in the growing solid that results in affecting the ultimate material characteristics. It is of utmost importance, then, to determine the mechanisms of particle entrapment and clarify the effects on the solidification process, i.e. the influence of particle flocculation, the applied external pressure in the principal phase solidification and collect the particle by the coagulating surface etc. This type of processing approach is commonly used in high level composite production where it allows the production of large quantities, allows a greater level of control and handling, is cost-efficient, and allows the production of

close to net-shapes [28-29]. Figure 1.9 is the process taken in the development of the composite.

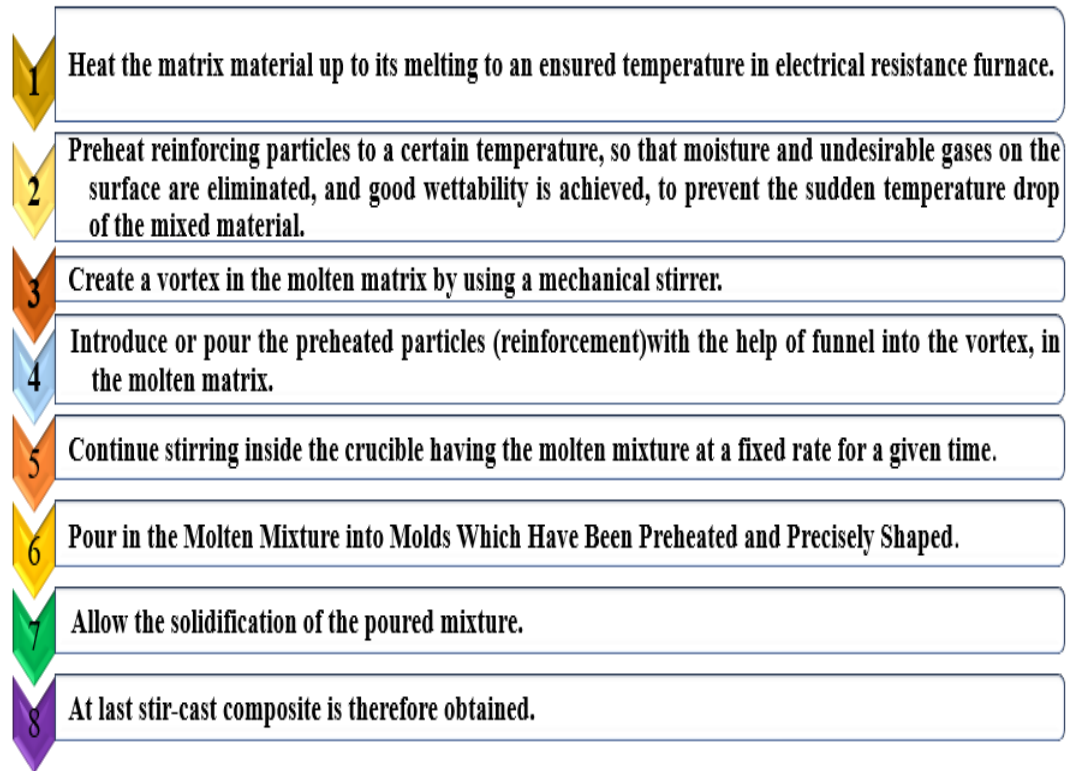


Figure 1.9 Procedure for the development of composite material by using Stir Casting Process

1.9 Characterization

1.9.1 Characterization of Composite Materials

The composite materials reinforced with industrial wastes and ceramic particles based on AA2024 were extensively studied in terms of their microstructural characteristics, mechanical, wear and thermal characteristics. These studies were critical for developing for confirming the effectiveness of the reinforcement incorporation by the stir-casting route.

1.9.2 Mechanical Characterization

Mechanical testing was used to test the load-bearing capacity and deformation behaviour of the composites. Tensile tests were performed using standard procedures to ascertain ultimate tensile strength, yield strength and percentage elongation. The results revealed some reinforcement-induced strengthening mechanisms like load transfer, grain refinement and dislocation pinning. A dynamic loading measured the energy absorption capacity and fracture resistance of, in this case, recycled Sand in impact testing. Hardness measurements were made to determine the surface resistance to plastic deformation which is a critical issue for wear-prone applications. Three-point bending tests were performed to assess the flexural strength and stiffness to gain an insight into the behaviour of the composite under bending loads. The total mechanical data were used for the interrelationship of reinforcing content and microstructural features with overall performance.

1.10 Microstructural analysis

Microstructural characterization by using Energy Dispersive Spectroscopy (EDS) coupled with Scanning Electron Microscopy (SEM) and Field Emission Scanning Electron Microscopy (FE-SEM). SEM facilitated us to investigate surface morphology, particle distribution, interfacial bonding as well as casting related defects such as porosity, agglomeration or microcracks. FE-SEM with its high resolution allowed to give some detailed information of dispersion uniformity of ceramic and industrial waste reinforcements into the aluminium matrix, especially in the matrix-reinforcement interface. EDS was used to confirm the elemental composition and phase distribution of the composites so that the reinforcement constituents were successfully incorporated and possible interfacial reactions during stir casting process

could be assessed. Together, these analyses helped us to understand the role of reinforcement type, size and distribution on the microstructural stability of the composite.

1.11 Wear Behaviour Evaluation

The tribological performance was determined by the pin-on-disk wear testing. This test was done to measure wear rate, coefficient of friction, and loss of material under controlled conditions of sliding. By analyzing the worn surface with SEM, able to identify the predominant types of wear activity, adhesive, abrasive or oxidative wear and the effects of the reinforcement particles. Hard ceramic reinforcements were found to have a major beneficial influence on wear resistance by limiting plastic deformation and reducing direct metal - metal contact.

1.12 Thermal Characterization

A test of thermal expansion rated dimensional stability on temperature changing. The ceramic and industrial waste reinforcements were determined the coefficient of thermal expansion (CTE) to understand the effect of the thermal behaviour. For automotive and aerospace applications reduced thermal expansion is desirable where dimensional stability under thermal cycling is important. The results obtained thermally were further corroborate the suitability of these composite in high-temperature and thermally-demanding environment.

Overall, the holistic characterization proved that stir casting-based Al composites had enhanced mechanical, wear, and thermal properties and, therefore, represent potential candidates for advanced structural and functional applications.

1.13 Process Optimization

The Taguchi optimization technique was employed to determine the optimal stir casting process parameters to produce Al-based composite materials using the industrial waste and ceramic particle. This design approach reduces the number of experiments to be done, but systematically evaluates how various processing variables will affect the performance of the composite. In this study, important stir casting parameters, which are reinforcement weight percentage, stirring speed, stirring time and melt temperature were selected according to past literatures and preliminary tests. Each parameter was tested at four levels in order to allow for ample processing coverage and an L-16 orthogonal array was used to create the experimental matrix. The L-16 array allowed reducing the number of experiments from 256 (with a full factorial design) to only 16 experiments, ensuring the efficient and statistically balanced evaluation of the selected factors. Each of the experimental runs was a different set of stir-casting parameters.

Signal - to - noise (S/N) ratios were determined for the following measured responses: tensile strength, hardness, wear rate, and thermal expansion. "Larger is better" criteria was applied towards mechanical properties and "Smaller is better" criteria were used for wear and thermal expansion. Main effects plots of S/N ratios identified the optimum parameter levels. For the analysis, the results were also complemented by the quantitative analysis of variance (ANOVA) methodology which indicated the relative influence of each stir-casting parameter, where those most influential parameters were the reinforcing contents and stirring speed. Confirmation experiments were used to verify the effectiveness of optimized parameter combination.

1.14 Recent applications of AMCs

The different AMCs have an economical significance and further research is necessary into applications. New AMCs will be composites of hybrid nature, with better qualities. The use of AMCs in many industries is shown in Figure. 1.10, and the roots indicate the important components that affect such applications.

1.15 Problem Statement

The worldwide tendency to employ high-performance, cost-effective, dependable engineering materials in a variety of applications has led to the increased research interest in advanced composite materials. Amongst them, aluminium based metal matrix composites (AMMCs) have become a promising candidate due to their excellent mechanical performance, wear resistance and tribological capabilities. Due to these properties, AMMCs are very attractive for critical applications to the automobile and aerospace industries. However, increasing fuel costs and stringent emission standards have forced manufacturers to make vehicles lighter without sacrificing any safety, durability or performance. Lightweight alloys and composite materials have therefore been seen as a successful approach to fuel efficiency and reduction in emissions.

In the aerospace industry, structural parts, e.g. wings and fuselage, are always under high tensile load and cyclic fatigue stresses. Conventional aluminium alloys, such as Al2024, Al7075 are commonly used in these applications, but they have been hampered, at least in their use as structural materials, by their limitations in strength to weight, fatigue life and long-term reliability under extreme service conditions. Although AMMCs can provide potential improvements, there are still some challenges

in optimizing their mechanical behaviour, understanding their performance under complex loading, and unfortunately also challenging their suitability for large scale industrial use.



Figure 1.10 Applications of AMCs in Different Field

Therefore, there is a very critical need to perform the systematic investigation regarding the mechanical characterization and computational study of aluminium based metal matrix composite. This research will overcome the limitations and help to develop light weight, durable, and efficient components for automotive and aerospace applications

1.16 Thesis Organization

Chapter 1 (Introduction)

This chapter describes the increasing demand for lightweight materials in engineering and explains why this is the case for advanced composite materials. It includes the development of composites throughout history, types and basic properties, giving particular attention to aluminium matrix composites. Topics include fabrication by stir casting, characterisation methods, optimisation of process, recent applications and formulation of problem statement and research objectives.

The chapter opens with the demand for lightweight solutions, outlines the development and kinds of composite and puts special emphasis on aluminium matrix composites (AMCs). It covers the topic of matrix materials and reinforcement materials, stir casting fabrication, as well as various characterization methods including mechanical testing, microstructure analysis, wear and thermal characterization. Process optimisation strategies and recent AMC applications are discussed and concluded with a clear statement of the research problem.

Chapter 2 (Literature Review)

This chapter overviews the available literature on aluminium matrix composites from the perspectives of matrix materials, reinforcements, fabrication methods and the consequences for the mechanical, tribological, thermal and microstructural behaviour. It critically reviews the studies related to stir casting, characterisation techniques, optimisation strategies and current applications of AMC and identifies the research gaps for motivating the present study and objectives.

Chapter 3 (Materials and Methods)

Materials and procedures for the investigation are outlined in this chapter. The matrix chosen is aluminium, while the reinforcements are titanium diboride (TiB_2), copper oxide (CuO), waste glass powder. Stir casting was used to make the composites and were followed by tensile, hardness, impact, flexural, wear and thermal tests.

Computational analysis of the mechanical behaviour in tension and microstructural examinations was also done to establish the relation between the processing parameters and mechanical and thermal properties.

This section presents a list of materials and methods that have been used in the development and evaluation of the aluminium matrix composites. Material of the matrix is aluminium, TiB_2 , CuO and waste glass powder. Fabrication and experimental protocol is carried on through stir casting technique. Standard tests for tensile, hardness, impact, flexural strength, wear, and thermal analysis are described as well as computational models of tensile response and microstructural characterization to make the link between processing and performance.

Chapter 4 (Result and Discussion)

This chapter shows the experimental and computational results of the aluminium matrix composite. It analyses the effects of the type of reinforcement, the processing settings and the fabrication conditions on tensile strength, hardness, impact resistance, flexural strength, wear behaviour and thermal characteristics. Correlations between microstructure and observed properties are established and discussed in comparison of relevance to the relevant literature.

Chapter 5 (Conclusion, Future Scope and Social Impact)

This chapter gives an overview of major conclusions of the research on aluminium matrix composites. It brings out the effects of reinforcements, the fabrication parameters, and processing conditions on the mechanical and wear performance, thermal performance, and microstructural performance. The conclusions obtained based on experimental and computational work show the effectiveness of the developed composites. Future directions are suggested, including advanced processing technique, new application areas of Aluminium matrix composites are suggested.

Chapter 2

Literature Review

2.1 Overview

Composite materials obtained from the combination of two or more different constituents having different physical or chemical characteristics [30-31]. Out of the many varieties of composites, metal matrix composites (MMCs), polymer matrix composites (PMCs) and ceramic matrix composites (CMCs) have gained a huge industrial relevance due to their superior strength-to-weight ratio, the possibility of engineering mechanical behaviour and the very good thermal stability of these materials make them very attractive for a wide variety of applications [32-33]. Within the aerospace field, the need to trim weight becomes a critical design requirement, which is directly linked to both improvements in fuel efficiency and payload capacity and total system performance. Aluminium-based composites, in which ceramic particulates such as SiC, Al₂O₃ and B₄C are used as reinforcement materials, are widely used in structural parts of aircraft, landing gear facilities and engines, for their enhanced specific strength, wear resistance and thermal stability [34-36]. Empirical investigations have shown that the use of the hybrid reinforcements allows to optimise the interplay between tensile strength, stiffness and fatigue resistance, which are indispensable parameters for high performance aerospace applications.[37-38] A parallel tendency can be seen in the automotive industry, where better use of composites is growing for the production of engine parts, brake discs, constituents of the car chassis and body panels, with the dual requirements being mechanical performance and weight savings. Aluminium matrix composites (AMCs), reinforced with particles of SiC, Al₂O₃ and graphite have shown significant improvements in their

hardness, wear resistance and coefficient of thermal expansion, thus resulting in excellent high temperature performance and good fuel economy improvements in the wear rate and coefficient of thermal expansion of the alloying components, resulting in excellent wear and thermal expansion characteristics. [39-42] Moreover, the investigations into hybrid composites and nano reinforcements, in particular graphene and carbon nanotubes, have been directed towards further enhancements of tribological behaviour and thermal conductivity in order to reduce critical automotive engineering issues [43-44].

Beyond aluminium, other metallic matrices, namely those made of magnesium, titanium and aluminium, or nickel alloys, are also exploited in aerospace and automotive sectors with the aim of developing composites according to very specific structural, thermal or tribological requirements. The sustained research and development effort into this arena has given birth to composites which combine lightweight design, high mechanical performance alongside advanced thermal management to become indispensable to modern high performance transport systems. Composite materials offer up something singular amalgamation of properties strict to for replication using conventional monolithic counterparts. The progressive improvements in reinforcement types, processing practises and hybridisation approaches provide a wide degree of latitude for optimising performance in applications to aerospace and automotive applications. The following sections of this review will critically consider the mechanical, wear, tribological and thermal properties of aluminium matrix composites and allied metal-based composites which have been designed to have such high-performance applications.

The historical development of these classes of materials can be seen in Figure 2.1 [45]

Decades back, industrial and agricultural garbage replace exogenous ceramic reinforcements. Composite reinforced with microparticles often yield to initiation of micro-cracks at interface weak points Numerous investigations have indicated that introduction of nano reinforcement into metal matrix alloys increases the alloy strength and modulus while ductility and toughness may be reduced. Nano reinforcements have greater strengthening efficiency as compared to their micron counterparts. Aluminium with nanoscale SiC, Al₂O₃, Carbon nanotubes (CNTs) and Graphene make use of strong van der Waal Forces, but internal incompatibilities between the Nano reinforcements and the majority of MMC alloys make it difficult to achieve a uniformly dispersed nano-reinforcement field experimentally. As a result, the use of many aluminium-matrix nano-composites (AMNCs) is limited to relatively modest strength gains, which restrict their application to limited areas of engineering and biomedical applications. Multiple research endeavours have therefore been aimed at relieving this bottleneck [46-48]. Generation of heterogeneous grain structures with differentiated soft/hard zones e.g. bimodal, harmonic or gradient architectures is a powerful strategy. These materials owe their excellent mechanical properties to the major role played by hetero- deformation induced (HDI) strengthening and hardening, which are the most prominent mechanisms controlling performance. Integration of Nano reinforcements into fine, ultrafine or nanograined (FG/UFG/NG) matrix is one of alternative ways to reconcile between strength and ductility. Hybrid micro/nano - reinforcement (micro - nano hybridisation) can be considered therefore as a particularly interesting paradigm for overcoming the current prevailing AMC challenges. hybrid approaches are available to increase the mechanical attributes of

AMCs the addition of micro- and nano-sized Al_2O_3 particles prominently enhances the hardness, tensile strength and wear resistance of the A356 aluminium alloy (being accompanied by the favourable thermal stability and microstructural refinement). Researcher advocates that compo-casting methods are a pragmatic way of obtaining efficient production of Al_2O_3 reinforced A356 composites. With regard to micro-level stress concentration, micro -stresses in hybrid composites can be distributed and locked down. Despite significant advances in the production of high strength ductile AMCs, the manufacture of strong, durable composites remains a daunting task of great challenge [49-52].

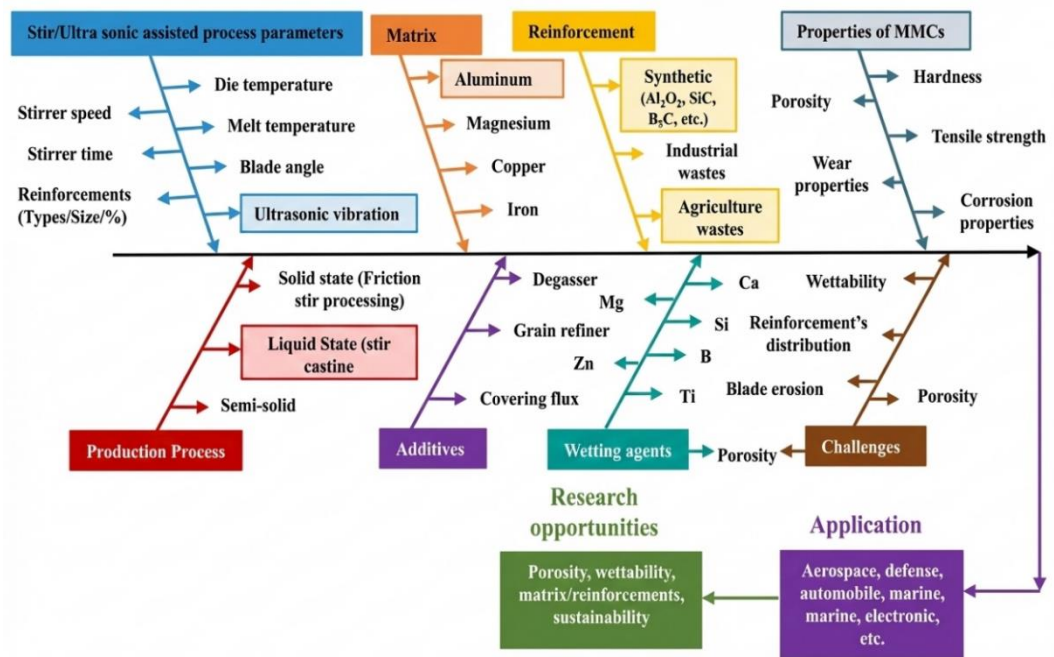


Figure. 2.1 Various process variables impact the MMCs Performance [30]

2.2 Circular Economy Approaches in Aluminium Alloy

In the case of aluminium, include mining and also the transportation of bauxite, refining the alumina, producing aluminium with primary and secondary processing,

and the use of energy sources during the production process. An integral part of AMCs production includes systematic by-products management, including red mud, comprehensive waste management protocols, semi-finished processing stages, including cold rolling, casting, hot rolling, heat treatment, forging and extrusion, as well as purification by-products. These processes, as stated in references [53-54], emphasise the necessity of sustainable practises, in view of the high environmental footprints related to greenhouse gas emissions, waste production and energy consumption. Figure 2.2 shows the impact of various sustainability initiatives as a function of technology readiness level (TRL), for different alloy groups. [55-56] Highly evident is that, for aluminium alloys, the implementation of electrically powered processes using renewable energy sources such as hydropower is especially powerful at high TRL, and it can be considered as one of the most effective strategies.

2.3 Rationale for Aluminium Matrix Composites (AMCs)

For instance, in the automotive industry, until the 1970s, cast iron and low-carbon steel were the preferred materials and the engine block and the cylinder head were key components of passenger cars. The significance of AMCs in this regard, as well as the overall drive to improve their mechanical properties, remains profound. By using ceramic or polymer reinforcements embedded inside a metal matrix, it is possible to significantly enhance some important properties, such as strength or stiffness, or wear resistance compared to a conventional monolithic metal. Numerous fabrication techniques - powder metallurgy, in situ synthesis, and liquid metal infiltration - have been investigated to produce said composites. Cast iron has been selected for both parts due to its superior wear resistance, high temperature strength and ease of

castability. Unfortunately, due to its significant density (7870 kg/m^3), the engine block is the most massive part of the car, and contributes about 3-4% to the total weight of the car. To cut down the weight of vehicles and hence cut down CO₂ emissions, car manufacturers are now substituting the cast iron of engine blocks with other lightweight materials. Natural fibres and hybrid fibre composites are being used more and more in this regard. These composites are so popular because they are cost effective with better strength available and environmental benefits as well [14-17].

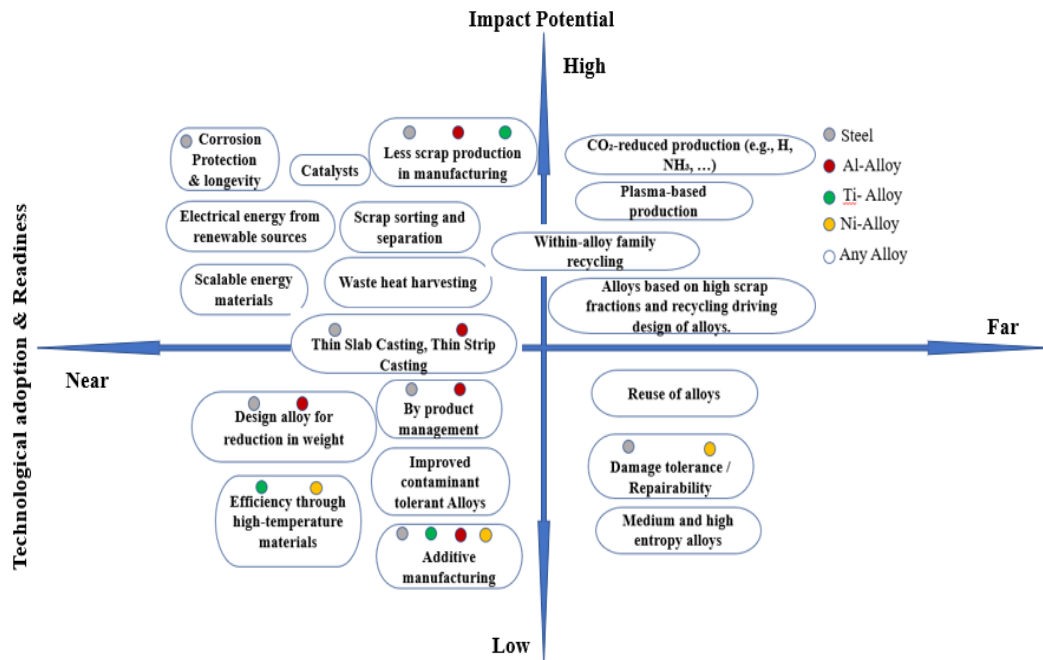


Figure 2.2 Technological Readiness and Impact Potential of Sustainability Measures in Structural Alloys [55-56].

Aluminium alloys are normally resistant to corrosion because they form a protective oxide layer naturally on them. Some composites, however, exhibit a lower corrosion resistance which is based on the type and amount of reinforcement added. The scientific and technological importance of AMCs and related research in the field of developing AMCs with enhanced properties is huge. Combining with a metal matrix

other materials like ceramics or polymers allows to improve key properties, like strength, stiffness or wear resistance, of a conventional metal. Several techniques are available for fabrication of AMCs, such as powder metallurgy, in situ synthesis and liquid metal infiltration. Achieving homogeneous dispersion of reinforcement in metal matrix creates serious difficulties. Precise control over the spatial dispersion of particles is an important necessary in ensuring a consistent mechanical performance.

2.4 Aluminium Matrix Composites (AMCs)

AMCs find increasing application as e.g., drive shaft, brake rotor, piston, cylinder liner [57-59]. One major problem in manufacturing composites is to ensure a good interfacial bond between matrix and reinforcement. If matrix and reinforcement are not well matched, the desired properties cannot be attained. Magnesium-based metallic composites are subjected to limitations because of the higher oxidation rates and low ductility at higher temperatures. To overcome these problems an inert atmosphere is employed during the manufacturing [60-62]. Copper composites are always used when thermal and electrical properties are significant; unfortunately, the pure copper is weak, relative to other matrix materials [63-64]. AMCs mitigate many of these limitations and possess good abrasion resistance [65-67]. The special properties that come with aluminium make it a good combination with other materials for the manufacture of composites. The classifications of aluminium alloys are distinguished into heat treatable and non-heat treatable alloys depending on their response to the hardening by precipitation. Heat treatable alloys develop maximum performance by age hardening while non heat treatable alloys develop desirable properties by cold working and natural aging. Heat treatable alloys can be performed only by using Age

Hardening, and non-heat treatable alloys by using work hardening (cold working). Figure 2.3 is a list of the wrought aluminium alloys that are suitable for metal matrix composites (MMCs). The alloys of 1000 series are around 99% of pure aluminium while the other elements are in alloys, like Al-Li (8000 series). Cast aluminium alloys, which have systems such as A356, are also used to produce composites. There has been a huge growth of research on aluminium MMCs in the past 10 years. Aluminium alloy 2024 (AA2024) is especially recognized widely known for its use in Aircraft body, rivets, thin sheets, sporting goods, orthopaedic braces applications.

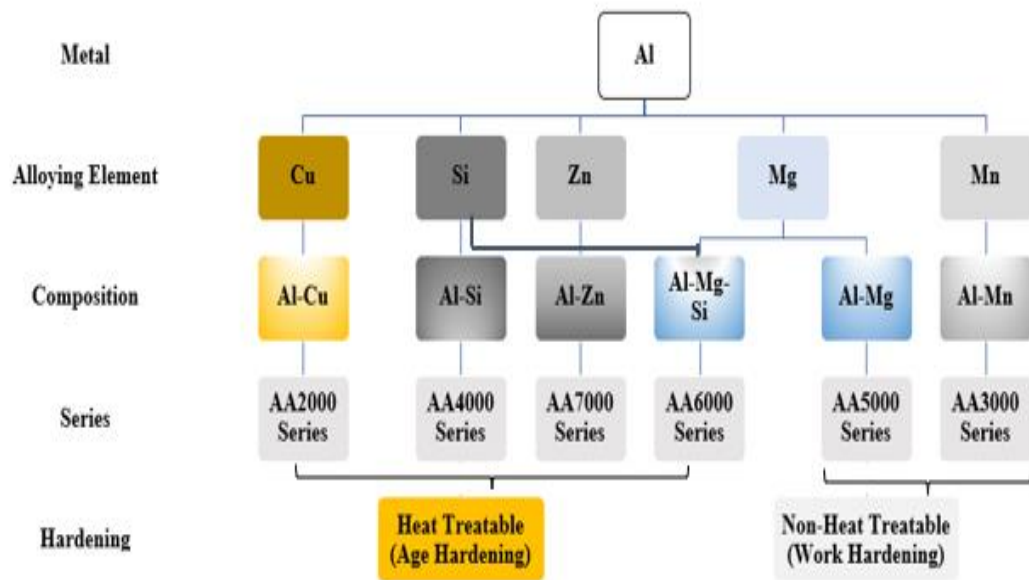


Figure 2.3 Aluminium alloys Series [30]

2.5 Reinforcement Materials in Aluminium MMCs.

The performance of aluminium MMCs is dependent on the type of reinforcement used. Silicon carbide (SiC), aluminium oxide (Al₂O₃), boron carbide (B₄C), titanium carbide

(TiC) and titanium diboride (TiB₂) ceramic reinforcements are common in the literature. Such reinforcements are very hard, highly elastic and thermal stable and therefore they lead to better composite properties.

One of the most common reinforcements that are in use is SiC due to its availability, high hardness, and compatibility with the aluminium matrices. Al₂O₃ is highly resistant to chemical acids as well as wearable, whereas the B₄C has an incredible hardness and low density. TiB₂ has received increased attention because it has high melting point, better hardness and good wettability with molten aluminium than other ceramics. Most of the researchers shows that TiB₂ reinforced aluminium composites have increased hardness, tensile strength and wear resistance. Weight reduction is often the top goal, which can be achieved by the strengthening of light metals.

2.5.1 Ceramic Reinforcement

The effect of ceramic reinforcement content on aluminium metal matrix composites (Al -MMC) has been systematically investigated over the last decade. Reinforcement weight %age is the overpowering parameter to the performance in its mechanical, tribological and thermal aspects. Most studies report ceramic additions of 0.5 - 30 wt %, depending on the type of reinforcement, particle size, and processing technique [68-71]. Property enhancement is enhanced with reinforcement contents up to a certain optimum content; beyond this content, agglomeration, porosity and interfacial stress concentrations cause a decline in performance [72]. Silicon carbide (SiC) reinforced aluminium composites, an increase in the reinforcement from 2 wt% to 10 wt% leads to 15%-35% increase in ultimate tensile strength (UTS) and a 20%-60% increase in hardness, compared with the base alloy [73-76]. At 15% to 20% wt% SiC, the hardness

increases by 80% to 120% and the elastic modulus increases by 20% to 50%. However, ductility decreases significantly, with elongations decreasing of 30% - 60% for more than 10 wt% SiC, as a result of particle clustering and microcrack initiation [77]. From wear studies, it is known that under dry sliding conditions 5 wt% SiC reduces wear rate by 40 % to 70 % and 15 wt% SiC reduces wear rate by up to 90 % in dry sliding condition [78]. Alumina (Al_2O_3) reinforced Al-MMCs it can be stated that optimum reinforcement concentrations are typically 5-12 wt%. Within this range, hardness increases by 25-70 % and UTS improves by 10 %-30 % [79-81]. Above the 15 wt% Al_2O_3 , tensile ductility decreases rapidly (>50%) because brittleness and stress concentration at the particle-matrix interface increases [82]. Wear resistance is largely enhanced, 30 % to 65 % reduction in wear rate of 6 % to 12 % wt% Al_2O_3 [83]. Titanium diboride (TiB_2) reinforced aluminium composites exhibit superior strengthening for lower levels compared to the other composites, which is attributed to their good wettability and good interfacial bonding. Additions of just 2 to 6 wt% TiB_2 result in between 30% - 65% of hardness and 20%-40% improvement in yield strength [84-86]. At 8 wt% to 10 wt% TiB_2 , the hardness is greater than 90% and tensile strength is increased 35% to 50% due to grain refinement and Hall-Petch strengthening [87]. TiB_2 also provides excellent wear resistance: a 50% - 85% decreased wear rate with wt%. of 4% - 8% [88], compared with 10-80 wt% of SiC. Boron carbide (B_4C) reinforced composites, hardness values of 40 to 100 % and tensile strength values of 15 to 35 % were achieved with addition of 5 to 10 % [89-90]. Wear rates are lowered by 60% - 90% at 8-12 wt% B_4C making these composites suitable for high abrasion applications [26]. However, ductility losses of 40% - 70% are common since of poor wettability and particle brittleness [91]. Similar trends are

obtained for other carbide reinforcements including TiC, WC and NbC. Additions of TiC ranging from 5 wt%-10 wt% give 30 wt%-80 wt% improvement in hardness and 20 wt%-40 wt% in tensile strength [92]. WC reinforcement gives extreme enhancement of hardness up to 120% at ~15% wt% but results in significant increase in the density and brittleness of the composite [93]. NbC additions of 2 wt% - 6wt% give rise to 15%-30% yield strength increments, mostly by grain boundary pinning and refinement [94]. Thermal properties are also very much affected by the content of the ceramics. Dimensional stabilities are improved in thermal cycling applications by SiC reinforced composites which reduce the coefficient of thermal expansion (CTE) by 10%-35% at 10% - 20% wt% SiC [95]. Thermal conductivity may be reduced at small levels 5%-15% because of interface scattering [96]. TiB₂ and AlN reinforcements reduce CTE by 15 % - 30 % at 5-10 wt%. AlN has the ability to enhance the thermal conductivity by 20 % - 40 %, which is suitable for electronic packaging [97-98]. Low-cost reinforcements such as fly ash and ZrSiO₄, added usually in amounts from 5 to 15 wt%, reduce composite density by 5 to 12% and increase wear resistance for 30 to 60%. Nevertheless, improvements in tensile strength are small 5-15 % [99 - 100]. Nano-reinforcements such as graphene, CNTs, even at 0.25% - 1% wt%, provide increase in tensile strength by 20% -50% and increase in thermal conductivity by 15% - 60%; dispersion problems are, however, of significance [101-102]. from the literature, the following wt% of reinforcement is found to be optimum ranges of mechanical, wear, and thermal properties: 5 wt%-12 wt% for SiC and Al₂O₃, 3 wt% -8 wt% for TiB₂ and NbC, 5 wt%-10 wt% for B₄C. Nano - ceramics, on the other hand, need less than 1 wt% of nano - ceramics to strengthen them effectively.

These results highlight the importance of reinforcement selection and contents optimization on the design of high-performance Al-MMCs.

2.5.2 Industrial Waste as a reinforcement

The use of industrial wastes as reinforcements in aluminium metal matrix composites (Al- MMCs) has attracted much attention during last decade. Increasing focus on sustainability, cost reduction, and mitigation of environmental impact have been the drivers for this interest. Industrial by-products such as fly ash, red mud, blast furnace slag, rice husk ash and bottom ash, quarry dust, waste glass, bagasse ash, marble dust and steel slag have been investigated for alternative use as a reinforcement in place of conventional ceramics. These waste materials contain hard ceramic constituents (SiO_2 , Al_2O_3 , Fe_2O_3 , CaO and MgO) which are used to strengthen and provide wear resistance on the addition to aluminium matrices. Research from year 2010 to 2025 reveal that aluminium composite reinforced with industrial waste is able to meet the mechanical and tribological level of performance of the ceramic reinforced counterparts with economic and environmental contribution [103-106]. Fly ash is the most investigated industrial waste for Al- MMCs. Its low density, for its great quantity in supply and ceramic rich composition make it ideal. Studies show that adding 2-20 wt% fly ash will improve the properties, it will be good with most at 5-12 wt% [107]. one study reported that hardness and compressive strength of A356 alloy reinforced by 10 wt% flyash were increased by 20-35% and 15-25% respectively. The improvements are due to dispersion strengthening and load transfer. However, tensile strength enhancements are relatively small (5-15 wt.%) at 8-10 wt.% and the ductility decreases by 20-40% due to particle porosity and irregular particle shapes. [108-109]

Fly ash helps to enhance the wear performance to a great extent. Wear rates are reduced 30-65% at 8-15 wt% fly ash at dry sliding. It also lowers composite density from 5-12% which makes the material lightweight. Thermally the addition reduces thermal conductivity by 10-25 % and decreases the coefficient of thermal expansion by 8-20 %, which improves the dimensional stability, but has reduced the ability of heat dissipation [110-111]. Red mud - by-product in alumina extraction-contains large quantities of Al_2O_3 , Fe_2O_3 and TiO_2 , which is considered to be a suitable reinforcing phase. Addition of 3-15 wt% red mud gives 25-55% improvement in hardness and 20-30% more strength in compression than the base alloys. Tensile strength increases moderate 10-20 % at optimum levels, decrease of elongation 30-50%. Wear resistance is significantly improved, about 40-70 wt.% reduction at 8-12wt.% rate. Thermal conductivity decreases 10-20 % and CTE decreases 10-25 % [112-113]. Rice husk ash (RHA) is high in amorphous silica and is used in composites (3-12wt%). One of the studied shows that 6 wt% RHA showed 20-40% increase in hardness, and 10-25% increase in ultimate tensile strength. Wear rate reductions were between 35-60%. However, if subsequent poor wettability and ash porosity are present, the particles may agglomerate when reinforcement is greater than 10-12 wt %. Thermal conductivity is reduced 12-30 % and CTE is reduced 10-22 % [114-115]. Low-cost reinforcements like Waste glass powder and marble dust have also been used. Waste glass which contains silica improves hardness by 20-45% and tensile strength by 8-18% at dosage of 5 to 10 wt% or higher. Marble dust gives higher compressive strength but little tensile strength because of calcium content present. Wear rate reductions by 25-50% are reported for glass reinforced composites where as in case of marble dust, it has less wear resistance than fly ash and red mud Recently works on hybrid systems of

industrial wastes and conventional ceramics have been shown. For example, fly ash + SiC or RHA + Al_2O_3 hybrids increase the tensile strength by 20-40% and decrease the wear rate by 50-80% as compared with single waste reinforcements. Although industrial waste reinforced Al-MMCs have shown promising results in mechanical and tribological performances, the tensile performance is still behind those of ceramic reinforced composites. Main limitations have to do with the heterogeneity of the particles, bad wettability, as well as the chemical heterogeneity. Nevertheless, these composites reduce costs by 20-40 % and offer environmental advantages so that they can be used for non-critical structural and wear applications. Industrial waste materials can be used to reinforce aluminium composites effectively, and the several studies confirms this fact. Fly ash, red mud, RHA, slag and waste glass enhance hardness, wear resistance and dimensional stability - especially when reinforcement between 5-12 wt% is used. Hybrid reinforcement strategies and better processing provide routes to overcome the encountered limitations and pose waste-based Al-MMCs as sustainable options for future engineering applications [116-119].

2.6 Mechanical Behaviour of AMCs

Aluminium matrix composite (AMC) is an important material in the field of materials science because it is made of aluminium and has low density and much stronger mechanical properties such as high strength, hardness and wear resistance. This interest originates in the requirement of lightweight and robust material for aerospace, automotive and defense applications. Understanding the mechanical behaviour influenced by the use of individual reinforcements, the combination and weight fraction of the reinforcements is crucial for fundamental research as well as

engineering design. The mechanical performance of AMCs relies strongly to the type, distribution and volume fraction of reinforcement particles that are added to the aluminium matrix metal. Common reinforcements (silicon carbide SiC, aluminium oxide Al_2O_3 , boron carbide B_4C) have been widely investigated due to high hardness and modulus values which help hindering the dislocation movement and enhancing the load transfer from the ductile matrix to the hard particle. These mechanisms improve tensile strength, hardness and wear resistance when taken together often at the expense of ductility [5,29]. Empirical studies of single - phase reinforcement systems have shown that for most cases the reinforcement weight fraction increased leads to improved mechanical properties up to some optimum. Beyond that point it can be problems like particle agglomeration, interfacial defects that affect performance. For example, stir cast AA6061/SiC composites of up to 15 wt % SiC exhibit a 133.33% increase in microhardness and a higher ultimate shear strength than unreinforced AA6061[67]. Similarly, addition of 0-4 wt% SiC to AA6061 enhances hardness and tensile strength of about 25 and 12% respectively, compressive strength about 12 %. These results point out the reinforcement fraction as an important component of property tuning. Similar trends are observed for studies of Al/ B_4C and hybrid systems. B_4C generally improves the hardness because of its inherent hardness, and also improves wear resistance [88] Comparative studies have shown that B_4C can achieve higher mechanical improvements than SiC amounts of equal weight, in particular when higher weight fractions are used. Hybrid composites with both SiC and B_4C or the addition of the secondary reinforcement such as graphite or TiO_2 can be used to alter specific mechanical responses. For example, hybrid compositions of 7.5 wt% each of Al_2O_3 and B_4C fracture strength is 154 MPa but ductility is reduced with increase in

the amount of the ceramic [34]. Although, these results highlight a fundamental design strategy in using strengthening materials that exhibit complementary reinforcements in order to balance strength and ductility.

The literature also shows a nonlinear behaviour between the content of reinforcement and the mechanical response. The volume fractions of higher weight generally increase tensile strength and hardness, excessive reinforcement can result in particle cluster and higher porosity, which can reduce the load-transference efficiency and mechanical integrity. In powder-metallurgy AMCs, the best wear resistance and tensile strength are only obtained at moderate levels of reinforcement, beyond which properties level-off or worsen as the result of poorer densification and homogeneity. Hybrid systems combining the ceramic with ductile reinforcements, such as TiO_2 , can yield an improvement in strength and elongation at the same time and it has been shown that some combinations can compensate for the embrittlement that is typical of ceramics reinforcement alone [120]. Remarkable are quantified mechanical benefits, gains, across AMC systems. SiC reinforcement can increase the hardness by 25% to 130% than the base alloys and demonstrate how strong the ceramic particle has on plastic deformation resistance. Tensile strength increments are also remarkable; the tensile properties of Al7075 composites reinforced with B_4C and coconut shell ash (CSA) show the strength of hardness approximately 33% and tensile strength approximately 66% compared with the base alloy. However, these improvements often result in a loss of elongation and ductility, which is a crucial element with regard to structural application. Overall, from the literature, AMCs can be considered as highly tenable materials in which the mechanical properties can be precisely regulated by the proper choice of the types and weight fraction of the reinforcement. Relatively, in spite of

advancements, some problems remain to be tackled: uniform distribution of particles, less interfacial defects, ductility and strength increase are some of them. Future research should focus on advanced processing methods with a goal to minimise the microstructural heterogeneities and to investigate new hybrid reinforcement systems with the combined strength and toughness characteristics for next-generation structural materials. Over the past two decades, researches of Aluminium matrix composites (AMCs) made from aluminium and its alloys have been mainly concentrated on enhancing mechanical performance of AMCs by the use of particulate and hybrid reinforcement strategies. Investigations with alloys such as AA2024, AA6061, AA7075 and cast alloys such as LM6/A356 show steady increases in tensile strength, hardness, impact and flexural strength compared to monolithic aluminium matrices. The amount of these gains varies with reinforcement type, weight fraction, particle size and processing route, pointing out the critical relationship between the design of materials and investigation of their mechanical performance.

Tensile strength improvements are made in AMCs most commonly by means of the addition of hard ceramic particles, which can be SiC, Al₂O₃, B₄C, TiC, as load-bearing phases and grain refiners. In the case of AA2024, the ultimate tensile strength (UTS) is increased by the addition of Al₂O₃ and SiC by promoting the transfer of load and blocking the movement of the dislocations. For instance, UTS increases from around 97.8 MPa (unreinforced) to about 125.2 MPa in hybrid composites of 0.5/0.5 to 2.5/2.5 wt% Al₂O₃/SiC with reinforcements [88], which is about 28% improvement. AA6061/SiC composites produced by stir casting exhibited the increase of 25.6% in tensile strength with 4 wt% SiC than that of the base alloy owing to homogeneous SiC distribution and high particle-matrix bonding [121]. Hybrid AA6061 composites

reinforced with B₄C and SiC result in UTS improvements in the range of 16-20% with the increasing of the reinforcement content, which indicates the synergistic effects at nanoscale. Broad reviews show that tensile strength is enhanced by increase in reinforcement content up to an optimum (10-15 wt%). Beyond this, particle agglomeration and porosity can cause a reduction in benefits. Finer particulates contribute to strength improvement owing to the contact of large surface area and the restraining of dislocation movement [91].

Improvements in hardness are regularly achieved in AMCs. Ceramic reinforcements the possibilities of plastic deformation. In AA2024 composites, both the Vickers hardness increases significantly, as the amount of Al₂O₃/SiC increases up from the base alloy [35]. A holistic analysis of AA6061 composites has found that with more SiC, Al₂O₃, and B₄C, hardness as well as tensile strength increases. For example, a AA6061/15 wt% SiC has more than 130% higher micro-harder compared to unreinforced alloy [88]. Hybrid composites such as based on TiB₂ and AlN have about 25% increase in hardness compared to single reinforcement [97]. Industrial Waste derived Reinforcements (Fly ash) has also been found to improve hardness on LM6 based composites; the introduction of fly ash gives rise to an increase in hardness of 88 % as compared to unreinforced alloys [122].

Flexural strength testing using three-point bending provides information about tensile and compressive behaviour under bending loads and shows the composite resistance to the bending deformation [123]. Hybrid composites are often observed to exhibit good flexural gains over monolithic alloys. Studies on AA2024 and LM6-based composites with agro - waste and hybrid particulate reinforcements provide flexural strength increase of 18-30 percent considering that wellness of reinforcement phases

impedes crack growth and delay the bending failure.[124] AA6061 composites with these two materials (SiC and Al₂O₃) and hybrid nano-reinforcements of two materials (B₄C/SiC) showed flexural enhanced modulus and strength, which proved that using hybrid reinforcement not only stiffens but also resists bending fracture.[42]. Flexural gains are also related to the microstructural refinement and lower porosity obtained by means of sophisticated processing routes like squeeze casting and electromagnetic stirring.

2.7 Tribological Behaviour of AMCs

The tribological performance of aluminium matrix composites (AMCs) determine the suitability of these composites for friction intensive applications such as the brake rotor in the automotive industry, the bearings and sliding mechanical interfaces in the aerospace industry. Monolithic Aluminium alloys exhibit a low wear resistance and high friction in sliding dry conditions due to the low hardness and adhesive wear. In comparison, AMCs reinforced with ceramic particulates (SiC, Al₂O₃, B₄C, TiC, TiB₂) and hybrid combinations with solid lubricants have significantly lower wear rates, and altered coefficient of friction (COF) profiles, across a number of different conditions [125].

Ceramic particles perform the role of load bearing phase. They reduce matrix deformation, encourage abrasive rather than adhesive mechanisms of wear and result in reduced overall wear rate. Reviews find composites that have SiC and Al₂O₃ wear faster than the unreinforced alloys due to their higher hardness and stable sliding surfaces [126].

AA7075 composites reinforced with SiC/BN nano powders based on friction stir processing showed an improvement of 53-61% of the wear resistance. Nanoparticles can perform better than millimetre scale particles in terms of better supporting contact stresses and inhibiting material removal. the use of SiC-graphite hybrid increased wear resistance by 78% and also changes of wear mechanism from frictional fatigue to abrasive/exfoliative [127].

Fly ash (FA) in AMCs also minimises wear volume at a constant load and speed. Coarse FA particles have better anchorage with the matrix and do not suffer from pullout unlike fine particles, which leads to lower wear. However, an increase of load and sliding speed normally increases the rate of wear due to increased plastic deformation and oxide film breakdown. This clearly highlights the necessity to optimise at the same time the reinforcement and the operating conditions [128].

COF in AMCs is a function of the type of reinforcing utilised, weight fraction, load and sliding speed. Uniform dispersion of SiC reduces the COF compared to the matrix alloy by reducing the adhesive interactions and fostering stable debris. COF increased with increasing SiC content but decreased with increasing sliding speed pointers to tribolayer formation and temperature effect [129].

Loading, velocity of sliding, and distance have a significant influence on wear rate and COF. Taguchi and ANOVA studies have always shown that the load is the most significant mechanism for wear followed by the distance and velocity. Generally, wear rate increases with increasing loads and speeds, whereas COF trends can be related to tribolayer formation, temperature increases and softening of the matrix. Under moderate conditions oxides and reinforcement induced hardness improves wear and friction; beyond critical loads/speeds matrix damage can be more damaging [130-132].

Aluminium alloys including AA2024, AA6061, AA7075, AA6082, LM27, LM25, are all research of tribology. Reinforcement always results in wear rate and COF reduction when compared with unreinforced alloys. The amount of improvement is dependent on alloy chemistry, the type of reinforcement and microstructural integrity from fabrication. For example, LM27 alloys with TiO₂ exhibit large reduction of wear rate at higher reinforcement level, which reflects the wide uses of ceramic particulates in aluminium series.

The best improvements are observed for hybrid AMCs that combine hard ceramics and solid lubricants (e.g., SiC/Gr, SiC/B₄C/CNT) or nano-scale reinforcements. In comparison with the single-phase reinforcements, these systems utilise wear rate and COF reductions simultaneously by enhanced load transfer, tribolayer formation and synergy mechanisms that stabilise sliding contact.

2.8 Thermal Properties of Aluminium Matrix Composites (AMCs)

Thermal management is very important in the design of modern composite materials for aerospace, automotive, electronics and energy systems.[133] Aluminium matrix composites (AMCs) are being studied for their thermal conductivity, coefficient of thermal expansion (CTE) and thermal diffusivity properties as these properties regulate heat dissipation, dimensional stability during temperature change and thermal stress in structural parts. Aluminium alloys generally present high thermal conductivity and moderate CTE values, but the additional presence of ceramic or carbon or even hybrid reinforcements will allow the modification of both properties according to the requirements. Thermal conductivity measurement (k) is a measurement of the appropriateness for conductive heat and matters with heat sinks, engine parts of automobiles, brake discs, electronic housings [134-135]. Pure

aluminium conducts electricity well by free transport of heat. When it is alloyed or reinforced, the second phase particles scatter the phonons and interfere with the electron pathways, making it less conductive. SiC reinforcement normally reduces thermal conductivity as compared to unreinforced matrices due to increase in scattering in the interface and the broken heat path; the amount of reduction is a function of particle size and distribution. For example, stir-cast Al MMCs containing 0-30 wt% SiC were found to result in changes in thermal diffusivity and conductivity that were measurable up to 500°C with the main heat transfer behaviour being governed by the metal-ceramic interface. Al/SiC/graphite hybrids also prove that small fractions of weight of SiC and graphite affect the k at room temperature to high temperatures. Low wt.% hybridise the thermal transport and material integrity. Graphite and other carbon reinforcements are capable of improving conductivity in preferential directions due to their high intrinsic conductivity and, in particular, because arranging the reinforcement in the form of flakes or networks improves the conductivity. However, overall composite behaviour and behaviour in relation to orientation and processing method [136-137]. Powder-metallurgy studies of aluminium and graphite composites showed that with increase of graphite volume fraction conductivity dramatically increased (e.g., 10-90 vol.% of graphite increases k from 324 to 783 W/m-K) and also CTE differs. Multiscale reinforcements such as multi-walled carbon nanotubes (MWCNTs) and graphene help to enhance the transport of phonons, which are important at low temperatures. It is possible at high temperatures that the interface scattering reduces the conductivity, and indicates complex temperature dependent transport of hybrid AMCs. CTE is an indicator as to how much a material is expanded or contracted by temperature changes, which is

essential for composites that are experiencing thermal cycling or are attached to different materials. Aluminium alloys normally exhibit CTE of about $20\text{-}23 \times 10^{-6} \text{ K}^{-1}$. Reinforcements having lower CTEs such as SiC, Al_2O_3 , B_4C and graphite have lower CTEs compared to aluminium matrix, thus, reinforcements reduce the dimensional stability of composite resulting in lower thermal stress mismatch. Hybrid composites with SiC and graphite indicate the improvement of dimensional stability with an increasing graphite content without dramatic variation in different particle sizes. Adding of SiC further reduces the expansion, in comparison to base alloy, due to constrained matrix expansion. Ceramics such as B_4C and oxides also perform well to reduce CTE in general, as the volume fraction of the reinforcing phase, and the particle size is reduced, the CTE of AMC will be reduced, but excessive amount of reinforcing phases will lead to the clumping and stress concentration. Key microstructural features - particle dispersion, interface quality, porosity and reaction phases Al_4C_3 have a strong influence on thermal behaviour. Porosity and heterogeneities cause the scattering of phonons and electrons which reduces the conductivity. Processing methods (stir casting, powder metallurgy, squeeze casting, spark plasma sintering) modification and manipulation of interfaces by alloying or coating could be used for by-passing these problems. AMCs intended to fulfil specific thermal applications-for brake discs, engine components and electronics packaging-need to combine conductivity with CTE to efficiently remove heat while maintaining dimensional integrity with loads. Ongoing advances in high temperature measurements and thermal transport modelling are paving the way to more accurate predictions and control of composite thermal behaviour, which is a critical requirement in applications of high-performance engineering applications [138-141].

2.9 Computational Analysis of Reinforced and Unreinforced Al-2024-Based Composites

Computational modelling has played a decisive role in elucidating the deformation, strengthening, and failure mechanisms of aluminium matrix composites (AMCs), particularly those reinforced with ceramic particulates. Early combined experimental-theoretical studies laid the groundwork for understanding microstructural evolution and mechanical response under service conditions.

The transition toward fully coupled experimental-computational frameworks was marked by the work of Li et al. [142], who developed a damage evolution model for discontinuously reinforced aluminium matrix composites. Their micromechanical simulations accurately predicted strain localization, particle cracking, and matrix damage accumulation, demonstrating that reinforcement volume fraction directly controls stiffness enhancement and failure strain reduction. This study quantitatively linked increased elastic modulus and tensile strength to effective load transfer, while also capturing the premature damage initiation at higher particle contents.

Finite-element-based micromechanical modelling was significantly advanced by Aghdam et al. [143], who simulated yield and collapse behaviour of metal matrix composites. Their results showed that increasing ceramic particle volume fraction leads to higher macroscopic yield strength--often by 20-40% depending on reinforcement geometry--but also intensifies local stress concentrations, ultimately limiting ductility. These findings were reinforced by multiscale approaches developed by Xia and Curtin [144], who demonstrated that damage evolution in aluminium matrix composites is governed by particle fracture and interface decohesion,

mechanisms that computational models can predict with high fidelity across length scales.

Although Cannillo et al. [145], focused on glass-alumina composites, their numerical fracture modelling provided transferable insights into ceramic-reinforced metal systems, particularly regarding crack deflection and toughening mechanisms. These principles were later applied to AMCs to explain enhanced hardness and stiffness alongside reduced fracture toughness at higher reinforcement contents.

Process-oriented computational modelling gained prominence with Ilie et al. [146], who simulated extrusion of Al-SiC composites using coupled macro- and micro scale methods. Their analysis demonstrated that reinforcement particles induce heterogeneous strain and residual stress fields, which directly influence post-processing mechanical properties. This observation aligns with later progressive damage frameworks for composites developed by Tay et al. [147], which emphasized the importance of incorporating stiffness degradation and failure criteria into numerical simulations.

Microstructure-based finite element modelling by Prabu and Karunamoorthy [148], quantitatively showed that particle-reinforced AMCs exhibit substantial increases in stiffness and strength--typically 25-50% improvement in elastic modulus and yield strength--depending on particle size and distribution. Their work confirmed that computational models can predict failure initiation sites with strong agreement to experiments.

Computational machining and tribological studies further expanded the application of numerical methods. Umer et al. [149], employed cohesive zone modelling to simulate machining of particle-reinforced AMCs, demonstrating that ceramic particles

significantly increase cutting forces and tool wear due to elevated local hardness. Kursun et al. [150], combined experiments and simulations for alumina-reinforced aluminium composites, reporting hardness increases exceeding 40% at moderate Al_2O_3 contents, while numerical stress analysis revealed increased brittleness at higher reinforcement levels.

Review-level syntheses by Abidin et al. [151] and Talreja and Varna et al. [152], emphasized that modern computational frameworks--ranging from micromechanics to continuum damage mechanics--are now capable of predicting stiffness enhancement, strength gains, and failure modes with high accuracy, provided that particle morphology and interface properties are explicitly modelled.

Recent studies have increasingly focused on quantitative prediction of strength improvements. Biswas et al. [153], combined experiments and finite element modelling to analyse compressive failure in in-situ Al-Mg₂Si composites, showing compressive strength increases exceeding 30%, with simulations accurately capturing particle-induced constraint of matrix plasticity. Balokhonov et al. [154], further demonstrated that residual stresses around carbide particles significantly influence yield strength and fracture behaviour, with numerical models predicting up to 25% variation in strength depending on residual stress state.

Advanced computational frameworks have also been applied to fibre-metal laminates and hybrid composites. Thomas et al. [155], provided a comprehensive computational review showing that numerical models reliably predict stiffness and strength improvements of 20-50% in laminated aluminium composites. Farid et al. [156], specifically quantified the strengthening effect of TiC reinforcement in aluminium matrices, demonstrating via coupled experimental-computational analysis that 5-10

wt% TiC yields hardness increases of approximately 30-80% and tensile strength improvements of 20-40%, attributed to grain refinement and effective load transfer captured in simulations.

State-of-the-art reviews by Bhuvaneswari et al. [157], highlighted the increasing role of simulation-driven design in composites, while recent multiscale optimization studies by Shaquib et al. [158], demonstrated that fly-ash-reinforced AMCs can be computationally tailored to achieve balanced improvements in stiffness, wear resistance, and thermal stability. Kumar et al. [159], applied numerical wear models to hybrid AMCs for piston applications, reporting wear rate reductions exceeding 40% with reinforcement addition, closely matching experimental observations.

Finally, digital materials modelling tools such as DIGIMAT have enabled rapid parametric studies. Votarikari et al. [160], showed that computational homogenization predicts increases in elastic modulus and yield strength of 15-35% depending on particle type and volume fraction, confirming the reliability of virtual material design for AMCs.

Concluding Synthesis Collectively, these studies demonstrate that computational analysis has evolved from qualitative interpretation to quantitative prediction of mechanical property enhancement in aluminium matrix composites. Across a wide range of reinforcements and modelling approaches, numerical simulations consistently predict stiffness, hardness, and strength improvements ranging from 20% to over 80%, while also identifying critical trade-offs such as reduced ductility and increased stress concentration. These findings firmly establish computation-driven design as a cornerstone for the optimization of next-generation aluminium matrix composites.

AA2024 composites are known for having a high strength to weight ratio and a wide range of applications in the aerospace and automotive industries. Computational modelling has become crucial for unravelling the mechanisms of deformation, predicting the mechanical property enhancement, and for the optimal design of the microstructure for AA2024 composites. Numerical simulations provide an accurate value of the effects of reinforcements on hardness, yield strength, fatigue life, and impact resistance. Early studies of fibre and particulate reinforced with matrix AA2024 focused on the improvement of wear resistance and strength. Naplocha et al. [161], found that the use of fibre reinforced AA2024 decreases the material loss during dry sliding, while the computational models of wear show an accurate prediction of stress distribution depending on the load, and that this corresponds to the observed reduction of the wear - of up to 70 %. Rao et al. [162], researched on AA2024 with fly ash particles and found 15-25% improvements in the yield and tensile strength, which was supported by simulations of effective load transfer from the matrix to the particles. Shabani et. al. [163], have performed computational optimization on cast AA2024 composites and have found that the presence of low-volume fractions (5–10 wt%) increases the hardness by 30-50% and tensile strength by 15-30%. Higher fractions, result in focusing of stress and there is a possibility of ductility loss. Their models indicated various optimal intermittent structures for reinforcement, which maximised controlled microstructure for maximum performance. Failure mechanisms of bolts in bolted joints and complex structures have been explained by the finite element analyses. Fallahnezhad et. al. [164], provided a double-lap bolted AA2024-T3 joint modelling performed by showing a maximum stress in any fastener holes of more than 250 MPa for single fasteners. Simulation results were consistent with experimental

crack initiation sites, and implied that the use of matrix reinforcement may reduce the local stress peaks by as much as 20%. Electro - discharge machining of particulate reinforced materials AA2024 was studied by Daneshmand et. al. [165], Their simulations predicted hardness increases of a 40% and altered heat affected zones with 7.5 Wt% Al_2O_3 , which matched the value of a 30 to 35 percent reduction in surface wear observed experimentally. Computational parametric studies were employed in order to optimise EDM parameters in terms of surface cracking and tool wear. The particle fracture and fatigue were extensively modelled. Wisner et. al. [166], were able to quantify particle induced stress concentrations under cyclic loading conditions and found that 5-10wt% of ceramic reinforcement increased fatigue initiation stress by 15-25% but decreased elongation by 20-30%. Shin and Bae et al. [167] obtained 25 to 40 of fatigue life improvement using multiple walled carbon nanotube reinforcement that was verified through crack growth simulations. Mazlan et. al. [168], took this one step further to high temperature cases, showing a reduction in fatigue life by 20-35% for AA2024-T3. good prediction of the crack propagation rate using numerical models. High strain rate and impact behaviour was studied through analytical and finite element methods. Gara et al. [169], simulated high-speed impact on AA2024 and the results indicated a good agreement with the experimental results in predicting stress and strain distributions and a 15-20% increase in the energy-absorbing capability of the reinforced alloys. Balokhonov et al. [170], using polycrystalline simulations have determined that residual stress heterogeneity can alter local yield strength by a significant amount (up to 25 convexity) which affects the initiation of fracture. Fragmentation under extreme strain rates was further investigated by Gara et al. [171], demonstrating the accurate prediction of crack coalescence and particle breakage by

numerical models with an increase of strain localization of 10%-15% in microstructurally heterogeneous areas. Additively manufactured AA2024 also has the advantage of being computer microstructurally designed. Gairola et al. [172], estimated a 20-30% decrease in the fatigue-crack growth rates and 15% increase in the fracture toughness using micro-informed finite element models. Nanocomposite reinforcement with TiO₂ has been made successfully analysed numerically. Mahan et al. [173], found that 2 -5 wt% TiO₂ nanoparticles can increase the hardness of the material by 35 - 50 wt% and the yield strength by 20 - 30 wt% that can be attributed to particle-induced dislocation pinning and decreased local plastic strain. Farid et al. [174], reported a 30 to 80 wat percent increase of hardness and a 20 to 40 wat percent increase of tensile strength with 5-10 wt% TiC indicating successful transfer of loads and grain refinement actions that were predicted by simulations. Finally, ballistic simulations by MK et al. [175] showed that multi-layered AA2024 has 15-25% more energy-absorber capability than monolithic plates. Their models predict stress wave propagation and sequence of failure with high fidelity and hence value of computational analysis in the design of AA2024 structures for extreme mechanical loading applications, including aerospace and defence applications.

2.10 Historical Development of hybrid aluminium matrix composites (HAMCs)

HAMCs are innovative matrix materials that are being used in aerospace and automotive industries to provide a lightweight solution that is combined with high strength [176]. Among the manufacturing techniques, stir casting is highly appreciated by its simplicity and cost-effectiveness [177]. Generally, HAMCs are made through one of the following: a) solid-state processing (diffusion bonding, powder metallurgy,

physical vapor deposition) b) liquid-state processing, c) in situ processing. Researchers have found stir casting to be the most successful of such techniques [178]. Key process parameters melting temperature, stirrer speed, stirring time, stirrer position and reinforcing movement, stirrer design, die preheat, reinforcement choice, etc. are some of the process parameters that need to be optimized since they determine the final properties of the composite [179].

Reinforcements have a significant influence on the composites, such as strength, toughness, and wear resistance, and while fabrication is an issue, it involves the uniform dispersion of particles and minimization of defects [180]. During the past two decades, there has been significant development for aluminium matrix composites (AMCs). numerous researchers have offered some solutions to overcome these limitations. One is to reinforce the AMCs with agricultural and industrial waste, which created improvements in performance when compared with unreinforced composite materials [181]. A second approach involves the use of nano and micron-sized particles (approx. 50 micrometres to 100 nanometre) which improve strength, ductility and fracture toughness [182]. The disadvantages of this method are the shortage of suitable nanoparticles, insufficient wear resistance and non-economical production. The third strategy presents high-performance HAMCs consisting of composite materials composed of nano, micro and macro particles combinations, which provide a less mixing cost than the single reinforced developed AMCs [183]. HAMCs also substitute synthetic ceramic reinforcements with industrial and agricultural waste, which is cost-effective and has a smaller impact on the environment [184]. These composites have been viewed as promising for allowing the demands of high-end engineering applications to be met. To prepare AMCs exhibiting desired properties

fairly dispersion of the reinforcements in the aluminium matrix and the optimal process parameters are the keys [185]. Nonetheless, some studies have been done in the frame of single reinforcement AMCs aiming at improving mechanical and tribological performances [186]. In order to further improve these properties, more than one reinforcement can be added to a single matrix, i.e., Al. Common wear mechanisms experienced in AMCs are mild abrasive wear, oxidative wear, delamination and severe plastic deformation. To overcome the shortcomings of the single reinforcing system, hybrid aluminium matrix composite (HAMC) has been designed by incorporating two or more synthetic reinforcements in the aluminium matrix [187]. Many technical areas - such as aviation, automotive, optics, antennas, advanced electronics and precision instruments - require dimensional stability and sufficient mechanical strength. High thermal conductivity with low density is also an important requirement for good thermal management for electronic applications [188]. Strengthening in these materials is due to the load transfer, dislocation pinning and Orowan mechanisms. Though promising in aerospace and automotive industries as well as biomedical engineering, single-reinforcement AMCs with low reinforcement content cannot provide the best possible combination of properties [189].

In recent decades, the wastes generated in industrial and agricultural processes such as graphite, fly ash, red mud, ash of bamboo and rice husk, leaf ash, bagasse ash, maize stalk ash, palm kernel shell ash, and coconut shell have been included in research works. These wastes, if used judiciously, do not have a negative effect on the composite's properties while contributing to sustainability., which provide a way to achieve sustainable alternatives to synthetic ceramics. Dual synthesis ceramics, however, have a tendency of making composites less ductile and more brittle, thus

resulting in more roughness on the surface during machining and weight due to density mismatch between particles and matrix [190]. In addition, synthetic ceramics are known to difficult abrasives that are expensive. Using agro-wastes is the solution to overcome these issues, and at the same time reduces the amount of environmental pollution. In the ex- situ method, the reinforcements are added to molten metal, under this condition of poor wettability and particle agglomeration is expected. Studies shows the addition of reinforcement improves mechanical properties over the original as-cast alloy, but at a certain point, excessive clustering decreases performance. Conventional stir casting is popular because it makes such clumping easily and this is a major drawback. Ultrasonic treatment of the melt after the mechanical stirring process has been used to reduce agglomeration, which improved the particle distribution. [191].

As a result, non-uniform distribution of reinforcement is achieved due to uneven mixing. The in-situ method, in which reinforcement is formed by an internal chemical reaction, eliminates these issues well. When selecting reinforcements for a particular application, consideration must be given to factors such as force, temperature, particle load, sliding speed, sliding distance and opposing surface hardness as this has a critical effect on the durability of composites [192]. Understanding the relationship between these elements and morphology and wear processes allows accurate determination of aluminium MMC wear performance. This review is focused on the fabrication of aluminium metal matrix composites (MMCs) by all the methods currently employed and analyses the influence of the fabrication method on the wear behaviour and mechanical characteristics of various reinforcements in the aluminium matrix are the subject of continuing investigation. The microstructure of diverse composites is

discussed in detail, keeping in mind the refinement of grains. The review also discusses the complex use of aluminium. MMCs, the many challenges faced as well as proposing solutions to such issues.

2.11 Stir Casting Technique for Aluminium Metal Matrix Composite

The effectiveness of MMCs is largely determined by their fabrication process. There are many processing methods for the development of composite such as casting, stir casting, powder metallurgy, squeeze casting, infiltration and additive manufacturing. Among them, the most inexpensive and scaled-up technique of producing aluminium-based MMCs is the stir casting technique as shown in Figure 2.4 primarily to create an automotive and aerospace parts [193]. The stir casting process may be affected by low processing parameters between the matrix and reinforcement necessitating good optimization of processing otherwise reinforcement agglomeration, porosity take place [194]. Gas injection and stir-casting method was developed to prepare the graphite composite and found that developed composite had the better mechanical properties than monolithic alloy [195]. These composites exhibited good tensile strength and hardness due to high SiC content. Another research work was performed to predict the mechanical properties of aluminium based composite by simulation and numerical methods [196].

A mechanical stirrer was used for mixing of Al_2O_3 reinforcement and Al-6061. The developed composite had superior mechanical properties than the matrix metal. Tee et al. Produced an Al/TiB₂ composite prepared by stir casting in argon atmosphere [197]. Metallurgical investigations revealed the fair distribution of scattered particles. Stir

speed effects were investigated during AMC production [198] and suggested that constant stirrer speed is better to avoid defects

The ultimate tensile strength (UTS) was found to increase using stirrer speeds of up to 300 rpm. At such conditions, the addition of BLA gave an increase of hardness and tensile strength of 4% respectively. fabricated SiC/Al-6061 AMCs using stir-casting technique and investigated the effect of SiC on the mechanical characteristics. The study revealed that the composite having 15 wt.% SiC enhanced the ultimate tensile strength by 65.2% and micro hardness by 133.3%, to the base matrix [199-200.] Computational modelling and simulation ensured the correlation of several factors involved in the process such as blade number and stirring velocity in stir-casting.[201] A detailed computer model examined the effect of feeder on the fabrication of AMC Reinforcing particles were applied by improved funnel type feeding mechanism and a

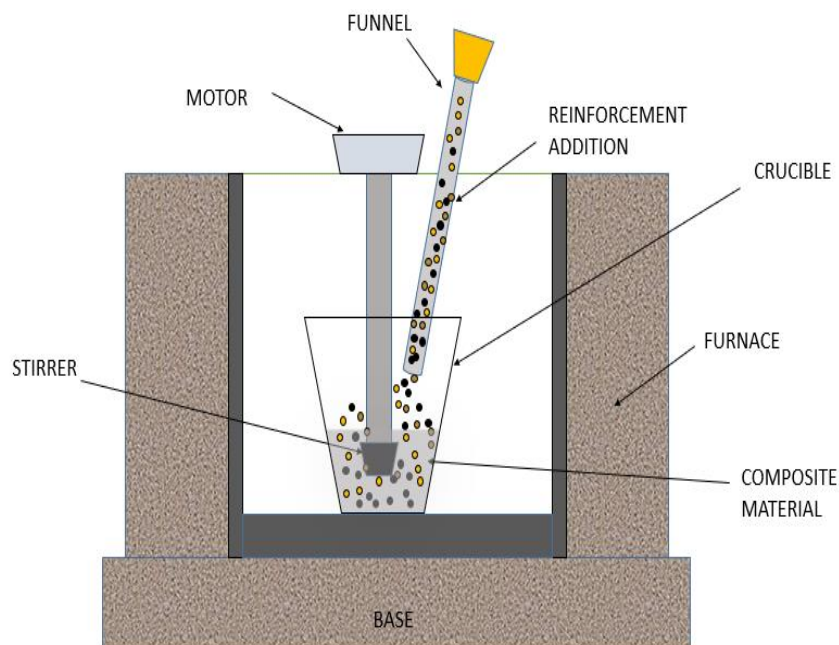


Figure 2.4 Line diagram of a conventional stir-casting set-up

stirrer to ensure relatively fairly distribution of reinforcement into the molten base

metal. In a separate research Stir Casting method was used to develop AMCs using Fly Ash Reinforcement (2, 4, and 6 wt %). Tribological test with AMCs containing 6% fly ash showed low wear rate while the 4 percent fly ash composite exhibited low coefficient of friction [202]. A detailed investigation showed that the stirring intensity and times had major influences on the agglomeration, inclusions and oxidation of pure Al and TiB_2 compounds. SiCp addition lead to the decrease of dendrite length and the increase of nucleation frequency, which lead to the increase of tensile strength [203]. Vacuum moulding assisted stir-casting used by Singh et al. [204] was employed to produce Al-6063 based SiC reinforced composites by optimizing the process parameters to enhance the wear characteristics. Kannan et al. [205] used stir and squeeze casting for the preparation of SiC/Al7075 and SiC/ Al_2O_3 /Al7075 composites and compared and deliberated the properties. The UTS enhanced was attributed to two factors: improved bonding between the reinforcing and molten aluminium and chemical protection of the fibres. Another work has also been carried out with a thermo mechanical simulator to simulate the isothermal compression on SiC/Al6061 composites manufactured by squeeze casting [206].

The reciprocating wear experiments exposed that the wear resistance of composites was increased by 20-40% with the increase of the reinforcement and decreased with the increase of the wear parameters. Bembalge and Panigrahi fabricated bulk ultrafine grained (UFG) AA6063/4(wt.%SiC) composite sheets using hybrid technology combining stir casting and cryo-severe plastic deformation. The sheets contained SiC reinforcements of various sizes. Reinforcements were as small as: 1nm, 12nm and 45nm. In these UFG composites, the effectiveness of cryo-rolling and the particle size resulted in microstructural refinement with all the UFG grains obtained less than 350

nm. The refinement resulted in a high dislocation density with a great improvement in tensile strength. Specifically, tensile strength increased by 88%, 108% and 141% compared to the un-reinforced alloy, according to SiC particle size [207].

Sambathkumar et al. [208] used a two-stage casting route to manufacture AA7075 HMMC reinforced with nano Al_2O_3 and the micro fibre coconut shell ash resulted appreciable enhancements in mechanical nature. Pazhouhanfar and Eghbali produced Al6061 based composites with 3, 6, and 7 weight percent of TiB_2 by stir casting and investigated the mechanical performance and microstructure. Tensile testing revealed an increase in the ultimate tensile strength to 257 MPa after 9 wt.% TiB_2 addition; an increase of 29.2 percent compared to base alloy [209].

Stir-casting parameters affect the mechanical behaviour of AMCs. While a large number of studies have been conducted on the stir casting process, there are very few that have optimized the parameters of stir-process. This study aims to develop hybrid composites and find the best values of the parameters to enhance Ultimate Tensile Strength (UTS), Hardness (HN), Impact Strength, Flexural Strength and Wear Rate of the developed composites. There were parameter levels that were tested in order to identify the combination that will show the best performance.

Reinforcement size: In stir casting, the particle size is one of vital parameter that affects the strength of the material. As a general rule of thumb, the smaller the particles size there was an improvement in the mechanical properties however the proper mixing of the fine or smaller was difficult [210-211]

Stirring speed: Stirring helps in distributing the reinforcement particles in the matrix and follows the viscosity of molten aluminium. The viscosity has to be good: too high, the particles found it difficult moving; too low, the particles could not be suspended.

Increased speeds result in an increased spacing between particles. Exact stirring speeds cannot be mentioned because they are dependent on the geometry of the stirrer blades [212].

Stirring time: Impact on particle dispersion: To make a dispersion homogeneous is important to ensure good mechanical performance. An increased stirring time results in a more fairly distribution and optimal particle separation. However, no such optimum value are specified it may be differ for different condition [212-213].

Melting temperature: The viscosity is reduced, which may not be desirable at high melting temperature however the wetting ability of the molten matter enhanced. At the low melting temperature, there is a particle agglomeration. For this reason, it is essential to maintain a suitable melting temperature [32-214].

Reinforcement and mould preheating temperature: Reinforcement and mould preheating temperature has a great effect on the MMC characteristics. Before pouring the reinforcement materials into the molten matrix it kept for the preheating in muffle furnace at controlled temperature, the preheating temperature was varied for reinforcement to reinforcement. At 300°C, the form factor drops dramatically, resulting in reduced performance. Mould temperature that is too low results in cold shut defects and poor mechanical quality. Extremely high temperatures of dies negatively impact the working environment and diminish productivity [213].

Stirrer blade Geometry: Mixing of the reinforcement particles and matrix material also depend on the blade design. The impeller or blade design was very important in creating a vortex and ensuring good melting. To reduce a reaction between the stirrer made of stainless steel and matrix material (Al alloys) at high temperatures, stirrer blades coated with zirconia [215-216].

2.12 Identified Research Gaps

From the archival literature review following research gaps have been identified.

- Waste materials offer potential as alternative reinforcements to enhance base material properties, though their application in developing MMCs for specific uses remains underexplored.
- Several studies suggest that combining waste materials with ceramic particles can enhance base material properties, yet the individual contribution of each reinforcement still requires detailed investigation.
- It has been observed that very few researchers utilized Waste glass powder along with TiB_2 in the development of an aluminium-based hybrid composite.
- The Process parameters of stir casting still needs the optimum solution to get the MMCs with negligible defects.
- The wear performance of materials for specific applications involving metallic contact remains insufficiently explored and requires further detailed investigation.

2.13 Research Objectives

- Development of TiB_2 + Waste glass powder + Nano CuO particles reinforced metal matrix composite with AA2024 aluminium alloy matrix by Stir Casting and its Characterization.
- Investigation of Mechanical, Wear, and Thermal properties of developed composite material.
- Investigation of failure behaviour of developed composite material and its computational analysis.

Chapter 3 Materials and Methods

3.1 Matrix Material

Aluminium Alloy was chosen as a matrix material, in view of their extensive use in the production of various components used in Aerospace, Missile, Defence Sports Equipment Automotive Medical and Marine industries [217-218]. Aluminium 2024 is considered a Matrix in this current study. In the 2000 aluminium Series, the widely used material is AA2024.

Table 3.1 Chemical composition of AA2024 is as follows:

Component	Al	Cu	Mg	Si	O	Ca	Fe	Na	Ti
Weight Percentage (Wt. %)	90.8	4.1	1.4	0.5	2.4	0.1	0.4	0.2	0.1

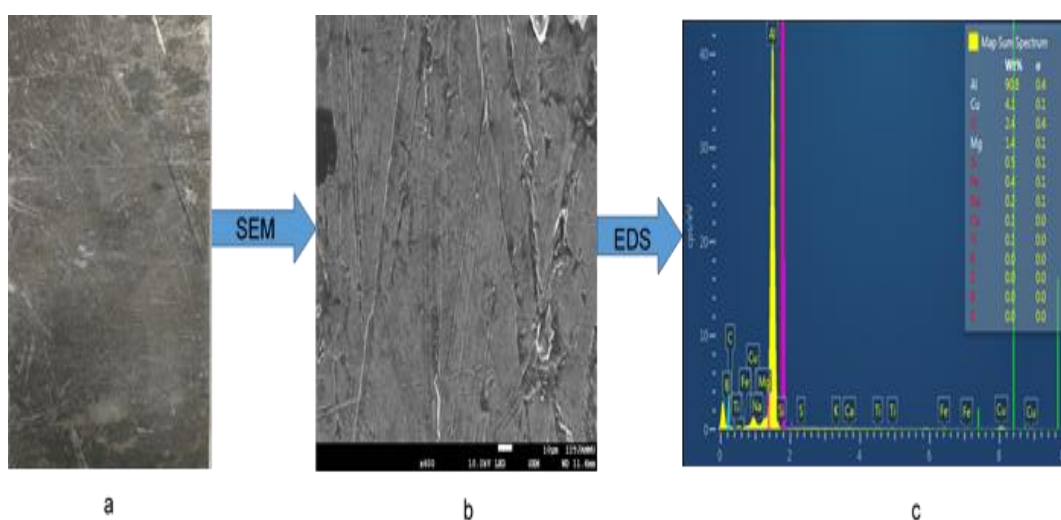


Figure 3.1. a) Matrix Material AA2024 b) SEM Image of AA2024 and c) EDS Result of the Matrix Material

Lightweight, high-strength, efficient & economical components are required to produce in Aerospace and automobile industries, due to increased fuel costs day by day as well as emission norms. The higher amount of tension as well as fatigue have been faced by aircraft wing, and fuselage structure, are manufactured by using AA2024 [219]. Table 3.1 and Figure 3.1 a) Matrix Material AA2024 b) SEM Image of AA2024 and c) EDS Result of the Matrix Material the Shows chemical composition respectively.

3.2 Reinforcements

AMCs are being developed using different type reinforcement materials and fabrication techniques. In the present study, three reinforcements we have explored TiB_2 , Nano-CuO, and Waste glass powder composites. Each reinforcement has its own advantages: TiB_2 enhances the oxidation stability and corrosion resistance; Nano-CuO enhances the wettability of silica in the Al matrix which leads to better mechanical performance; crystalline silica enhances hardness and strength; and Waste glass powder adheres well on Al which also strengthens and hardness the matrix [220-221]

3.2.1 Titanium Diboride (TiB_2)

Due to the exceptional properties of TiB_2 , it is considered a primary reinforcement in the development of AA2024-based composite material. The hexagonal crystal structure of the TiB_2 makes it suitable for both functional and structural applications, also it exhibits excellent thermal and electrical properties. The presence of TiB_2 in the composite material improves the thermal stability and refractoriness, which is desired for high-temperature applications [85-86]. The strong interfacial bonding and high stiffness with the matrix material permit efficient load transfer, grain refinement, and

resistance to plastic deformation, making it a prominent reinforcement for high-performance applications [87, 222]. Chemical Composition of TiB₂ and SEM & EDS micrograph for TiB₂ reinforcement particles mentioned in table 3.2 and depicted in Figure 3.2 respectively.

Table 3.2 Chemical composition of TiB₂ is as follows:

Component	Ti	C	O	Nb	Pt	Zn	Cu	Others
Element Weight	39.4	25.8	21.2	6.1	4.1	1.8	1.5	0.1
Percentage (Wt. %)								

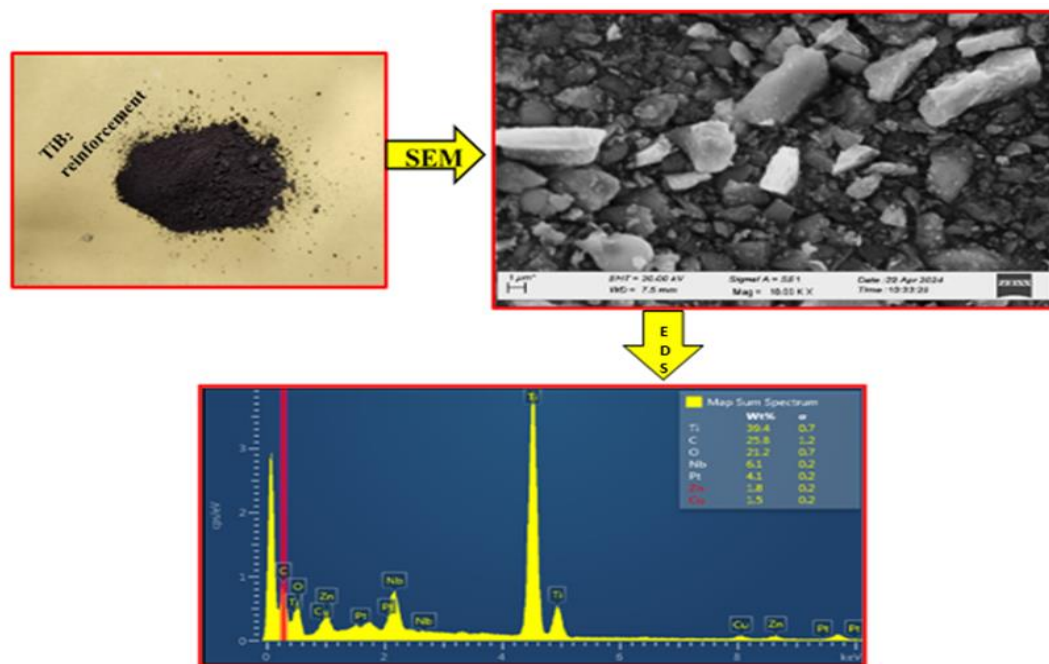


Figure 3.2. SEM and EDS micrograph for TiB₂ reinforcement particles

3.2.2 Copper Oxide (CuO)

Copper Oxide (CuO) is an inorganic compound used as a secondary reinforcement in MMCs to improve thermal conductivity, oxidation resistance, and tribological performance. It also plays a role in enhancing the dispersion of primary ceramic

particles in the metal matrix. CuO is relatively soft compared to ceramic reinforcements but helps form oxide films during wear, reducing the coefficient of friction [220,223]. The Chemical composition of CuO and SEM & EDS micrograph for CuO reinforcement particles depicted in table 3.3 and Figure 3.3

Table 3.3 Chemical composition of CuO is as follows:

Component	C	Cu	Nb	Pt	Others
Element Weight	72.9	11.6	9.7	5.7	0.1
Percentage (Wt. %)					

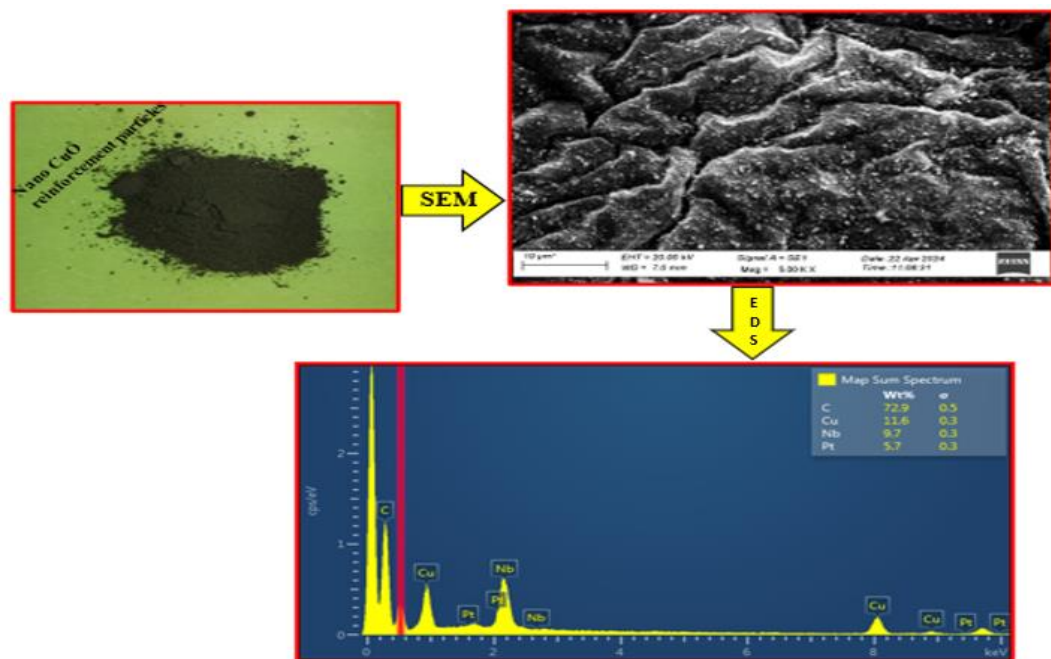


Figure 3.3 SEM and EDS micrograph for CuO reinforcement particles

3.2.3 Waste Glass Powder

Waste glass powder (commonly soda-lime or borosilicate) is increasingly used as a cost-effective, eco-friendly reinforcement in aluminium and polymer composites. It is derived from recycled glass, making it a sustainable additive. Glass powder enhances

hardness, wear resistance, and thermal insulation, but its brittleness must be managed during processing. Glass powder reinforcement in AA2024 composites increases hardness and wear resistance by acting as a rigid filler that impedes dislocation motion. Its low density contributes to lightweight composites, though excessive content may cause brittleness. Glass powder improves composite stiffness while maintaining cost-effectiveness and environmental sustainability in material design [116,117]. The Chemical composition glass Powder and SEM and EDS micrograph for Glass Powder reinforcement particles depicted in table 3.4 and Figure 3.4 respectively

Table 3.4 Chemical composition of Glass Powder is as follows:

Component	O	Si	Al	Nb	Fe	Pt	K	Ti	Ca
Element Weight	66.1	15.9	11.8	2.4	1.5	0.9	0.6	0.5	0.3
Percentage (Wt. %)									

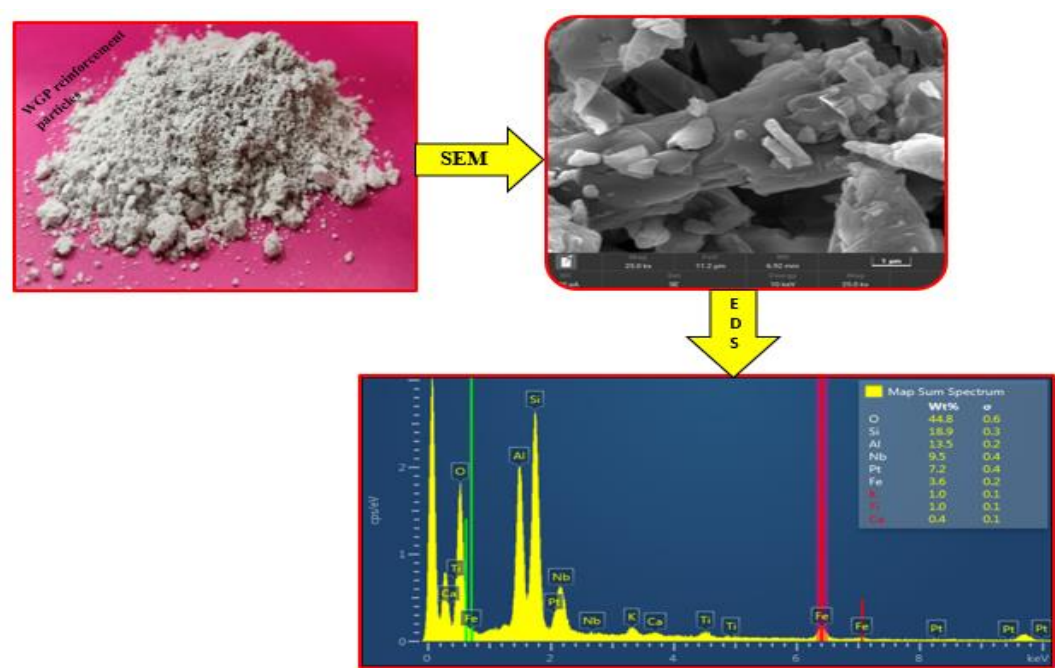


Figure 3.4. SEM and EDS micrograph for Glass Powder reinforcement particles

3.3 Fabrication Method

For the development of the AA2024 composite material, stir casting as shown in Figure 3.5 and Figure 3.6 Step-by-step process of fabrication of composite material has been considered as one of the suitable techniques due to its low cost and fairly distribution of the reinforcement particles. AA 2024 matrix material was cut into small pieces and melted in the furnace between 700°C to 750°C[72]. The electric muffle furnace having a ceramic/graphite crucible. Preheating of the reinforcement at 200°C for 20–40 minutes in a muffle furnace is essential to reduce the surface moisture, enhance wettability, and minimize the risk of gas porosity or interfacial debonding within the composite before pouring into the molten metal. Stirrers at a speed of 400 rpm were used for mixing the matrix material and reinforcements for 10-12 Minutes [179,224]. Due to the movement of the stirrer vortex is generated into which preheated reinforcement particles are gradually poured into the molten matrix. In this way, try to fair distribution of the particles is ensured with minimum agglomeration. To eliminate the dissolved hydrogen and other gaseous impurities from the melt, nitrogen gas is introduced. It will help to reduce porosity in the developed composite. Finally, the mixed molten melt pours into the preheated metallic mould at 150-200°C. Preheated mould reduces the thermal gradient as well as minimizes the residual stresses [221,225]. Total 7 Samples has been casted as per combination shown in table 3.5. The stir casting technique relatively simple and cost-effective as compare other available techniques allows for the fabrication of high-performance hybrid composites with enhanced mechanical and tribological properties. The process variable such as stirring speed, preheating temperature stirring time, stirrer blade design and melting

temperature, play a critical role in determining the microstructural uniformity, interfacial bonding strength, and mechanical performance of the resultant composite.

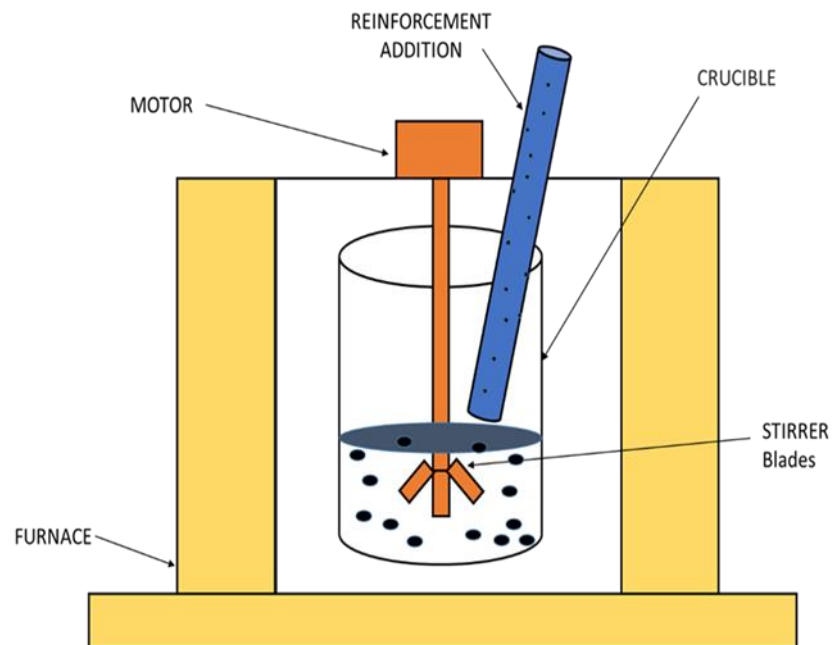


Figure. 3.5 Schematic Diagram of Stir-Casting Process set-up

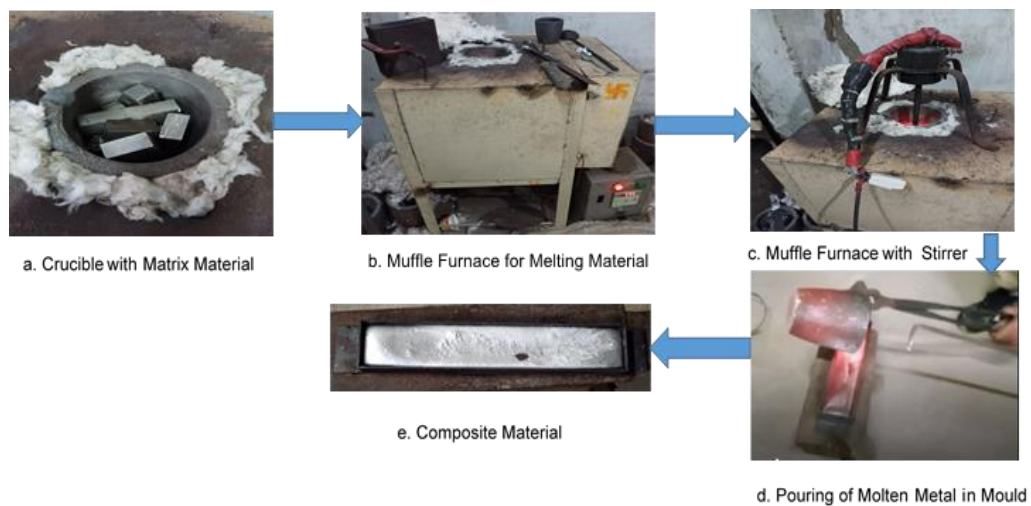


Figure 3.6 a to e Step-by-step process of fabrication of composite material

Table 3.5. Composition of Fabricated Samples

S. No.	Composite material compositions	TiB ₂ weight percentage (wt.%)	Glass Powder Weight percentage (wt.%)	Nano-CuO weight percentage (wt.%)
1.	Composition 1(Base Metal)	0	0	0
2.	Composition 2	7.5	0	0.25
3.	Composition 3	6.25	1.25	0.25
4.	Composition 4	5	2.5	0.25
5.	Composition 5	3.75	3.75	0.25
6.	Composition 6	2.5	5	0.25
7.	Composition 7	1.25	6.25	0.25
8.	Composition 8	0	7.5	0.25



3.4 Experimental Procedure

3.4.1 Tensile Testing

Tensile testing specimens of AA2024 based hybrid composite material were prepared as per the ASTM standard E08 [226] to investigate the Mechanical Properties and the effect of reinforcements (TiB₂, Nano CuO, and Waste Glass powder). Further the standard sample were prepared with the help of a Wire cut EDM Machine to achieve the dimensional accuracy. Emery paper and acetone were used to cleaned or remove the surface dirt, which may affect the test accuracy. Tensile tests were conducted on an Tinius Olsen 100ST Universal Testing 100kN as presented in the Figure 3.7a. Electromechanical extensometer for strain measurement were used. The experiments were performed under the following conditions: temperature maintained ($25 \pm 2^{\circ}\text{C}$) and at a constant strain rate of 10^{-3}s^{-1} . samples as presented in the Figure 3.7 b and c were tested from each casted composite and the average values were reported to ensure

statistical consistency. The test yielded values for UTS, yield strength (0.2% offset method), and percentage elongation. The incorporation of TiB_2 enhanced the load-bearing capacity of the matrix due to its high stiffness and interfacial bonding. CuO and glass powder acted as secondary reinforcements, contributing to grain refinement and hindering dislocation motion.

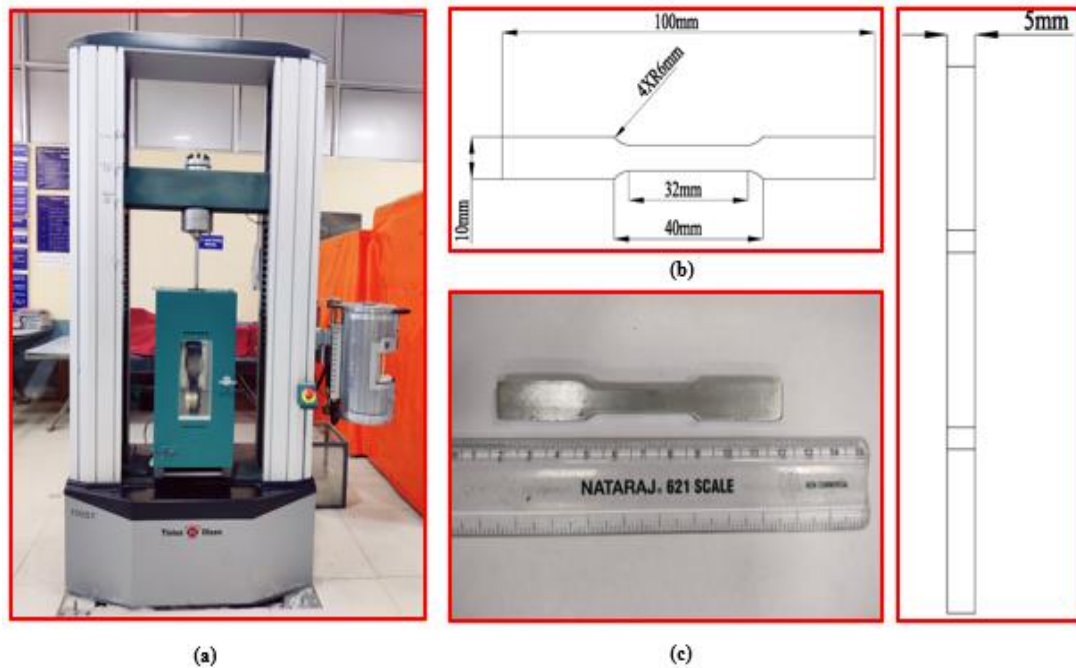


Figure 3.7 (a) Universal testing machine, (b) Line diagram of Tensile test specimen c) Prepared samples along with scale

3.4.2 Hardness Testing

The surface hardness of AA2024 and hybrid composites was evaluated using the Vickers microhardness test as shown in Figure 3.8 a. Specimens as presented in Figure 3.8 b and c were cut from the cast samples as per ASTM standard E18[227] and polished using successive grades of emery paper, followed by fine polishing with diamond paste to produce a smooth, defect-free surface suitable for accurate indentation. Hardness measurements were performed using a Tinius Olsen Vickers

microhardness tester. A 0.2 kgf load was applied for a dwell time of 15 seconds. Testing was conducted under controlled room temperature ($25 \pm 2^\circ\text{C}$) and dry conditions to maintain consistency. five indentations were made on each specimen, spaced adequately to avoid interaction of plastic zones, and the average Vickers Hardness Number (VHN) has been evaluated.

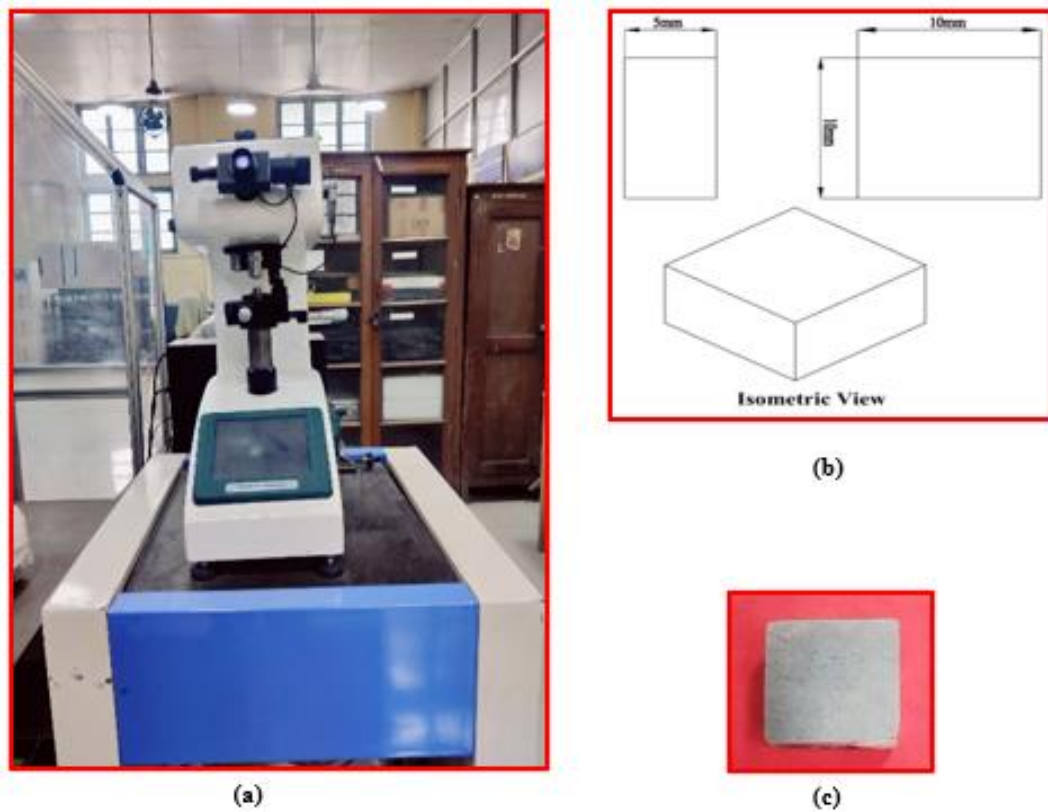


Figure 3.8 (a) Hardness Testing machine, (b) Schematic diagram of Hardness test specimen c) Prepared samples

3.4.3 Impact Testing

AA2024 composites reinforced with TiB_2 , CuO , and Waste glass powder was evaluated using the Charpy impact test, following ASTM E23-18[228] standards. Specimens were machined into standard V-notched rectangular bars measuring $55 \times 10 \times 10$ mm. The notch was carefully machined to ensure consistent stress concentration. Testing was performed on a Walter + Bai Ag Impact Tester as presented

in Figure 3.9 a at room temperature ($25 \pm 2^{\circ}\text{C}$) under dry conditions. Three sample as presented in Figure 3.9 b and c were tested from each casted sample and the average impact energy.

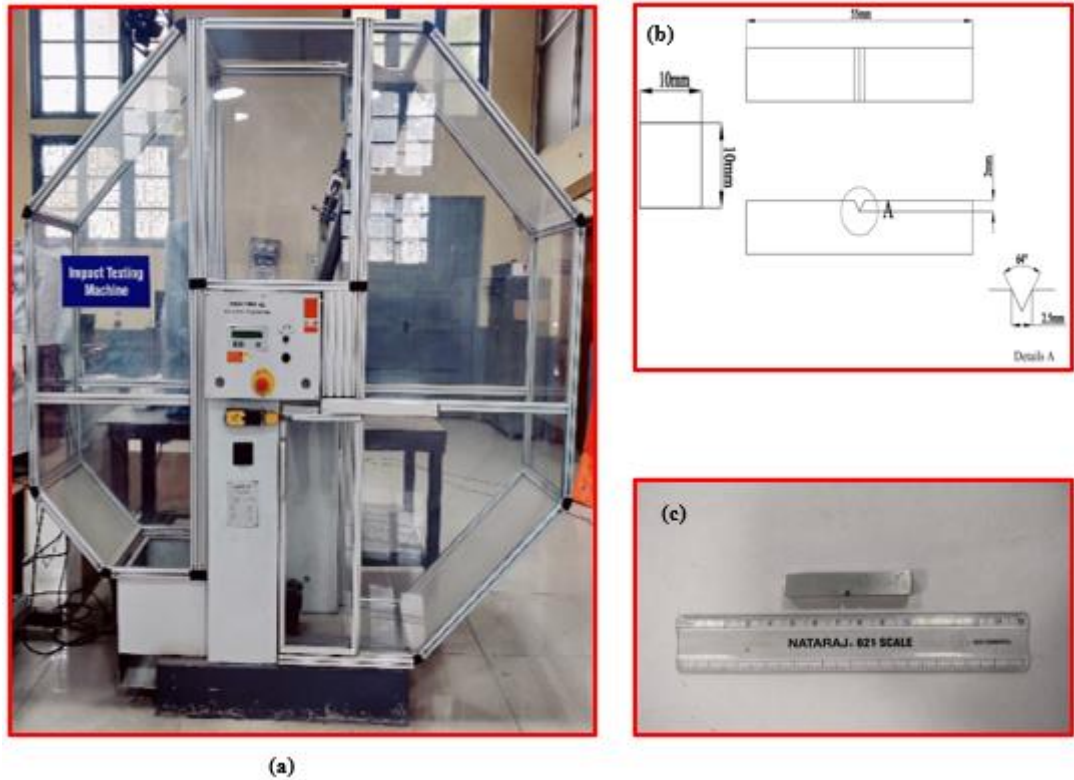


Figure 3.9 (a) Impact testing machine, (b) Schematic diagram of impact test specimen c) Prepared samples along with scale.

3.4.4 Flexural Strength

The 3-point bending test of developed composite material compositions have been performed on a universal testing machine with special attachments by utilizing the ASTM E290[229] standard. The specimens with the dimension $70 \times 7 \times 1.75$ mm as shown in Figure 3.10 was tested at room temperature. The schematic diagram of the specimen diagram of 3-point bend testing is mentioned in Figure 3.10 b. The following equations were used to evaluate the flexural strength of each sample.

$$\text{Bending stress } (\sigma) = \frac{(M \cdot y)}{I} \dots \dots \dots (1)$$

$$\text{Moment of Inertia}(I) = \frac{bh^3}{12} \dots \dots \dots (2)$$

$$\text{Bending moment } (M) = \frac{WL}{4} \dots \dots \dots (3)$$

$$\text{Deflection}(\delta) = \frac{WL^3}{48EI} \dots \dots \dots (4)$$

Where E-Young's modulus L- Span length, W-load, and y- Distance from the neutral axis

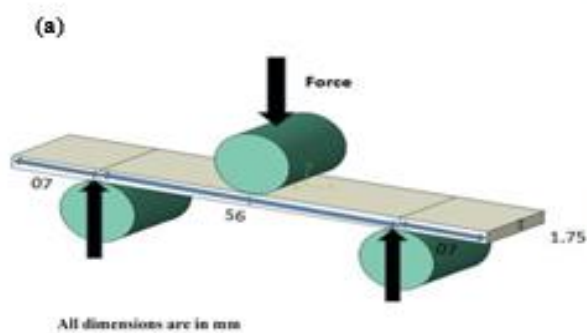


Figure 3.10 (a) Schematic diagram of 3-point bending test specimen
b) Prepared samples along with scale c) Bending Specimen

3.5 Wear Testing

Pin-on-disc apparatus was used for conducting the experiment as presented in Figure 3.11. Wear loss and friction of coefficient has been evaluated by wear test of fabricated composite. ASMT standard G99 [230] were used to fabricate the wear sample as per following dimension a 30 mm length and 8 mm of diameter for test in the form of cylindrical pin made from the composite material. The machine is made up of rotating disc with high hardness of the steel (EN31) and pin holder to maintain the pin at right angles to the disc surface. The load exerted was 15-45 N and the distance of sliding was between 1000-2500 mm and the frictional forces were measured to calculate the coefficient of friction (COF) and wear measured by the loss of weight of the pin. The prepared sample was pressing against the rotating disc. As the disc rotated friction was generated between sample and the rotating disc. Friction force were recorded continuously. This configuration produces a point contact condition that gives rise to high localised contact stresses that are typical of many engineering applications such as bearings and rolling-sliding contacts. Three samples were tested for each experimental run with the average of the coefficient of friction represented. The weight loss of the developed composite specimens during the wear test was calculated with the help weight difference between the specimen before and after the wear test. The density of the fabricated composite specimens was calculated by using the principle of Archimedes. The samples were cleaned carefully in ethanol to remove the containment such dirt on the surface and dried to get accurate mass readings prior to the measurement at room temperature. Digital weighing machine with an accuracy of ± 0.1 mg was used for weighing of each specimen for the first in air further weight was evaluated in the immersion of sample in distilled water at the same temperature, avoid

to entrap air bubbles at the surface of the specimen while being immersed. The density of the developed composite material has been evaluated as per the Equation (6) Figure 3.11 (a) 2D dimension of the sample (b) prepared sample of composite material of wear test. (c) pin on disc tribometer (d) pin on disc holder with pin (e) Prepared samples along with scale (f) Samples as per the orthogonal array L₁₆.

$$\rho = \frac{(W_a \times \rho_w)}{(W_w - W_a)} \dots\dots\dots (5)$$

Where, ρ = density, W_a = Developed composite weight in air, W_w = Developed composite weight in water, ρ_w = pure water density

Wear Rate was calculated with help of following equations

$$\text{Weight Loss}(\Delta m) = (W_i - W_f) \dots\dots\dots (6)$$

$$\text{Wear Rate} = \frac{\Delta m}{s} \text{ (g/m)} \dots\dots\dots (7)$$

$$\text{Volume loss}(\Delta V) = \frac{\Delta m}{\rho} \text{ (m}^3\text{)} \dots\dots\dots (8)$$

$$\text{Specific Wear Rate (k)} = \frac{\Delta V}{L \times S} \text{ (m}^3\text{/N-m)} \dots\dots\dots (9)$$

L = Load (N)

V = Sliding velocity (m/s)

T = Time (s)

S = Sliding distance (m)

Δm = Weight Loss (Kg or g)

ρ = Density (kg/ m³ or g/cm³)

W_i = Initial Weight

W_f = final Weight

ΔV = Volume loss

Coefficient of friction (COF) was calculated with help of following formula

$$\mu = \frac{F_f}{L} \dots\dots\dots (10)$$

μ = Coefficient of friction (COF) and F_f = Friction Force (N)

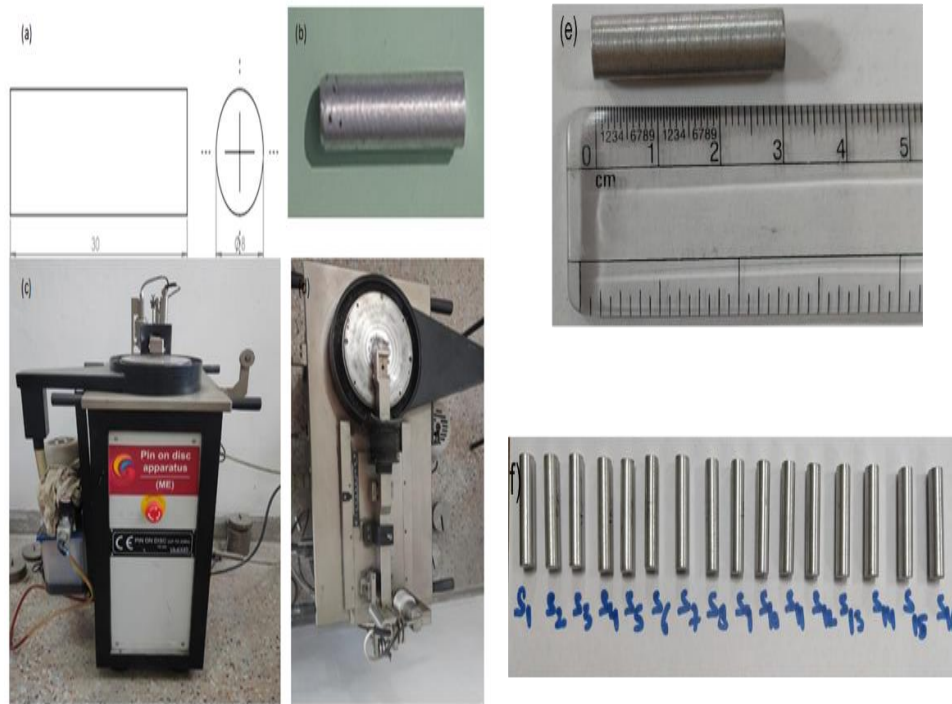


Figure 3.11 (a) 2D dimension of the sample (b) prepared sample of composite material of wear test. (c) pin on disc tribometer (d) pin on disc holder with pin (e) Prepared samples along with scale (f) Samples as per the orthogonal array L16.

The Taguchi approach is a powerful design approach that optimizes the process settings with a low number of experimental runs and an improved quality [131]. Its main concept is that variation sources are minimized as much as possible by carefully selecting the levels of the control factors. In this work, a Taguchi Design of experiments (DOE) based study was carried out on five process parameters each of which was tested at different four levels. An L_{16} orthogonal array was chosen as shown

in Table 3.7 that allowed handling of the experimental conditions efficiently and greatly reduced the total number of tests as compared to using a complete factorial design. The response rendition was measured using the signal- to- noise (S/N) ratio. Reliant on the objective the S/N ratio is calculated for a "Larger is better" attributes.

$$S/N = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right) \dots\dots\dots (11)$$

where the summation runs from i=1 to n, yi is the observed values and n is the number of observations

For a "smaller is better" attributes is

$$S/N = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n y_i^2 \right) \dots\dots\dots (12)$$

For a “nominal-the-best” characteristic, it is defined as

$$S/N = 10 \log_{10} \left(\frac{\mu^2}{\sigma^2} \right) \dots\dots\dots (13)$$

with μ and σ representing the mean and standard deviation of the response, respectively

The parameter combination with the highest S/N ratio was selected as best, in terms of better performance with less variation. The relative significance of each parameter was further evaluated by the analysis of variance (ANOVA), to determine the most relevant ones in this study when considering how they influence the response of the system [132].

ANOVA is a statistical technique for assessing the importance and contribution of each process parameter to the response, which one wants to measure. In this experiment, the five parameters of control on the responses were quantified with the help of analysis of variances (ANOVA) for four levels of parameters. Its goal is to break down into parts the total variations on the response due to each of the parameters and to experimental error. The total sum of squares i.e., S_T is

$$S_T = \sum_{I=1}^N (Y_I - \bar{Y})^2 \dots\dots\dots (14)$$

Which can be reduced to the following form?

$$S_T = \sum_{I=1}^N \left(Y_I^2 - \frac{T^2}{N} \right) \dots\dots\dots (15)$$

The total sum of squares and variable sums of squares are the basic calculations required and these are the ones that are needed for the ANOVA table. More values derived from the sum of squares for the factor A are:

$$\text{Mean Square (or Variance)} V_A = \frac{S_A}{f_A} \dots\dots\dots (16)$$

Where S_A is the sum of square of each variable

$$\text{F - Ratio } F_A = \frac{V_A}{V_e} \dots\dots\dots (17)$$

$$\text{Percentage Influence} = \frac{\text{Mean squares of A}}{\text{Sum of Mean square value of error}} \dots\dots\dots (18)$$

$$\text{Sum of square for the error terms } S_e = S_T - (S_A + S_B + S_C + S_D) \dots\dots\dots (19)$$

$$\text{DOF for error terms } f_e = (\text{Total DOFs}) - (\text{Total of all factors DOFs}) \dots\dots\dots (20)$$

$$\text{Variance of error terms } V_e = \frac{S_e}{f_e} \dots\dots\dots (21)$$

$$\text{Percentage of error terms } P_e = 100 - (P_A + P_B + P_C + P_D) \dots\dots\dots (22)$$

From the response tables of the analysis of variance it could be observed that parameters having higher percentage contribution were deemed to be more dominant which would support the best parameter set found from the assessment of signal to noise ratio.

A multivariable regression model was then constructed in order to quantitatively describe the effect of the process variable on the responses. Regression has the advantage of predicting the response variable with several independent variables, and showing response effects of the control settings individually and collectively. In this case, the five parameters of variation were set based on four levels of variation using the Taguchi design. The typical linear regression model equation is represented in the equation no. 23.

$$Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \beta_5X_5 + \varepsilon \dots\dots\dots (23)$$

where Y is the predicted response, X_1 - X_5 are the parameters of the process, β_0 is the intercept, β_1 - β_5 are the regression coefficients and ε is the error term

Table 3.6 Process parameters and their level

			Levels of Factors			
Notation	Parameter	Units	1	2	3	4
R₁	TiB ₂	wt. %	0	2.5	5	7.5
R₂	Waste glass powder	wt. %	0	2.5	5	7.5
L	Load	N	15	25	35	45
V	Sliding Velocity	ms ⁻¹	0.75	1.5	2.25	3
D	Sliding Distance	m	1000	1500	2000	2500
CuO is Constant (0.25%)						

There were 5 process parameters, which were varied: reinforcement 1 (TiB₂ wt.%), reinforcement 2 (Waste glass powder wt.%), load, sliding velocity (m/s) and sliding distance (m). All parameters were tested in 4 levels, as shown in Table 3.6. CuO was added in a small constant amount (0.25 wt.%). L₁₆ array picks the sets of the combinations that are favourable, which saves time and cost without the cost of quality. A reduced-orders model was used in analysing the quality characteristics. Statistical software Minitab 19 was used for the data analysis.

Table 3.7 Orthogonal array L16

S. No.	TiB ₂ (wt.%)	Waste glass powder (wt.%)	Load (N)	Sliding velocity (m/s)	Sliding distance (m)	Average wear rate $\times 10^{-3}$ (g/m)
1	0	0	15	0.75	1000	8.2
2	0	2.5	25	1.5	1500	12.4
3	0	5	35	2.25	2000	15.3
4	0	7.5	45	3	2500	17.4
5	2.5	0	25	2.25	2500	16.2
6	2.5	2.5	15	3	2000	12.9
7	2.5	5	45	0.75	1500	10.2
8	2.5	7.5	35	1.5	1000	7.2
9	5	0	35	3	1500	14.8
10	5	2.5	45	2.25	1000	13.5
11	5	5	15	1.5	2500	6.9
12	5	7.5	25	0.75	2000	5.4
13	7.5	0	45	1.5	2000	13.9
14	7.5	2.5	35	0.75	2500	9.1
15	7.5	5	25	3	1000	6.8
16	7.5	7.5	15	2.25	1500	4.2

3.6 Thermal Analysis

The thermal expansion test has been conducted to determine the dimensional stability of composite materials under constant temperature conditions [133-135]. The coefficient of thermal expansion (CTE) test for the AA2024 alloy-based composite was conducted using a controlled furnace setup to evaluate the dimensional stability of the material under elevated temperatures. Three samples corresponding to each composition were tested to ensure repeatability and accuracy of the results. Each specimen was prepared as per the following dimensions 20 mm x 10 mm x 5 mm and initially measured at room temperature. Then samples were gradually heated in muffle furnace shown in Figure 3.12 to 200 °C, allowing sufficient time 30 min for thermal equilibrium at each temperature stage. The change in length of each specimen with respect to the temperature rise was precisely recorded, and the thermal expansion coefficient was calculated. thermal expansion coefficient curve using the relation between the change in length, original length, and temperature difference.

This procedure provided insight into the thermal expansion behaviour and stability of the AA2024 alloy based composite material under thermal loading conditions. The thermal expansion coefficient (CTE) is calculated from the relationship.

$$\text{Strain} = \alpha \Delta t \dots\dots\dots (25)$$

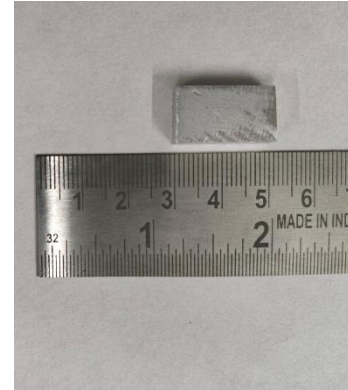
$$\text{Strain} = \Delta L / L_0 = \alpha \Delta t \dots\dots\dots (26)$$

Where

α = Coefficient of thermal Expansion, ΔL (Change in Length) = $L - L_0$, L = Final Length and L_0 = Initial Length. Δt = Change in temperature



(a)



(b)

Figure 3.12 (a) Muffle Farnace and (b) Sample for Thermal Expansion with Scale

3.7 Microstructural Analysis

The microstructural investigation samples were prepared by a double-disc polishing machine. Further, Keller's agent was used to etch the samples. The Chroma India Metallurgical Microscope (MVG2005) was utilized to extract optical micrographs for all the composition Further, Zeiss SEM was utilized for extracting the SEM micrograph.

3.7.1 Optical Microscope

Optical micrographs will be acquired from the semi-automatic Chroma India Metallurgical Microscope (MVG2005) as represented in Figure 3.13 This light microscope uses a combination of light and lenses in order to magnify images. The eyepiece, which is attached to the eyepiece holder, is used for viewing the specimen with 25mm field of view. The objective lens has a 10x magnification. A focus knob

adjusts the ocular lenses and the focus drive has last bore 25 mm of stage for coarse and fine adjustment.



Figure 3.13 Chroma India Metallurgical Microscope (MVIG2005)

The specimen ends on an aperture (hole in the stage). Lighting is provided by a high-power LED illuminator. Micrographs are taken to a maximum scale of 500x

3.7.2 Instrument used for Microstructural Analysis

A Nova Nano SEM 450 Field Emission Scanning Electron Microscope (FE-SEM) and Carl Zeiss EVO 50 Scanning Electron Microscope (SEM) was used for high resolution surface analyses and microstructure analyses as presented in Figure 3.14 a and Figure 3.14 b respectively.

The Nova Nano SEM 450 is designed for use in ultra-high-resolution imaging of cutting-edge materials. It has a Schottky field emission electron source that operates well over the entire accelerating voltage range, 0.2 kV-30 kV. This allows to obtain high resolution surface images at low voltages as well as do efficient micro-analytical work at higher beam currents. The instrument has the best resolution 1.0 nm at 30 kV, can have a magnification from 5x up to 1,000,000x, ideal for detailed Micro and nano-scale studies. The Nova Nano SEM 450 provides secondary - electron (SE) imaging in both field - free and immersion mode, with the ability to obtain comprehensive low to high resolution imaging of various material systems. An advanced Silicon- drift Detector (SDD-EDS) delivers elemental and compositional analysis, precisely determining and visualizing the variation in the composition of the surface layers. Additional detectors include In-lens SE (TLD-SE), In-lens backscattered electron (TLD-BSE), Everhart-Thornley SE Detector, Low vacuum SE detector, and high sensitivity low-kV DBS (Directional Backscattered). Backscattered electron detection is available in all modes due to the use of a quadrant semiconductor diode system. With an analytical working distance (~5.0 mm) and a 35° off angle for X-ray analysis, the NovaNanoSEM450 provides excellent flexibility in imaging at high resolution, compositional analysis and detailed examination of microstructures in advanced engineering materials and composite materials.

Carl Zeiss EVO 50 SEM Microscope has a large specimen chamber which takes relatively large samples and operates at an analytical distance of approximately 8.5 mm. This is done by means of a precise array of inclined detectors and a sharp conical objective lens. The machine has a wide operating range, varying the accelerating voltage of 0.2 to 30 kV and its magnification from 5* to 1 000 000*. Consequently, it

is able to address features to micrometres down to nanoscale. At 30kV it can resolve details of 2.0 nm.

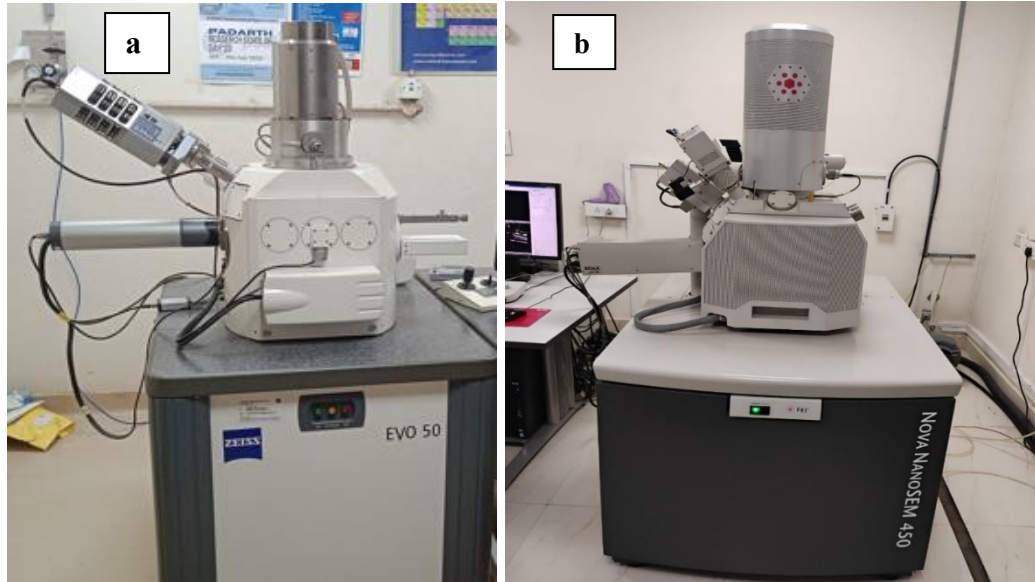


Figure 3.14 a) Carl Zeiss EVO 50 b) Nova Nano SEM 450

The EVO 50 SEM is also used for Energy-Dispersive X-ray (EDX) microanalysis, thus allowing non-destructive elemental and phase composition analysis with good accuracy. It is useful for the elements qualitative and quantitative information for testing the homogeneity of composition and the distribution of reinforcement in the composite. The microscope is also equipped with Electron Backscatter Diffraction (EBSD) for grain structure and crystallographic orientation and phase analysis. Advanced INCA and AZtec software from Oxford Instruments make data acquisition and analysis time efficient at micro- and nanoscales. For imaging, the device has secondary-electron detectors such as Everhart-Thornley detector for surface morphology and backscattered-electron detectors on quadrant semiconductor diodes for composing contrast imaging. These are advanced features that make the Carl Zeiss

EVO 50 ideal to study the detailed microstructural and elemental characterization of engineering materials and composites. Signals from the surface of the material under study are generated by the device by directing a focused high energy electron beam to it. From these electron-sample interactions, information of the morphology of the surface, the crystal orientation and the chemical composition can be derived. A two-dimensional image is formed from the selected specimen region which allows detailed analysis of the properties.

3.8 Computational Analysis of Tensile Behavior

The plastic flow behaviour of TiB_2 /Waste Glass Powder/CuO reinforced AA2024 composite material. Abaqus FEA has been implemented to investigate the tensile behaviour of sample no.4 of the developed composite material composition. Further, the validation of evaluated power law constants was also performed.

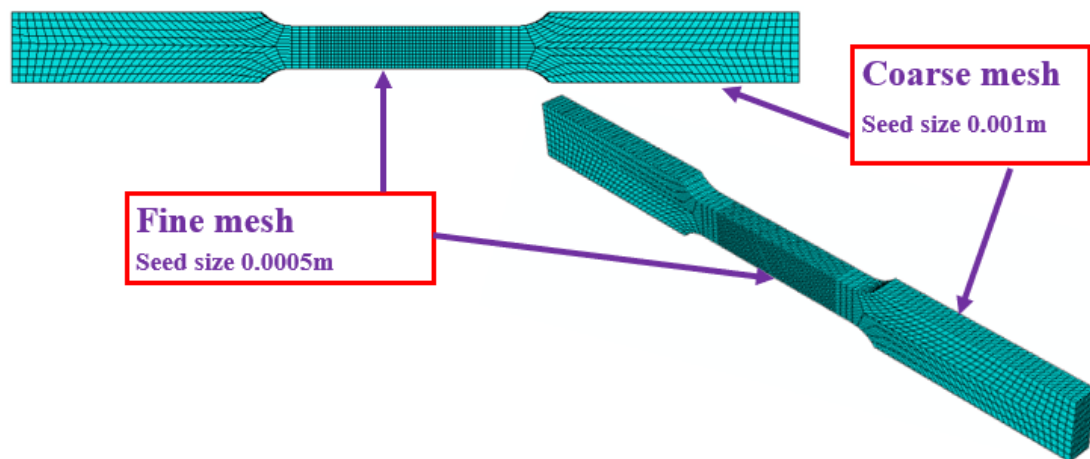


Figure 3.15 Validation of Hardening (Power-Law) Model

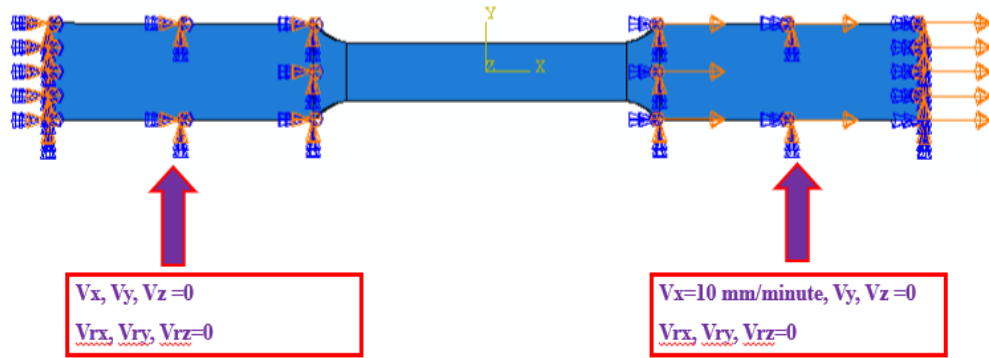


Figure 3.16 Loading and Boundary Condition of Specimen

The standard static solver has been utilized to perform the present FEA investigation. The tensile test specimen assembly was meshed with the help of C3D8R element as shown in Figure 3.15. The 10608 elements and 13257 nodes are generated in the tensile test assembly meshing. The specimen has been subjected to loading and boundary condition Velocity x, Velocity y, Velocity z = 0. Further, the top portion of the tensile specimen moved along x direction with the boundary condition Velocity x = 10 mm/min, Velocity z = 0, Velocity y = 0, where Velocity x, Velocity y, and Velocity z are the velocity in the x, y, and z direction as shown in Fig 3.16. The fracture in tensile testing occurs in the middle of the specimen gauge length.

4. Results and Discussion

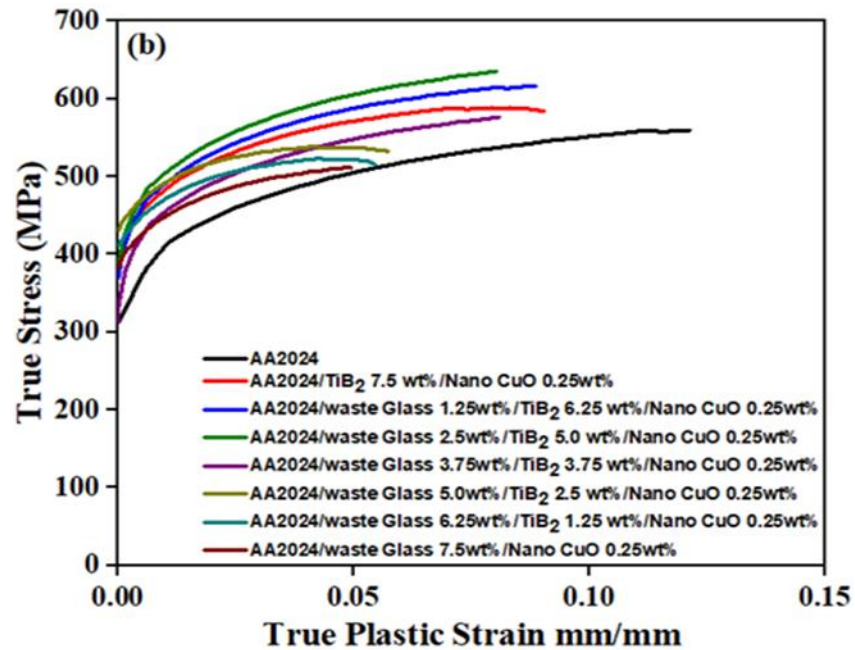
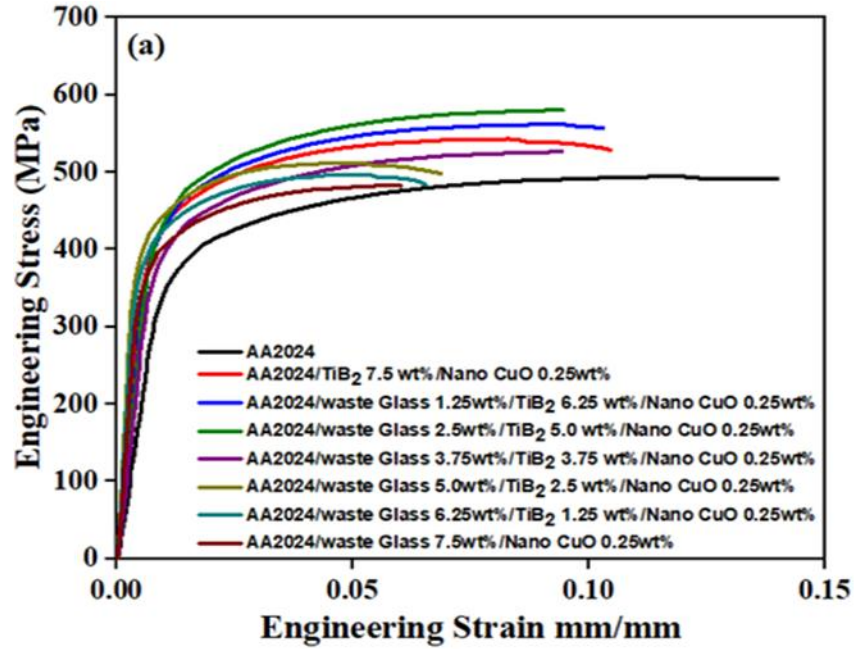
4.1. Influence of weight %age of reinforcement on tensile properties

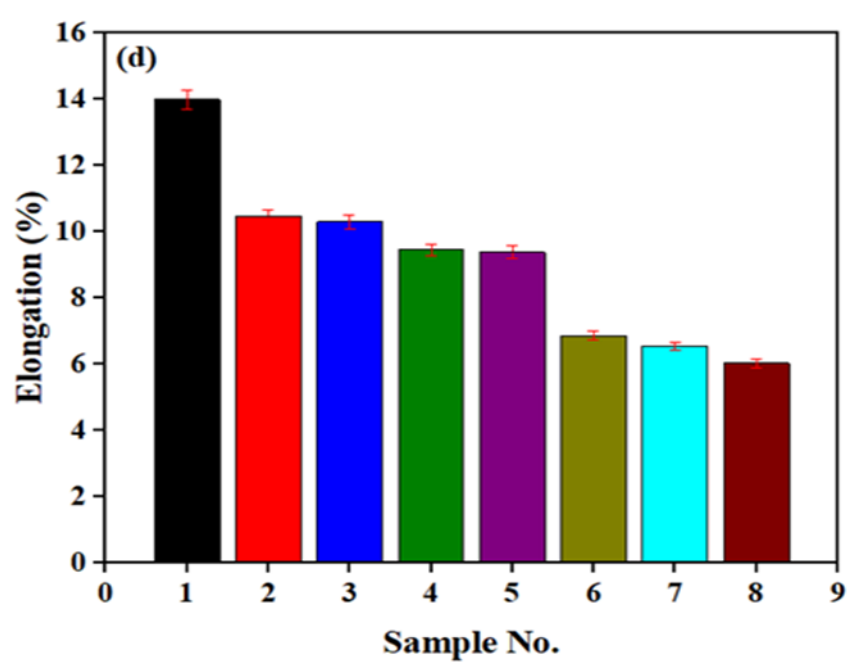
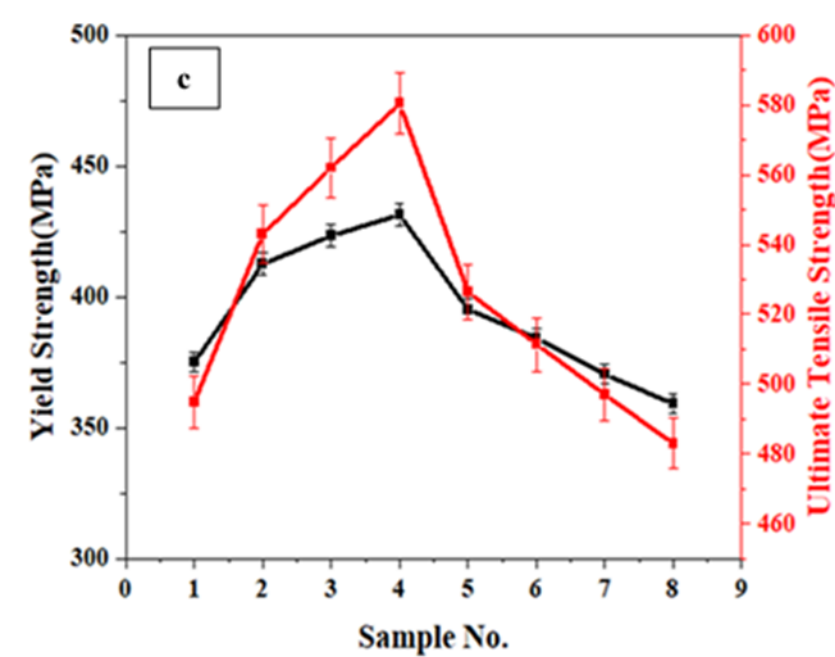
Figure 4.1 (a) presents the engineering stress–strain responses of all eight composites developed using the AA2024 aluminium alloy matrix and clearly illustrates the progressive modification of elastic–plastic behaviour with the addition of ceramic and hybrid reinforcements. The unreinforced alloy (Sample 1) exhibits the typical ductile aluminium response characterized by a lower initial slope, early yielding, moderate strain hardening, and the highest terminal strain, attaining an ultimate tensile strength (UTS) of 495 MPa and yield strength (YS) of 375.07 MPa with 13.99% elongation. Reinforcement addition has the effect of shifting all the stress-strain curves to the right (upwards) thereby showing an increase in load-bearing capacity and stiffness. The change is due to the enhanced load transference and pinning of the dislocation. Sample 2 with 7.5 wt.% TiB_2 and 0.25 wt.% CuO produced 17.3% and 15.0% increments in the ultimate tensile strength and yield strength of the base alloy respectively. Sample 2 Shows increases in the ultimate tensile strength to 543 MPa; an increase of 9.7%, and the yield strength to 412.54 MPa; an increase of 10.0%. This confirms that hard ceramic particles help to strengthen the matrix. Adding of reinforcement particles in the range of 6.25% TiB_2 1.25% WGP and 0.25% CuO (Sample 3) gives a higher result on UTS to 562 MPa and 423.40 MPa on YS, 13.5% and 12.9% respectively, compared to Sample 2. Sample 4, with 5% TiB_2 , 2.5% WGP and 0.25% CuO, shows the highest stresses at all stages of deformation. But its strain fracture decreases from 13.99% to 9.45%, a decrease of 32.5%, a fairly typical strength

versus ductility trade-off. As WGP content increases and TiB_2 content decreases, progressively lower stresses are exhibited in samples 5-8. Their ultimate tensile strengths decrease to 6.3%, 3.3%, and 0.4% for samples 5-7; sample 8 decreases to 483 MPa, 2.4% compared to the base alloy and 16.8% to sample 4. These decreases are associated with decreased efficiency of the reinforcement, particle clustering, and stress concentration. True stress versus true plastic strain is shown in Figure 4.1 (b), which provides a better representation of strain hardening. The base alloy has lower flow stress, but accumulates more plastic strain, indicating that the base alloy is more ductile, but less resistant to plastic deformation. Reinforced samples demonstrate higher flow stresses and steeper hardening slopes, confirming improved dislocation obstruction and interfacial load transfer. Sample 4 shows consistently the highest true stress point over the whole plastic regime with a continued work hardening and delayed saturation. Which means great microstructural stability and perfect particle dispersion. Samples 2 and 3 harden more than the base alloy but attain peak flow stresses approximately 6 to 9% lower than Sample 4. In contrast, samples 6-8 have earlier as well as slower saturation rear and therefore imply early initiation of damage and weaker particle matrix bonding at large WGP fractions. Thus, TiB_2 -NanoCuO-WGP exhibits the synergistic strengthening effect within an optimum compositional range; the excess addition of glass but lessens the plastic stability.

The discrete values of yield and ultimate tensile strengths are summarised in Figure 4.1(c). Sample 4 leads followed by samples 3 and 2 Compared to Sample 4, Sample 3 has < 1.9% and 3.3% lower YS and UTS, respectively; Sample 2 has 4.6% and 6.9% lower YS and UTS, respectively. The decrements become more prominent for Sample 5 (about -8 - -9%), for Sample 6 (11 - 12%), for Sample 7 (14 - 15%) and for

Sample 8 (17%) confirming that excessive WGP content decreases the efficiency of strengthening and decreases the interfacial integrity.





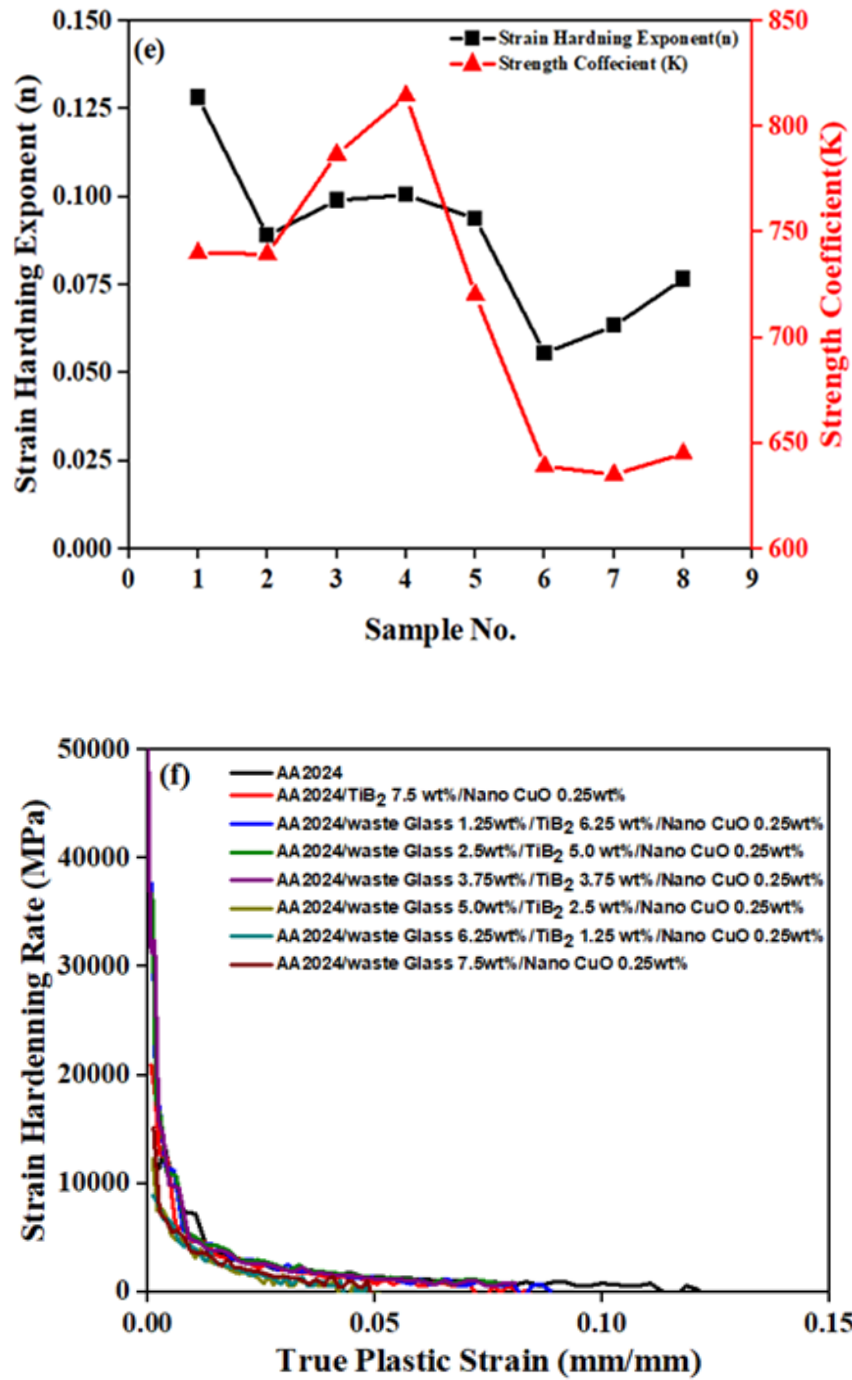


Figure 4.1. The mechanical properties of developed composite material, (a) Engineering stress vs. Engineering strain, (b) True stress vs. True plastic strain, (c) Yield and ultimate tensile strength, (d) Percentage elongation vs. sample number, (e) n , K vs. sample number, (f) Strain hardening rate vs. True plastic strain

Figure 4.1 (d) presents the percentage elongation which shows the inverse relationship between strength and ductility. The ductility of the base alloy is the highest at 13.99%. All reinforced composites lose elongation due to the restriction of plastic flow by rigid particles. Sample 4 maintains a moderate value of ductility (9.45%), an acceptable compromise because of its high strength. Compared with Sample 4, samples 6-8 experience further ductility losses of about 27%, 31% and 36% respectively, which is an indication of a more brittle behaviour and a low level of plastic accommodation at high glass contents. Integrating Figures 4.1 (a-d) the mechanical balance is the best for the Figure 4.1 (c) hybrid composite of the Sample 4 (5 wt.% TiB₂, 2.5 wt.% WGP, 0.25 wt.% CuO) with the highest strength, strain hardening and acceptably elongation. It is thus the optimum formulation among all the AA2024-based composites for structural applications. Figure, 4.1 (e) shows the variation of strain hardening exponent (n) and strength coefficient (K) as a function of the number of samples which reflects work hardening response of TiB₂, glass powder and nano CuO reinforced metal matrix composites. Tensile results indicate that yield strength and ultimate tensile strength increase from Sample 1 to Sample 4 (YS: 375 MPa to 431 MPa; UTS: 495 MPa to 580 MPa) due to effective load transfer, dislocation pinning, and grain refinement from well-distributed reinforcements, while elongation decreases from about 14% to about 9%. For higher reinforcement levels (Samples 5 to 8), both strength and ductility decline (UTS about 483 MPa to 526 MPa; elongation about 6%), attributed to particle agglomeration and interfacial debonding. Sample 4 therefore represents the optimum composition with maximum strengthening and improved work-hardening behaviour, supported by the trend of n and K. Figure 4.1 (f) presents the variation of strain hardening rate with true plastic strain for all samples, demonstrating the evolution of

work-hardening during plastic deformation. At low true plastic strain, the strain hardening rate is significantly high, for example Sample 1 11,000 MPa, Sample 2 20,800 MPa, and hybrid reinforced Samples 3 and 4 reaching 37,000 MPa and 35,000 MPa, respectively, indicating strong dislocation multiplication, particle-matrix load transfer, and effective dislocation pinning by TiB_2 , waste glass, and nano-CuO. As the true plastic strain increases, i.e., passing from 0.01 to 0.05, the hardening that occurs is lower, passing from approximately 5000 to 2000 MPa, indicating the occurrence of dynamic recovery processes, the rearrangement of the dislocations, and the saturation of the harden mechanisms. Samples with over enforcement (5 to 8) have a faster reduction in hardening rate, typically under 1,500 MPa at higher strains. This reflects the early localized damage that was caused by the clumping and interfacial debonding of particles. The occurrences of negative values of hardening at large strains confirm the occurrence of strain softening and microcrack propagation leading to plastic instability. Overall, Figure 4.1(f) indicates that the optimum hybrid compositions (especially Samples 3 and 4) have excellent initial work-hardening and delayed softening behaviour as compared to the base alloy and to the highly reinforced compositions.

4.2. Impact and Hardness behavior of developed composite material

Figure 4.2 describes the variation of hardness and impact caused by the variability of reinforcement in AA2024 aluminium alloy-based composites. Hardness was increasing from Sample 1 to Sample 8 as a result of TiB_2 , nano-CuO and waste glass were added. Sample 1 - base alloy - the hardness of the reference was set up to 137.74 HV. The hardness of Sample 2 was increased to 154.38 HV (an increase of 12.08 wt.%)

for added TiB₂ and 0.25 wt.% of nano CuO). Replacing TiB₂ by waste glass with increasing amounts gave the samples 3-6 155.86 HV (13.15% above base), 159.12 HV (15.52% above base), 161.05 HV (16.93% above base), and 164.83 HV (19.67% above base). The highest values were in Samples 7 (168.16 HV, 22.09 %) and 8 (170.93 HV, 24.10%).

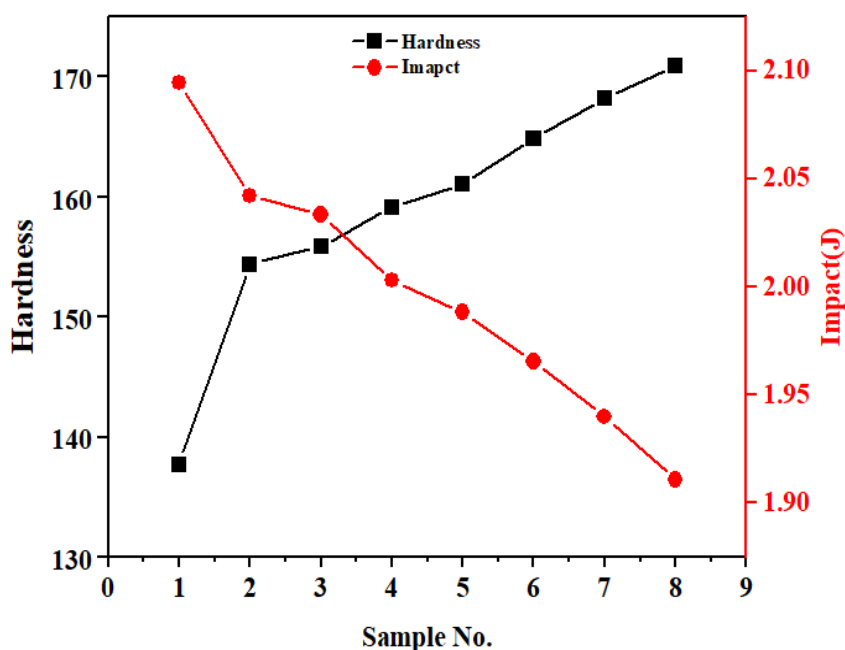


Figure 4.2. The hardness and impact properties of the developed composite material

These results show that the waste glass enhances the strength of the surface by the distribution of the hard particles and the resistance to localised plastic deformation. However, to increase the hardness it had to sacrifice the impact energy. Sample 1 absorbed the most energy-(2.094J) With reinforcement, Sample 2 fell to 2.042 J (about 2.5% loss). The decrease persisted. 2.033J (Sample 3, 2.9% loss). 2.003 J (Sample 4,

4.4%). 1.988J (Sample 5, 5.1%). 1.966J (Sample 6, 6.2%). Samples 7 and 8 went down further to 1.940 J and 1.911 J (7.4% and 8.8% loss, respectively). The trend confirms one of the classic strength-toughness trade-offs: As waste glass is increased, the glass's hardness is increased but its brittleness and strength also increase, reducing the material's impact toughness.

4.3. Influence of reinforcement particles on the flexural behavior of developed composite material compositions

Flexural strength as a function of flexural strain is shown in Figure 4.3 (a). Figure 4.3 (b) compares the peak flexural strength across the sample number and gives the corresponding percentage changes. The base alloy (Sample 1, AA2024) has a flexural strength of around 640 MPa which reflects the bending resistance of the matrix. Introducing 7.5 wt% TiB₂ and nano- CuO (Sample 2), the strength was further enhanced i.e., up to 719 MPa, that is, a gain of 12.4%. Further strengthening of the composite was obtained by addition of both waste glass and TiB₂ Sample 3 gave approx. 761 MPa (18.8% above base) and sample 4 a peak of approx. 803 MPa, an improvement of 25.5%. These gains are attributed to fairly dispersion of particle, grain refinement, crack deflection, as well as high interfacial bonding which retard the initiation of the micro-cracks under bending. Beyond this optimum value, introducing more waste glass and less TiB₂ contents (Samples 5-8), flexural strength decreased from around 731 MPa to 666 MPa. Although still 4.0 to 14.3% higher than the base alloy, these samples were 9.0 to 17.1% weaker than Sample 4. The decrease is caused by the reduced efficiency of strengthening, particle clustering, decreased ceramic content and stress concentration leading to premature fracture.

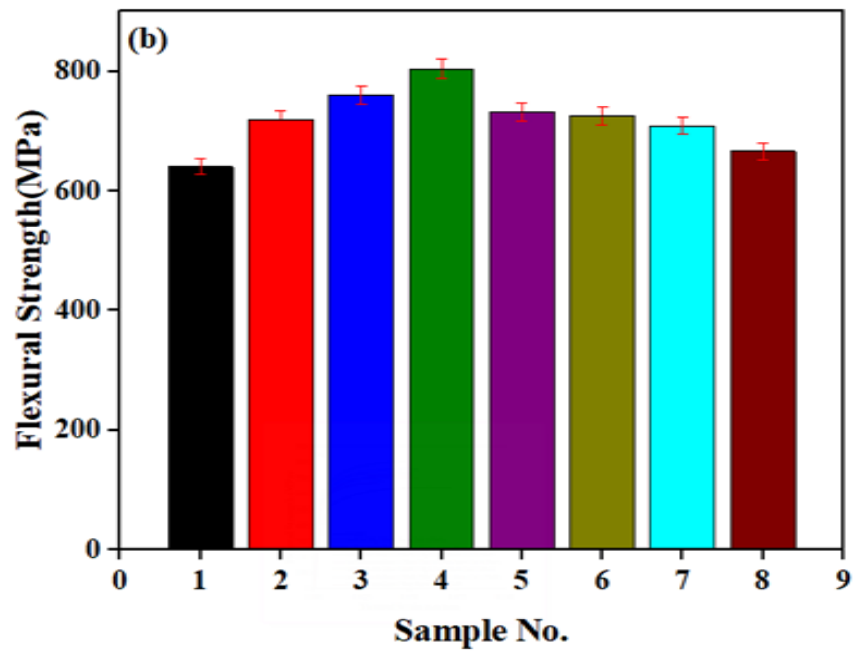
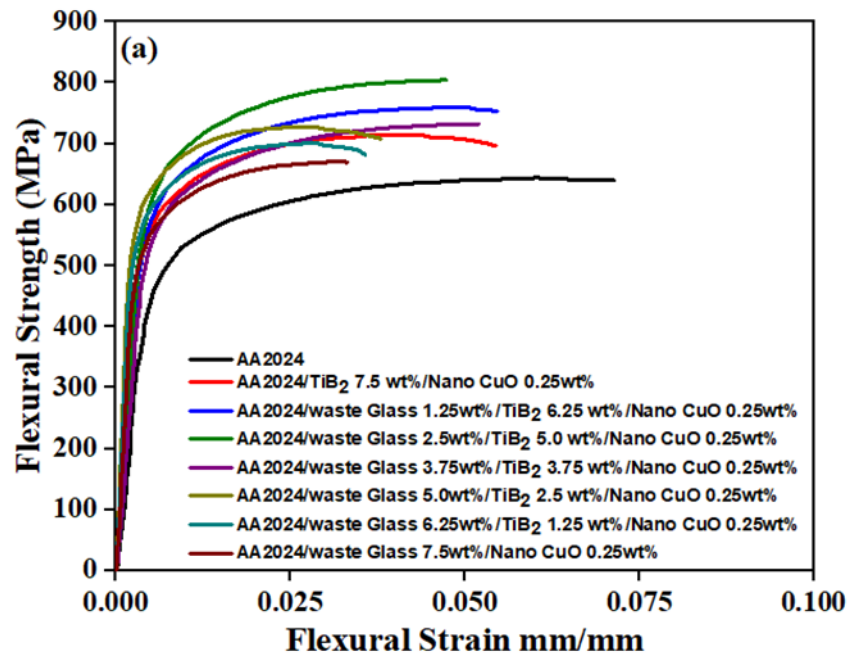


Figure 4.3. (a) Flexural strength vs. Flexural strain,
(b) Flexural strength vs sample number

The curves in Figure 4.3 (a) indicate higher slopes, higher stiffness and delayed crack propagation in Samples 3 and 4. Figure 4.3 (b) confirms that Sample 4 is the best composition of hybrid, before the solid synergy of TiB_2 , waste glass and nano CuO is predominant and when the glass content is higher the performances get worse.

4.4. Microstructural Investigation

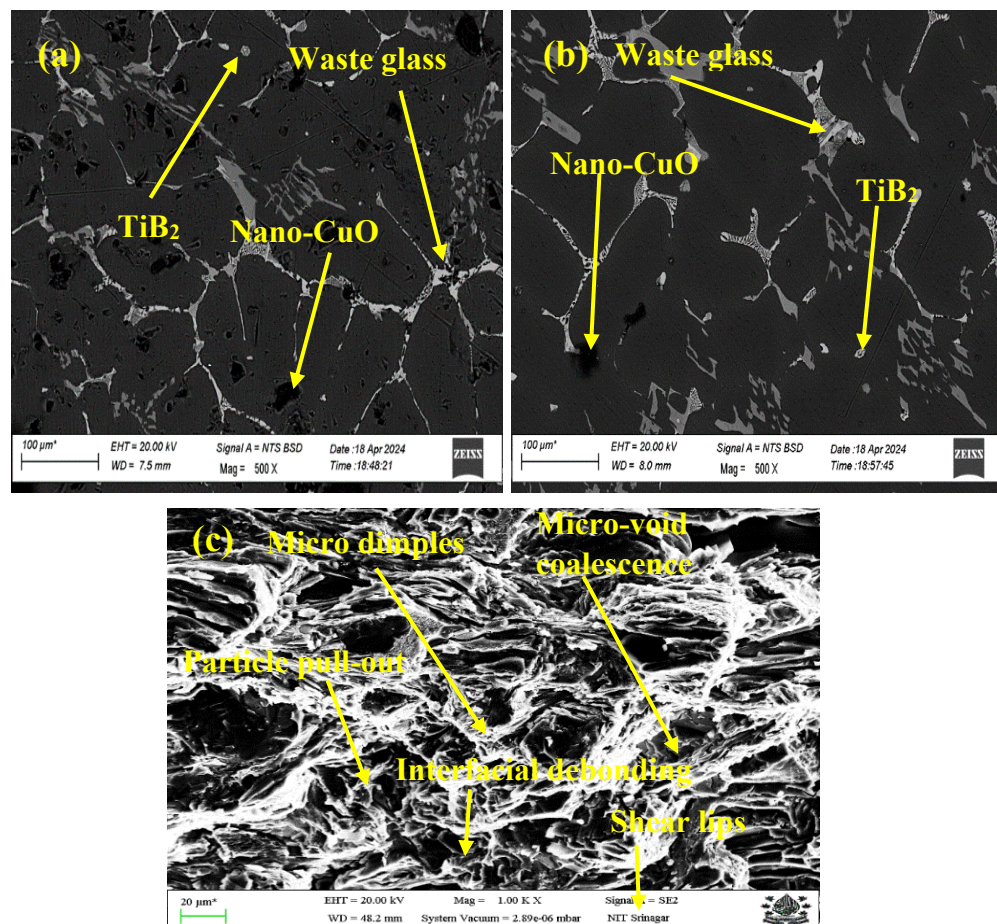


Figure 4.4. SEM micrograph of sample AA2024/waste Glass 2.5wt%/TiB₂ 5.0 wt%/Nano CuO 0.25wt% (Sample 4) at a working distance (a) 7.5 mm, (b) 8.0 mm (c) Fractography

Figure 4.4 presents the SEM micrographs of the Sample 4 at working distances 7.5 mm (a) and 8.0 mm (b). The images show a homogeneous dispersion of bright, angular

TiB₂ particles, irregular phases of waste glass on the grain boundaries and nano-CuO, as fine distributed features in the matrix. This microstructure favours the refinement of grain, dislocation pinning, crack deflection, as well as strong particle-matrix bonding with little agglomeration. The lack of a systematic variation at both distances is indicative of a stable particle hybrid distribution and explains the improved load transfer, stiffness and overall mechanical performance. Fractographic analysis in Sample 4 (Figure 4.4 (c)) reveals prevailing ductile fracture features of micro-dimples, micro-void-coalescence, poor particle pull-out, interfacial debonding, and shear lips. The fine and homogeneously distributed dimples indicate considerable plastic deformation for matrix and the growth of micro-voids controls the fracture path. Minimal particle pulls out and localised debonding suggest reinforced matrix with good bonding of particle with matrix and controlled initiation of voids in reinforcement matrix interface. Shear lips are a sure sign of shear assisted plastic deformation in the final failure. These features show mixed ductile fracture mechanism by showing good load transfer and improvement in toughness in Sample 4 due to synergistic hybrid reinforced.

Figure 4.5 is the EDS map of Sample 4 (AA2024 containing 2.5wt% waste glass, 5.0wt% TiB₂ and 0.25wt% nano-CuO). The successful incorporation of the hybrid reinforcements in the AA2024 matrix is confirmed by the map. Aluminium signals prevail showing the matrix, along with localised Ti and B signals showing discrete TiB₂ particles. Silicon and oxygen signals are on the trail, and they track down the waste - glass phase, predominately along the grain boundaries, that helps grains refine and crack deflection. Copper and oxygen co- indicator of fairly dispersed nano-CuO which pins the dislocations and increases the interface strength. Overlap of Al, Ti, B,

Si, Cu and O's signals, which indicates good particle matrix bonding and very little agglomeration, are responsible for good load transfer and enhanced deformation resistance. Overall, fairly elemental distribution is a good processing, it has low segregation, and a stable hybrid microstructure that is responsible for superior tensile, flexural and work hardening performance of Sample 4. This confirms the synergistic strengthening effect of TiB₂, waste glass and nano-CuO in the composite.

4.5. Validation of Hollomon power law parameters for sample AA2024/waste Glass 2.5wt%/TiB₂ 5.0 wt%/Nano CuO 0.25wt% (Sample 4)

Conducted a numerical simulation in order to validate the experimentally derived Hollomon parameters i.e, strength coefficient K and strain hardening exponent n for the hybrid composite. The response of the specimen during a tensile test was reproduced using finite element analysis (Abaqus). Among all compositions Sample 4 had the best mechanical performance with a yield strength of 431.37 MPa and an ultimate tensile strength of 580.37 MPa. The specimen geometry is to the standard design according to ASTM E8/E8M-04, as shown in Figure 4.6(a). The boundary conditions are shown in Figure 4.6(b). In the model the right end was fully constrained (no translation - V_x, V_y, V_z, and no rotation - V_{rx}, V_{ry}, V_{rz}) to represent a fixed support. The left end was given a displacement resulting in 10 mm/s movement at the x axis, other velocity components were set to zero simulating uniaxial tension at 10⁻³ s⁻¹ strain rate.

The measured Hollomon parameters were applied as input plastic hardening in the constitutive model. Simulation material properties: density: 2750 kg/m³; Young's modulus: 87.10GPa; Poisson's ratio: 0.32 A 3-d mesh of C3D8R elements was used,

then comprising 13257 nodes and 10608 elements, which ensures proper resolution of stress and strain gradients Figure 4.6(c).

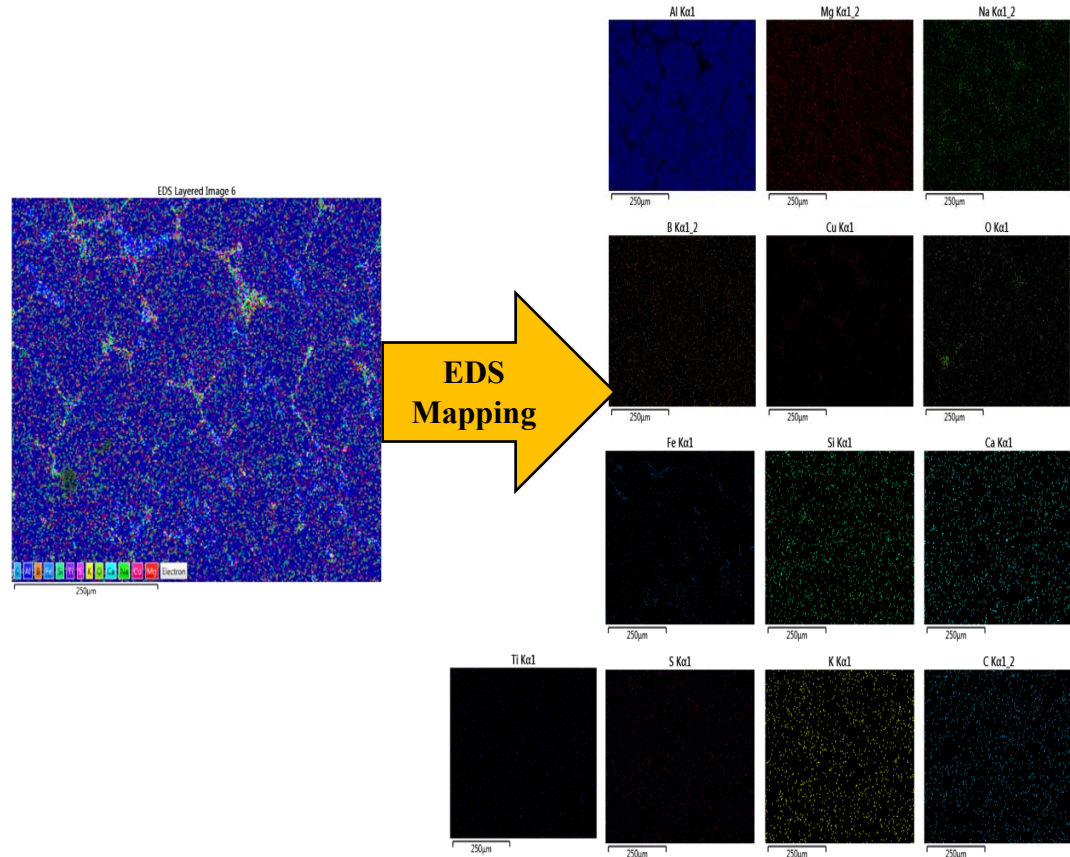


Figure 4.5. EDS mapping of sample AA2024/waste Glass 2.5wt%/TiB₂ 5.0 wt%/Nano CuO 0.25wt% (Sample 4)

Figures 4.7 and 4.8 are the Von Mises stress and the equivalent plastic strain (PEEQ) contours for each step in the analysis. Von Mises stress is concentrated at maximum in the gauge region and progressive strain localization and initiation of necking occurs. PEEQ contours confirm the highest plastic strain also localises in the gauge region and therefore the fracturing is also initiated in the necking zone which corresponds to experimental results. Experimental and FEA true stress-true plastic strain curves of Sample 4 are compared in Figure 4.9. Both of the curves exhibit a similar nonlinear strain-hardening trend, confirming that the selected Hollomon parameters can be used

to capture the plastic behaviour of the composite. At a plastic strain of 4.68×10^{-4} , the experimental true stress is found to be 399.40 MPa while the FEA prediction is 427.69 MPa which is about 4-5% deviation.

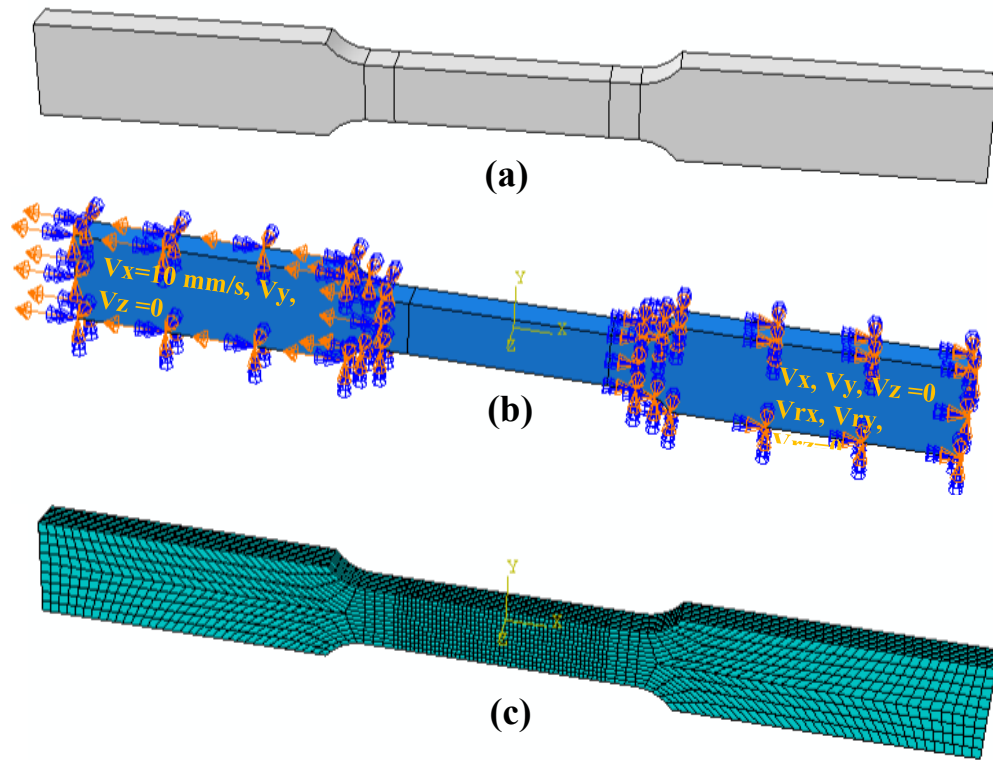


Figure 4.6. (a) Tensile test specimen CAD model, (b) Boundary and Load conditions, (c) Meshing

At 0.01065 plastic strain, experimental stress is 507.63 MPa vs. 519.34 MPa by FEA showing similar agreement. At 0.0647 plastic strain the experimental stress is 621.82MPa; FEA predicts 640.28MPa again in the same band of variation. FEA reaches a real plastic strain 0.08352, and predicts 651.11 MPa, according to the experimental hardening trend. Throughout the plastic deformation range the experimental-numerical variation is within 4-5%. The minute over-estimative curve in

the FEA curve probably stems from ideal material homogeneity, simplified b.c. and no microstructural harm to the model.

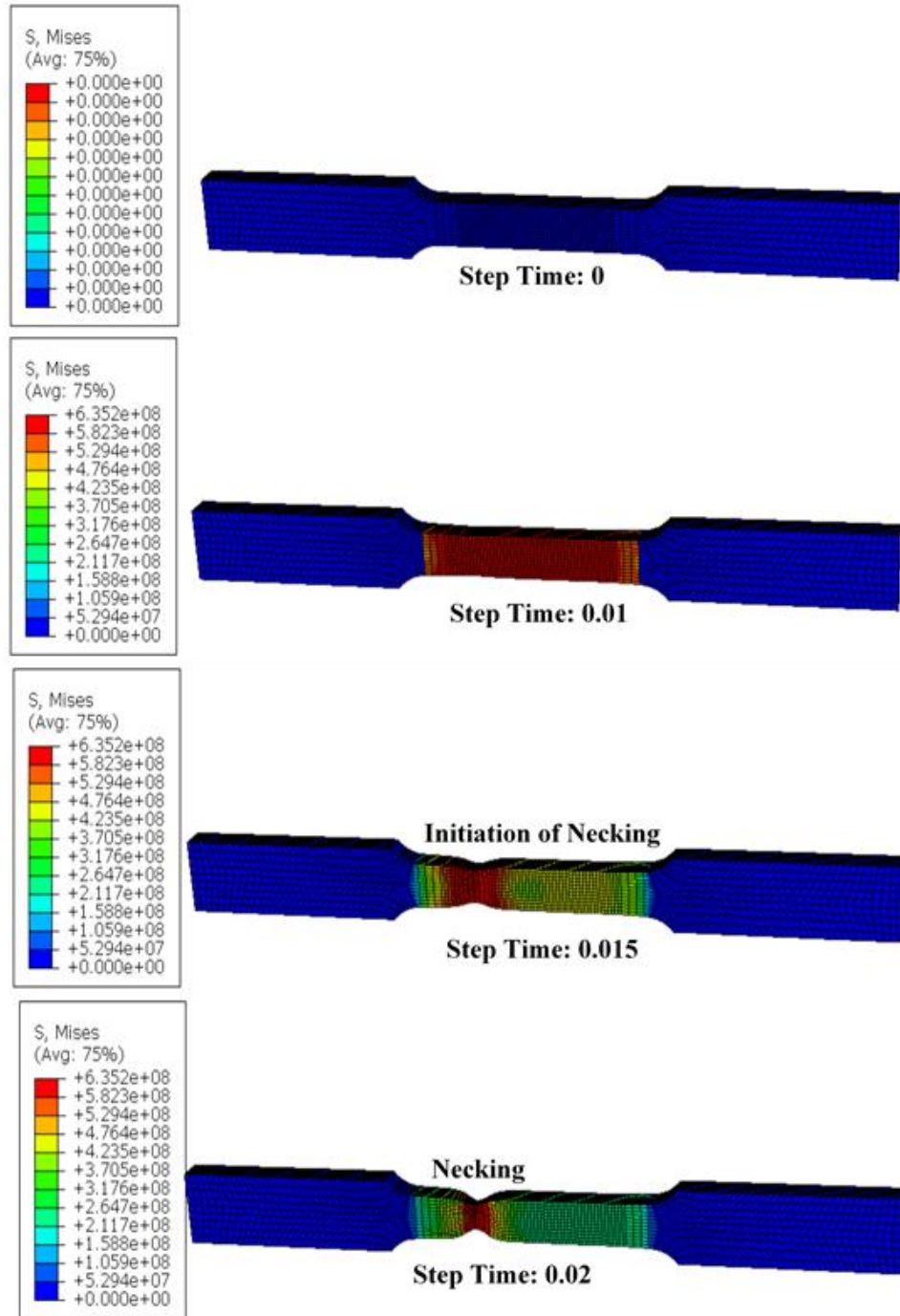


Figure 4.7. Von-mises stress contours up to necking AA2024/waste Glass 2.5wt%/TiB₂ 5.0 wt%/Nano CuO 0.25wt% at different step time

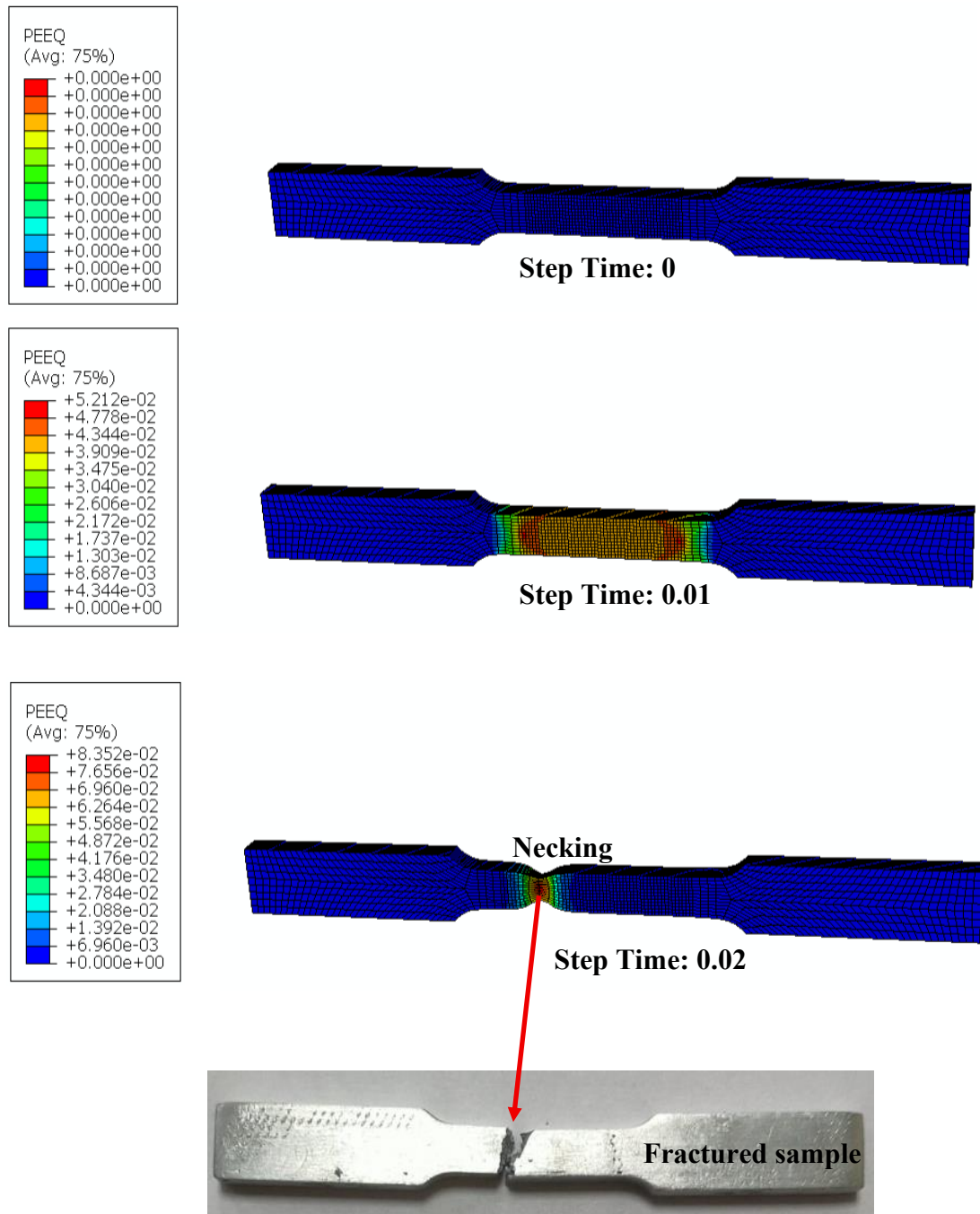


Figure 4.8. Equivalent Plastic Strain FEA results up to necking AA2024/waste Glass 2.5wt%/TiB₂ 5.0 wt%/Nano CuO 0.25wt% at different step time and Fractured Tensile test sample after testing

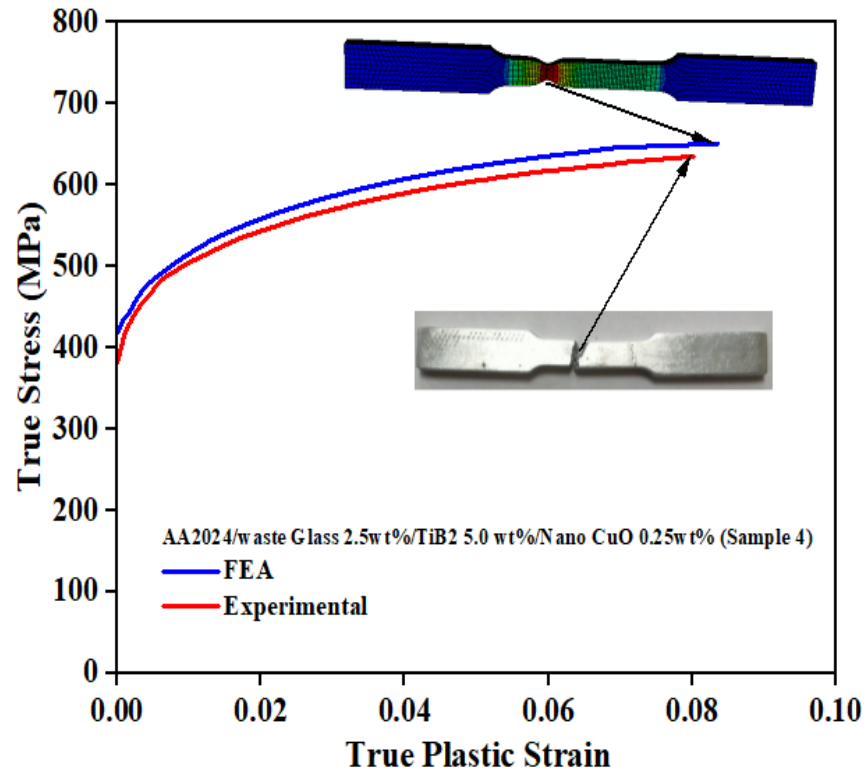


Figure 4.9. Experimental vs. FEA result for AA2024/waste Glass 2.5wt%/TiB₂ 5.0 wt%/Nano CuO 0.25wt% specimen

4.6 Tribological Behaviour

4.6.1 Development of regression model for the wear loss

Statistical analysis of the wear test was conducted by Minitab 19 software. Quality characteristics smaller is better were used for the analysis of the result. For the analysis of the effect of process parameters analysis of variance (ANOVA) was carried out as shown in Table 4.1. Results depicted that a higher F-value and lower p-value indicate that the results are statistically correct [23]. A multi-variable regression model was developed in terms of process parameters shown in Equation 1. The value of R-sq was 0.98 and R-sq (adj) was 0.97 respectively. The R-squared value is close to 1. Table 8 shows the response table for the mean. It can be observed that the most influencing process parameter is load and the least influencing process parameter was found to be

Sliding distance (m). The order of influencing process parameters was decided based on rank shown in Table 4.2.

Table 4.1 Analysis of Variance for the response variable wear rate

Source	DF	Adj SS	Adj MS	F-Value
Regression	5	255.238	51.0475	117.55
TiB ₂ (wt.%)	1	50.880	50.8805	117.17
Waste glass powder (wt.%)	1	53.465	53.4645	123.12
Load (N)	1	68.450	68.4500	157.63
Sliding velocity (m/s)	1	54.120	54.1205	124.63
Sliding distance (m)	1	28.322	28.3220	65.22
Error	10	4.343	0.4343	
Total	15	259.580		

Table 4.2 Response table for means

Level	TiB ₂ (wt.%)	Waste glass powder(wt.%)	Load (N)	Sliding velocity (m/s)	Sliding distance (m)
1	13.325	13.275	8.050	8.225	8.925
2	11.625	11.975	10.200	10.100	10.400
3	10.150	9.800	11.600	12.300	11.875
4	8.500	8.550	13.750	12.975	12.400
Delta	4.825	4.725	5.700	4.750	3.475
Rank	2	4	1	3	5

$$\begin{aligned}
\text{Wear rate} = & 12.03 - 1.595 \text{ TiB}_2(\text{wt.}\%) - 1.635 \text{ Waste glass powder (wt.}\%) \\
& + 1.850 \text{ Load (N)} + 1.645 \text{ Sliding velocity (m/s)} \\
& + 1.190 \text{ Sliding distance (m)} \dots\dots\dots (1)
\end{aligned}$$

4.6.2 Effect of process parameters on wear loss

The results of the investigation into the effect of process parameters on the wear behaviour of AA2024/TiB₂ + Waste glass powder (wt.%) and CuO composites reveal that the most influential factor in determining wear performance is the load (N). As depicted in the main effect plot of the Signal-to-Noise (SN) ratio in Figure 4.10(a) and 4.10(b), the load has the greatest impact on the wear rate of the composites, which can be attributed to the fact that increasing load intensifies the contact stress between the sliding surfaces, leading to higher frictional forces and greater wear. This result highlights the critical role of load in the tribological performance of the material. Following load, sliding velocity (m/s) is the second most influential parameter, as higher velocities exacerbate frictional forces, causing more rapid wear by increasing the temperature at the interface and accelerating material degradation. Waste glass powder (wt.%) emerges as the third most significant parameter, contributing to the overall wear resistance of the composite due to its hard, reinforcing nature. However, excessive amounts of Waste glass powder may negatively affect the matrix-reinforcement bonding, potentially reducing the effectiveness of this reinforcement. Lastly, sliding distance (m), while still affecting wear, shows the least influence on wear behavior in comparison to the other parameters. The wear accumulation over distance is less significant when the immediate effects of load and sliding velocity are more pronounced. Diagnostic plots shown in Figure 4.11, further support the analysis

of these findings Figure 4.11 shows normal probability plot of wear rate, residual vs fitted value, frequency vs residual and residual vs observation order.. The normal probability plot suggests that the residuals follow a normal distribution, validating the assumptions made in the analysis and confirming the appropriateness of the model for the data. The residual vs. fitted values plot indicates that the residuals are randomly scattered around the horizontal axis, demonstrating that there is no discernible pattern or bias, which is a key indicator of the model's accuracy and the homoscedasticity of the residuals. The frequency plot of residuals vs. observation order reveals that the residuals are evenly distributed across observations, suggesting no autocorrelation and confirming that the residuals are independent of each other. Collectively, these plots reinforce the reliability of the model and the significance of the identified process parameters in influencing the wear performance of AA2024/TiB₂ + Waste glass powder (wt.%) and CuO composites.

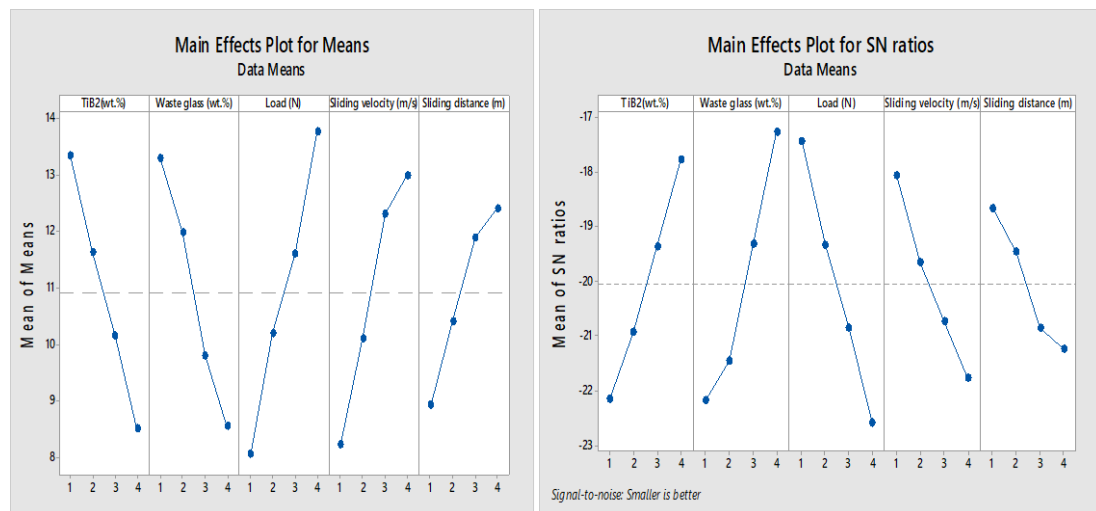


Figure 4.10(a) Main effect plot of means for wear rate (b) Main effect plot for SN ratios

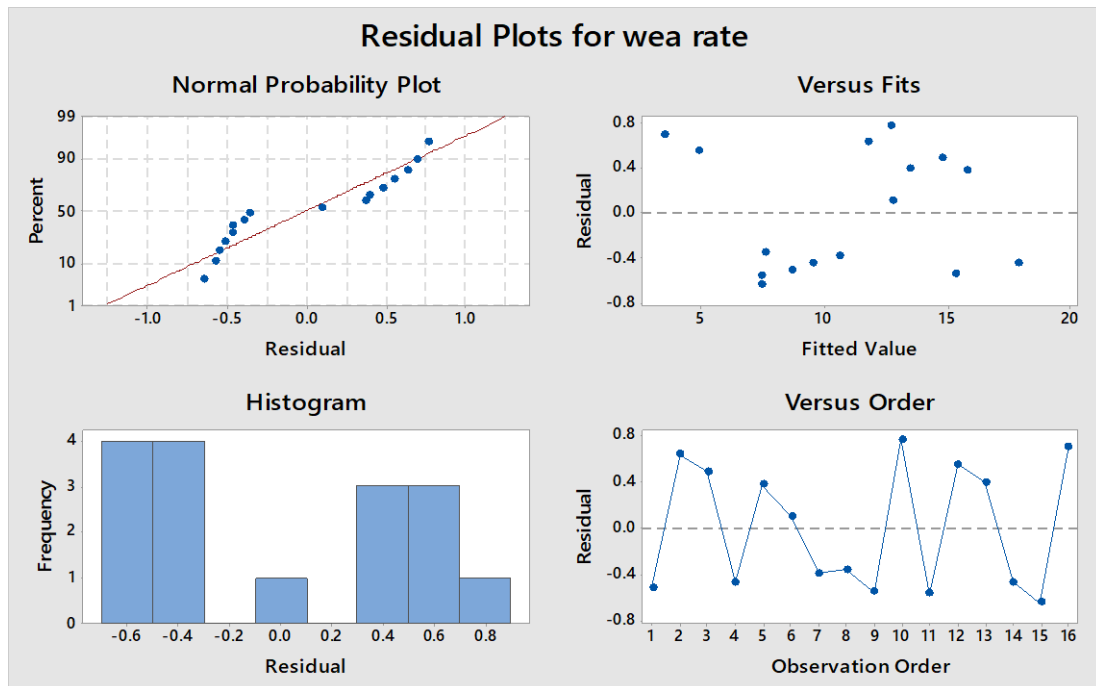


Figure 4.11 (a) Normal probability plot of wear rate (b) residual vs fitted value (c) frequency vs residual (d) residual vs observation order

4.6.3 Effect of reinforcement percentage on frictional coefficient

The experimental results indicate that the inclusion of TiB_2 , Waste glass powder, and CuO into AA2024 significantly affects the coefficient of friction (μ). As the percentage of reinforcement percentage of TiB_2 increases, the coefficient of friction decreases. Figure 4.12 shows the effect of reinforcement on the frictional coefficient of the fabricated composite. This can be attributed to the friction-reducing properties of the reinforcements. TiB_2 particles, being harder and more stable, tend to create a smoother surface by reducing the contact area between the composite and the opposing material, leading to a reduction in friction. Similarly, CuO , despite being present in a fixed amount of 0.25 wt.%, further enhances the frictional behaviour due to its ability to form a lubricating layer on the surface, reducing wear and friction during sliding

contact. Waste glass powder, although not as effective as TiB₂ or CuO, contributes to lowering the (μ) when combined with these reinforcements. The physical mechanism behind this trend is likely the formation of a low-friction layer on the surface of the composite, as well as the increased hardness of the material which helps to minimize surface deformation during contact, resulting in lower friction. Overall, the combination of TiB₂ and CuO is particularly effective in reducing friction, while the presence of Waste glass powder further improves the overall tribological performance of the AA2024 composite.

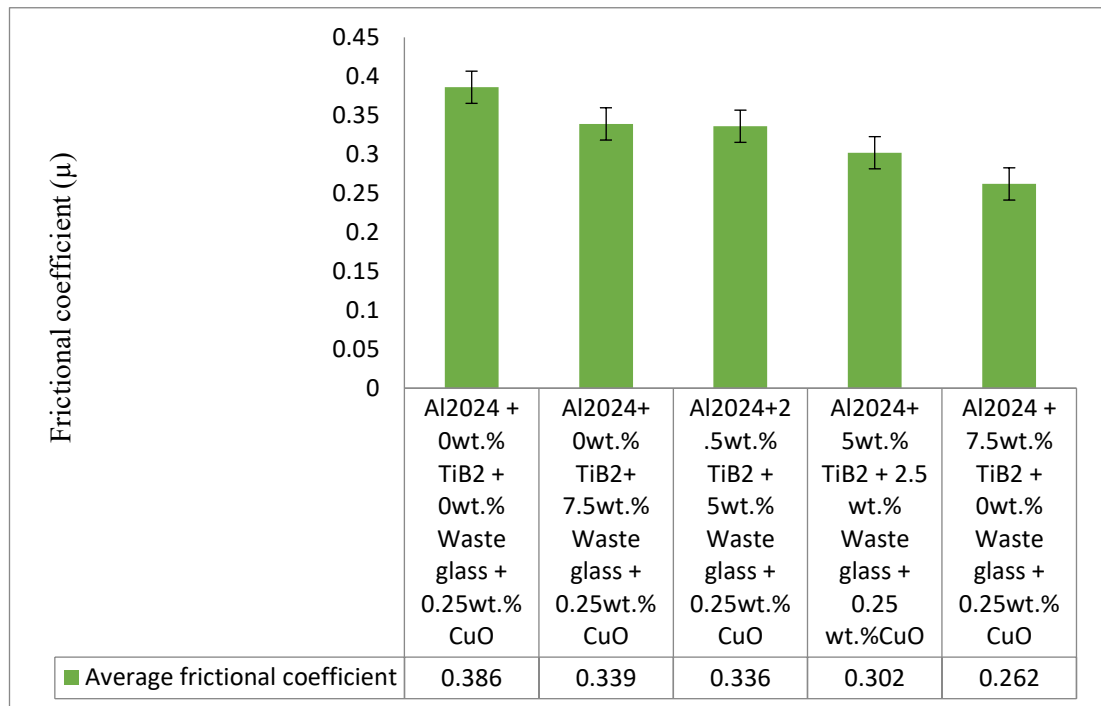


Figure 4.12 Effect of reinforcement on frictional coefficient

4.6.4 Effect of reinforcement percentage on the wear rate

The experimental results reveal that the inclusion of TiB₂, Waste glass powder, and CuO into AA2024 significantly affects the wear rate of the composite material. As the percentage of TiB₂ increases, the wear rate decreases. This is due to the high hardness and wear resistance of TiB₂ particles, which enhance the composite's ability to

withstand wear and reduce material loss during frictional contact. Figure 4.13 shows the effect of reinforcement percentage on the wear rate of the fabricated composite. In contrast, the addition of Waste glass powder as a reinforcement tends to increase the wear rate. This could be because waste glass powder, while contributing to the overall structure, may not provide sufficient hardness or strength compared to TiB_2 , leading to higher wear and material degradation. On the other hand, the fixed inclusion of CuO (0.25 wt.%) helps reduce the wear rate. CuO is known for its ability to reduce friction and enhance wear resistance due to its hardness and potential to form a protective layer during wear, thus reducing material loss. Overall, while TiB_2 effectively reduces the wear rate due to its hardness, the combination of TiB_2 and CuO improves the wear resistance of the AA2024 composite, while Waste glass powder has a detrimental effect on the wear performance when added alone.

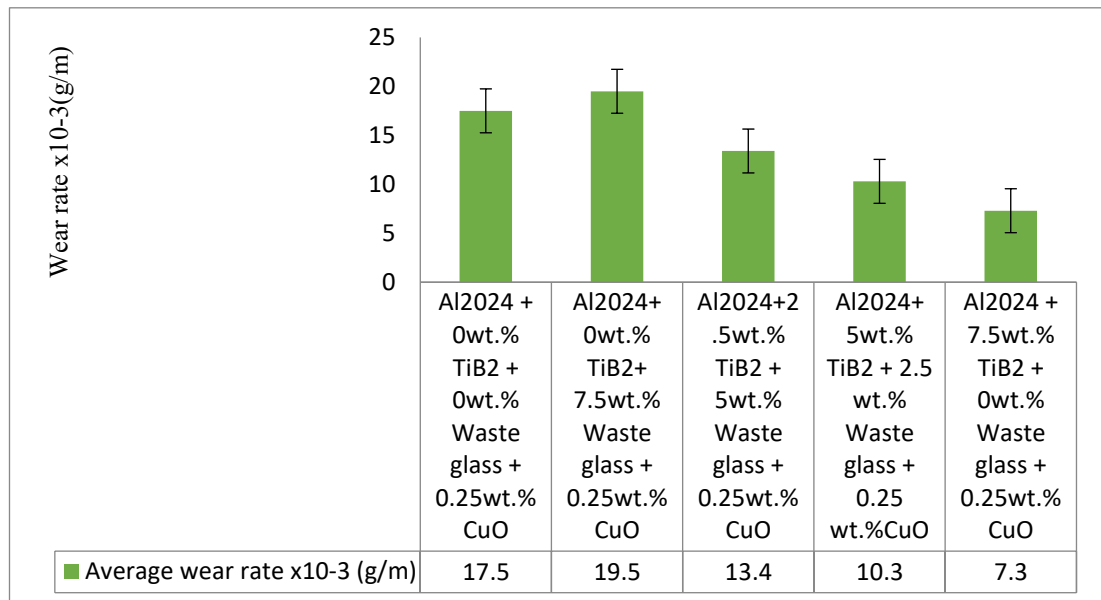


Figure 4.13 Effect of reinforcement percentage on wear rate

4.6.5 Microstructural examination of composite material

The microstructural analysis of AA2024 reinforced with TiB_2 , waste glass powder, and CuO composite material, prepared by the stir casting method was carried out to ensure fairly dispersion of reinforcements. After casting, the samples are prepared by cutting, mounting in resin, grinding, polishing, and etching to obtain a smooth, defect-free surface for analysis. For microstructural examination, an Olympus BX53 optical microscope was used at 100x and 200x magnifications to observe the dispersion of reinforcements and the matrix structure. Figure 4.14 (a) shows the optical micrographs of Sample 1 at 100x showing a general distribution of TiB_2 particles and waste glass powder, with some regions exhibiting agglomeration and minor porosity. Figure 4.14(c) shows the micrographs of sample 1 at 200x, finer details like the interface bonding between the matrix and reinforcements become visible, revealing some voids or poor bonding at certain areas. Figure 4.14 (b) shows the micrographs of sample 2, at both 100x and Figure 4.14 (d) shows the micrographs at 200x magnifications. It shows improved in the dispersion of the reinforcements and a more consistent matrix-reinforcement interface. Micrographs at these magnifications highlight the presence of TiB_2 , CuO, and glass phases, their morphology, and the phase boundaries, providing a clear picture of the composite's microstructure, which aids in understanding its mechanical properties and potential performance.

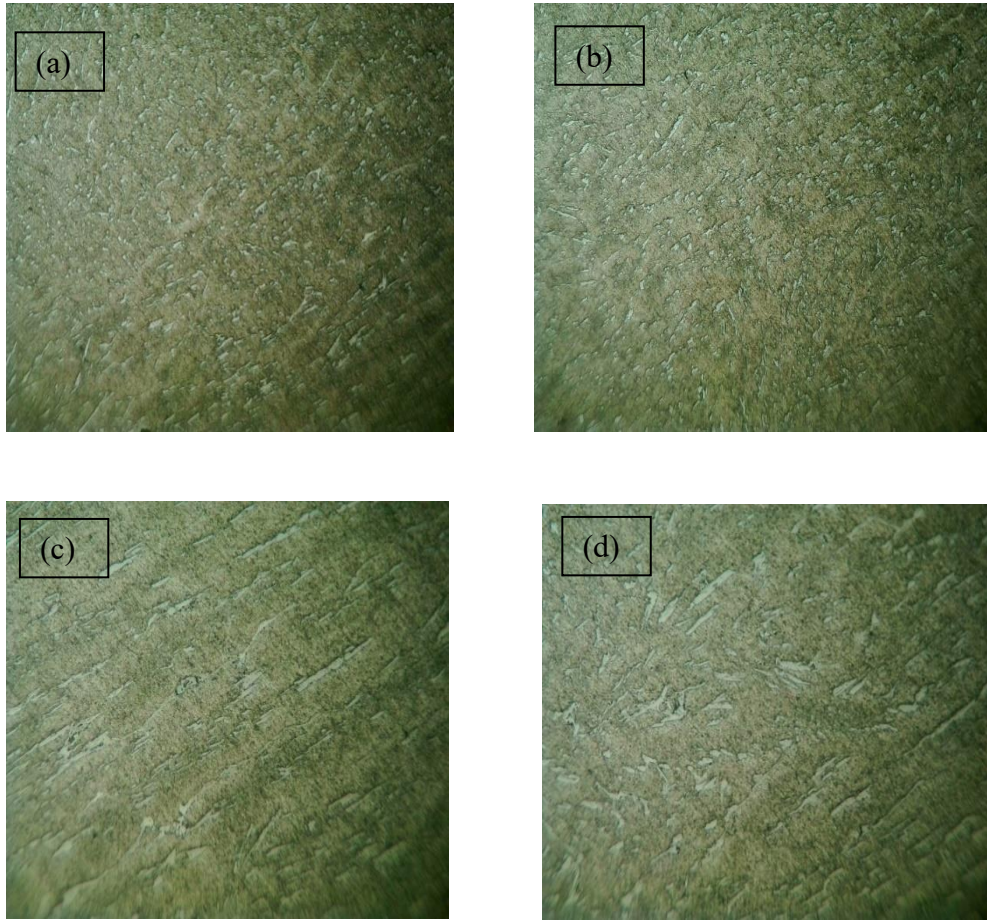


Figure 4.14 (a) No1 100 X (b) No.2 100 X (c) No1 200 X (d) No2 200 X

4.6.6 EDS elemental mapping of the composite material

For the elemental mapping examination of AA2024 + wt.% TiB₂ + wt.% Waste glass powder + wt.% CuO composite material, the EDAX Apollo X EDS machine was used in conjunction with Scanning Electron Microscopy (SEM) to analyze and map the distribution of elements such as carbon (C), oxygen (O), copper (Cu), iron (Fe), and magnesium (Mg). This machine provides high sensitivity and accuracy in detecting elements across various phases in developed composite materials. The results from the elemental mapping typically highlight the presence of specific elements like Cu, Fe,

and Mg, which were expected in the tested samples, along with the characteristic distribution of TiB_2 , waste glass powder, and CuO phases in the AA2024 matrix. Figure 4.15 EDS spectrum of the fabricated composite material. Figure 4.16 shows the different elements present in the EDS elemental mapping.

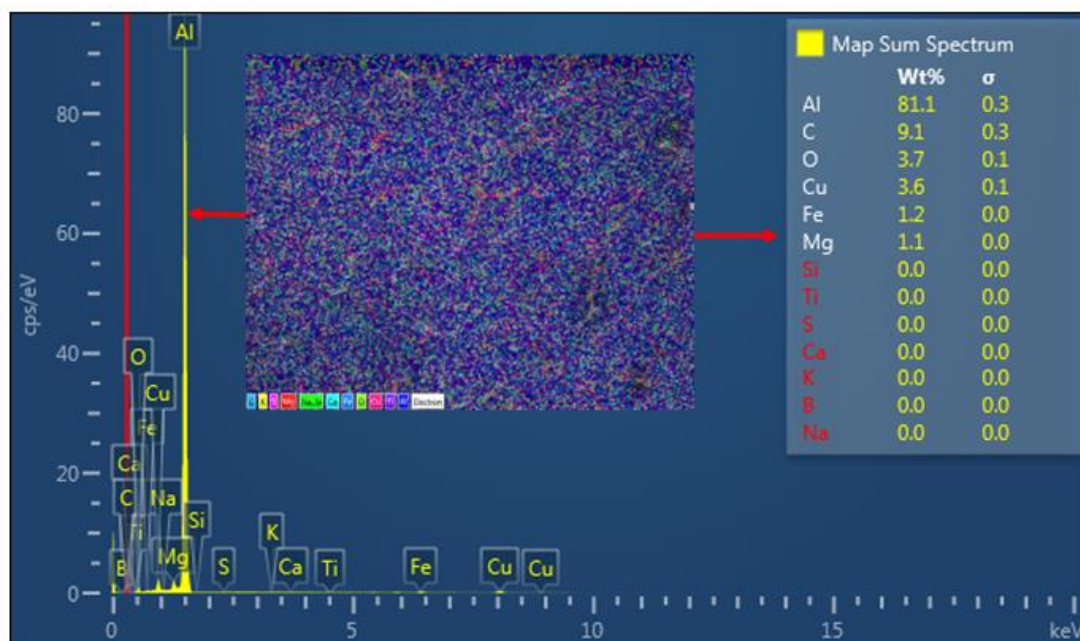
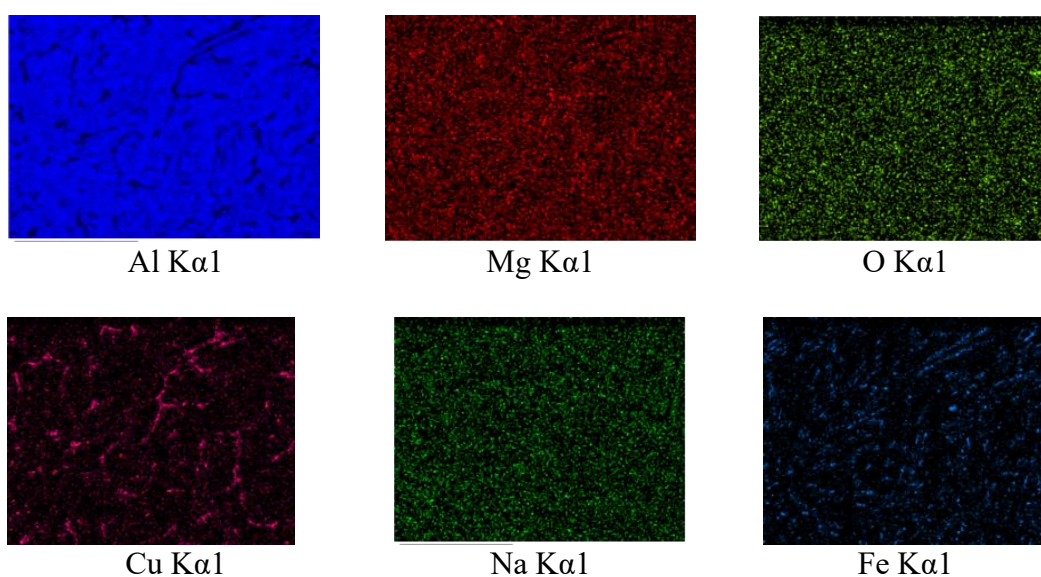


Figure 4.15 EDS spectrum of the fabricated composite material



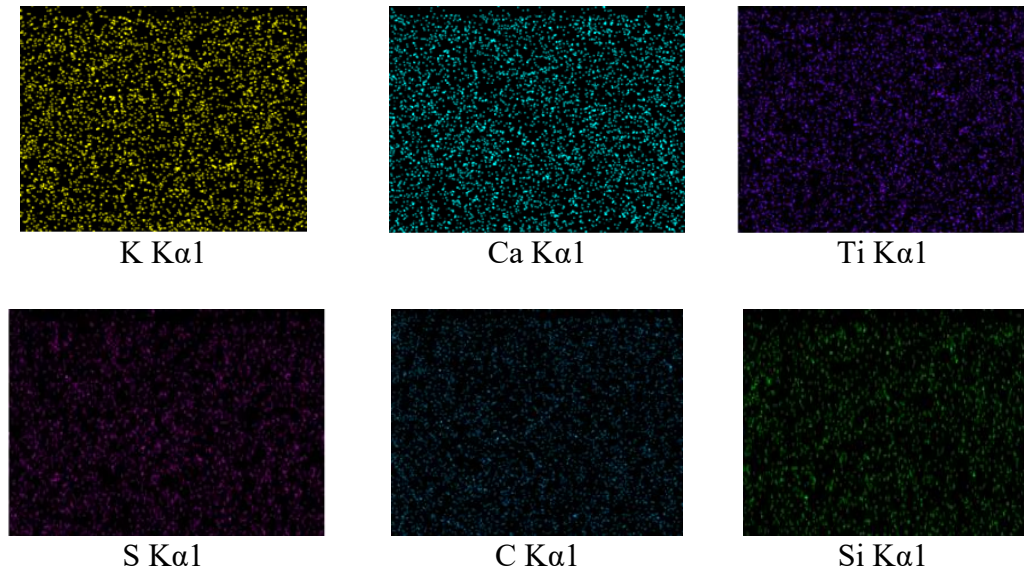


Figure 4.16 EDS Analysis of developed composite material

4.6.7 FESEM analysis of worn-out surface

Field Emission Scanning Electron Microscopy (FESEM) analysis of the worn-out surface of AA2024 + wt.% TiB₂ + wt.% Waste glass powder + wt.% CuO composite material was conducted by using the JEOL JSM-7100F FESEM machine. Advanced FESEM systems offer high-resolution imaging, which is essential for examining the wear surfaces of composite materials in great detail. The results from the wear surface analysis highlighted key points such as the extent of wear, surface roughness, and the presence of wear debris. The specific observations i.e. formation of microcracks, and delamination are shown on the worn surface. The distribution of TiB₂, CuO, and Waste glass powder particles on the worn surface shows how these phases contribute to wear resistance. The FESEM analysis provides crucial insights into the relationship between

the material's microstructure and its wear behavior under specific conditions. Figure

4.17 FESEM analysis of worn-out surface (a)500x (b)1000x (c) 5000x(d) 200x

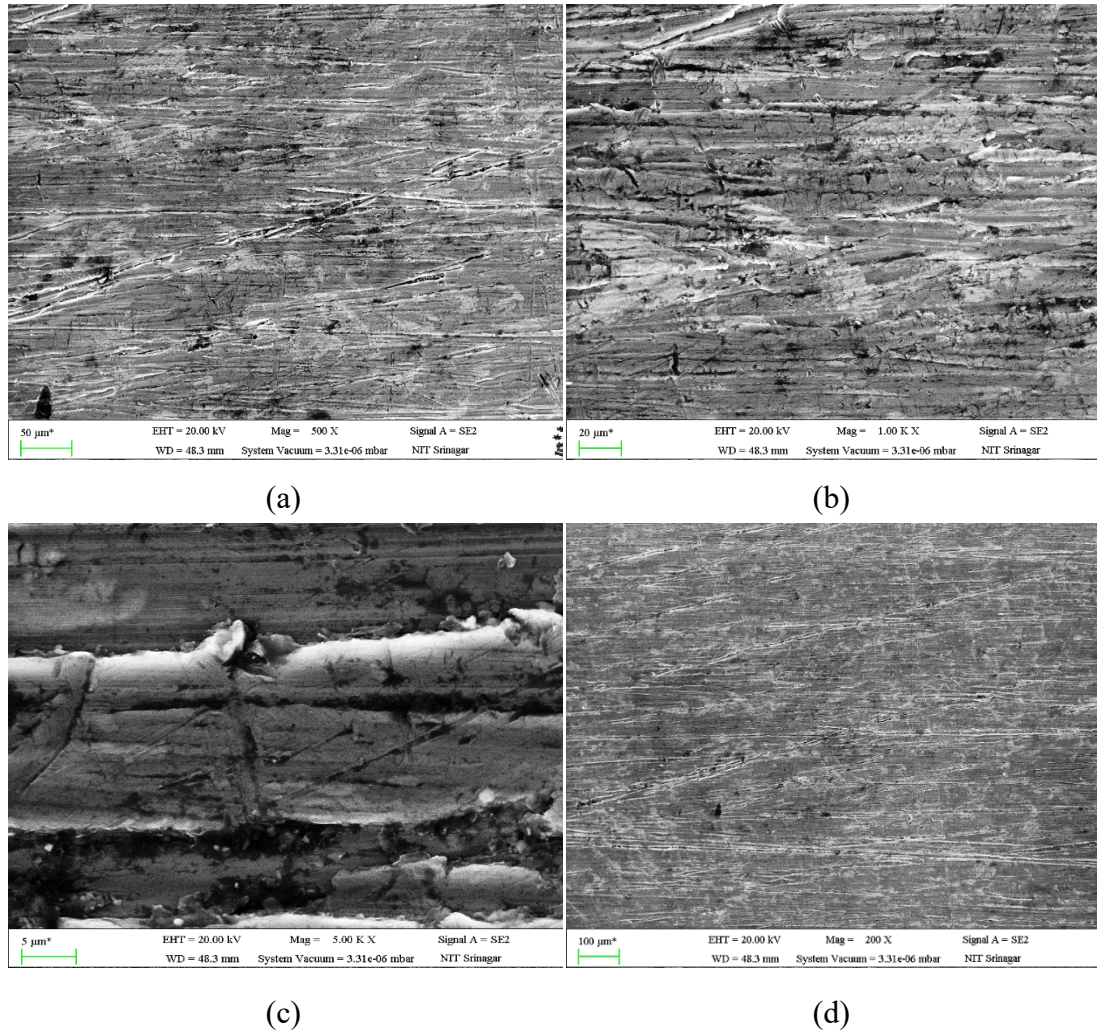


Figure 4.17 FESEM analysis of worn-out surface (a)500x (b)1000x (c) 5000x(d) 200x

4.6.8 Confirmation test

The confirmation test for the wear test has been conducted at the optimum level of process parameters. The optimum level of process parameters was found to be TiB₂ (wt.%) at 7.5%, Waste glass powder (wt.%) at 7.5%, a load of 15 N, a sliding velocity of 0.75 m/s, and a sliding distance of 1000 meters. To check the repeatability of the

experimental result, three experiments were conducted at the optimum level of process parameter and their average value is compared with the model value

Table 4.3 Confirmation test

Process parameters	Optimum level	Model value of wear rate $\times 10^{-3}$	Experimental value wear rate $\times 10^{-3}$
TiB ₂ (wt.%)	7.5	3.795	4.133
Waste glass powder (wt.%)	7.5		
Load (N)	15		
Sliding velocity (m/s)	0.75		
Sliding distance (m)	1000		

. The optimum level of process parameters and their model, experimental value is presented in Table 4.3. The model value for the wear rate is 3.795×10^{-3} and the experimental value of wear rate was found to be 4.133×10^{-3} , which is close to the experimental value. The test validate that the experimental results align with the expected wear behavior as predicted by the model

4.7. Effect of Reinforcement Particles on CTE

The Figure 4.18 demonstrates the variation of the coefficient of thermal expansion (CTE) of eight different composites of the AA2024 with TiB₂-mixed with Waste glass powder and nano-CuO. Sample 1, the base alloy, has the highest CTE about $23.4 \times 10^{-6} \text{ K}^{-1}$ which is typical for aluminium alloys because they expand relatively much as the temperature changes. When 7.5 wt.% TiB₂ and 0.25 wt.% nano- CuO are added (Sample 2), CTE is reduced to about $22.8 \times 10^{-6} \text{ K}^{-1}$ indicating that the ceramic reinforcement reduces the expansion of the aluminium matrix. As the mix changes

from higher TiB₂ content to higher waste glass powder content from Samples 3 to 8, there is a slightly greater decrease in the CTE which levels off between 21.8 to 22.4 x 10⁻⁶ K⁻¹. This drop is due to the lower thermal expansion of the ceramic particles and the high bond between particles and matrix.

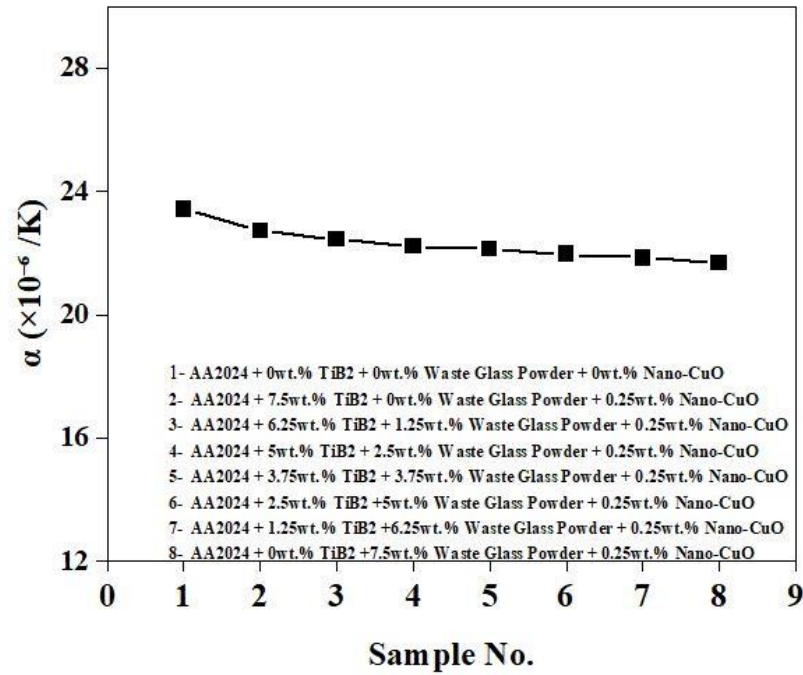


Figure 4.18 Coefficient of Thermal Expansion

Moreover, fairly distribution of TiB₂ and waste glass along with the nano-CuO aids in controlling the lattice expansion and improving the thermal dimensional stability. In sum, the use of these hybrid reinforcements fairly reduces the expansion of AA2024 composites, which is convenient for applications that require dimensional stability over temperature variations.

Chapter 5

Conclusions, Future Scope and Social Impact

In this study, the development, characterization, optimization and numerical validation of a hybrid aluminium matrix composite based on AA2024-T6 reinforced with TiB_2 , waste glass powder (WGP), and nano-CuO has been carried out. The main goal was to investigate the synergistic strengthening effect of the hybrid reinforcements and to find out an optimum reinforcement composition with enhanced mechanical, tribological and thermal performance while keeping ductility at an acceptable value. Through systematic experimental investigation, microstructural characterization, statistical optimization using Taguchi methodology, and finite element simulation, shows that the structural performance of AA2024 based composites can be significantly improved using properly engineered hybrid reinforcement and established a predictive model for advanced engineering applications.

5.1 Conclusions

- AA2024-T6 was effectively used as the matrix material for the preparation of the hybrid metal matrix composites due to its higher strength for its application in structural materials with high requirements of mechanical and tribological performance.
- The addition of TiB_2 , waste glass powder (WGP) and nano-CuO has created an effective hybrid reinforcement system at different scales to achieve a synergistic strengthening effect in the aluminium matrix.

- Stir casting was found to be a suitable and economic fabrication method to prepare hybrid composites of AA2024 based materials that contain adequate reinforcement incorporation and distribution.
- Microstructural modification of the matrix material was promoted by the reinforcement system, which resulted in grain refinement, matrix constraint and dislocation strengthening to improve and contribute to overall composite performance.
- It was observed that beyond the optimum WGP content, any further increase in WGP resulted in a reduction in mechanical performance and deterioration of the microstructural integrity.
- The mechanical performance of AA2024 was significantly improved by the addition of hybrid reinforcement, especially for the 5 wt.% TiB₂ + 2.5 wt.% WGP + 0.25 wt.% nano-CuO composition, which was found to be best combination for tensile, and flexural strengths.
- The strain-hardening capability of the composite was evaluated by using Hollomon parameters and it was found that the addition of reinforcement increased the resistance to localized plastic deformation up to the optimum reinforcement level.
- The decrease of strain-hardening properties with increasing WGP contents suggested that interfacial weakening and reinforcement clustering have adverse effects on the deformation behaviour.
- Hardness measurements showed that the addition of reinforcement material significantly enhanced the resistance to localized plastic deformation, with the highest hardness value at the highest composition of the WGP.

- Fractographic investigations showed that the best composite had a significant ductile fracture characteristic, which proves that the stress transfer was good and there was a good interaction between reinforcement and matrix.
- The higher WGP composites showed progressively brittle fracture characteristics and demonstrated 'direct link between the reinforcement agglomeration and failure mechanisms.
- The best wear condition obtained by Taguchi analysis has shown the ability of the reinforcement system to enhance the wear resistance considerably in comparison to the base alloy.
- The regression model produced was found to be reliable in predicting the wear behaviour and also good agreement was obtained between the regression and experimental results, thereby validating the statistical methodology used.
- In the case of the reinforced composites, the decrease in coefficient of friction that was obtained verified the positive effect of the use of ceramic reinforcements on the sliding wear performance.
- Worn surface analysis showed that the addition of reinforcement was an effective method to reduce severe adhesive wear and promote mild wear mechanism in sliding contact.
- Restriction of matrix thermal expansion was shown to be an effective method of enhancing the dimensional stability of AA2024 via thermal expansion studies of the hybrid reinforcement.
- The developed constitutive model was found to be suitable for describing composite behaviour as it was able to reproduce the experimental tensile response with finite element simulation.

- The developed composite achieved the required properties of strength, hardness, wear resistance and thermal stability within the acceptable level of ductility, which were successfully achieved using the hybrid reinforcement system.

The developed hybrid composite was tested extensively with experimental, statistical and numerical analysis to demonstrate technical potential for the use of industrial waste glass powder with TiB_2 and Nano-CuO as an effective reinforcement for sustainable material for advanced engineering applications.

5.2 Future Scope

The present study successfully demonstrated the development and characterization of AA2024 based Hybrid composites with TiB_2 , waste glass powder (WGP) and nano-CuO. While the mechanical, wear and thermal properties have been improved to a great extent, there is still a need for further research to increase the understanding of strengthening mechanisms, long term performance and industrial applications of the developed composites. The following research directions are suggested for further research:

- Advanced fabrication techniques like ultrasonic assisted stir casting, electromagnetic stirring, spark plasma sintering and friction stir processing can be considered for better dispersion of particles, less porosity and a more homogeneous microstructure.
- Advanced characterisation methods like TEM, STEM, EBSD and Atom Probe Tomography (APT) can also be applied for the investigation of strengthening mechanisms at the nanoscale, dislocation behaviour and interfacial phenomena.

- Further research on fatigue life, fracture toughness testing, crack propagation and damage evaluation can be done to ensure long-term structural reliability.
- The composite performance can also be assessed under service-relevant conditions by conducting the following tests: High-temperature mechanical testing, creep behaviour analysis, thermal aging and thermal stability studies.
- Complete corrosion and environmental durability tests such as potentiodynamic polarization, electrochemical impedance spectroscopy and salt spray testing can also be conducted to study corrosion in detail.
- For a wider range of understanding about wear mechanisms, advanced tribological studies can also be extended to the following lubricated, fretting and multi-body wear conditions.
- More advanced numerical methods like the representative volume element (RVE) modelling, cohesive zone modelling, and multiscale modelling can be done to accurately predict the evaluation of deformation and damage.
- Artificial intelligence and machine learning techniques assisted by artificial neural network or the optimization algorithms can also be used for reinforcement composition optimization and property prediction.

5.3 Social and Industrial Impact

The use of Waste glass powder (WGP) as reinforcement provides a valuable pathway in the utilization of industrial wastes to value-added engineering materials. The new hybrid composite material can be used to increase the sustainability of material development, while retaining improved engineering properties and conserving resources.

Introduction of WGP fosters the concept of circular economy by recycling and reusing waste resources and minimizing the use of virgin raw materials. Use of industrial waste material helps in reducing the amount of waste disposed in landfills and helps reduce the environmental impact of waste management.

The obtained composite materials have the potential to be used in lightweight structural applications due to their enhanced strength to weight ratio. The use of lightweight composites in the transport sectors can help to enhance fuel efficiency and lower operating expenses. Minimized components mass can contribute to reduced fuel consumption and carbon emissions, ensuring environmental sustainability.

The composites developed possess better mechanical, tribological and thermal properties, suitable for applications in aerospace, automotive, defence and other engineering applications. The research encourages the application of green manufacturing process using sustainable and ecological reinforcement materials. This successful adoption of industrial waste for advanced composite means that more effort is going into developing new materials and methods for composites, which is good for sustainable materials engineering.

Use of low-cost waste derived reinforcements provides opportunities for economical large-scale production of advanced composite materials. The developed composite system is an opportunity for future research and development in the field of sustainable technologies and high-performance materials in industry.

Overall, the study represents an effort to achieve sustainable engineering practices, as it aims to balance the performance of the materials used, environmental sustainability, and efficient use of resources.

Reference

1. Santin, J. J., Onder, C. H., Bernard, J., Isler, D., Kobler, P., Kolb, F & Guzzella, L. (2007). *The World's Most Fuel-Efficient Vehicle: Design and Development of Pac Car II*. vdf Hochschulverlag AG. Excerpt_12.10.07.pdf
2. Al-Mulali, U. (2014). Investigating the impact of nuclear energy consumption on GDP growth and CO2 emission: A panel data analysis. *Progress in Nuclear Energy*, 73, 172-178.
3. Saidi, K., & Omri, A. (2020). Reducing CO2 emissions in OECD countries: do renewable and nuclear energy matter? *Progress in Nuclear Energy*, 126, 103425.
4. Kumar, M., Shao, Z., Braun, C., & Bandivadekar, A. (2022). Decarbonizing India's road transport: A meta-analysis of road transport emissions models. *Int. Council Clean Transp*, 1-34.
5. Ramachandran, K., Boopalan, V., Bear, J. C., & Subramani, R. (2022). Multi-walled carbon nanotubes (MWCNTs)-reinforced ceramic nanocomposites for aerospace applications: a review. *Journal of Materials Science*, 57(6), 3923-3953.
6. Joost, W. J. (2012). Reducing vehicle weight and improving US energy efficiency using integrated computational materials engineering. *Jom*, 64(9), 1032-1038.
7. S. Zoepf, *Automotive Features; Mass Impact and Deployment Characterization* (M.S. Thesis, Massachusetts Institute of Technology, 2011) *Automotive features: mass impact and deployment characterization*

8. Karabulut, Y., & Ünal, R. (2022). Additive manufacturing of ceramic particle-reinforced aluminum-based metal matrix composites: a review. *Journal of Materials Science*, 57(41), 19212-19242.
9. Warren, A. S. (2004, August). Developments and challenges for aluminum--A boeing perspective. In *Materials forum* (Vol. 28, pp. 24-31).
10. Amirkhanlou, S., & Ji, S. (2020). A review on high stiffness aluminum-based composites and bimetallics. *Critical Reviews in Solid State and Materials Sciences*, 45(1), 1-21.
11. Scudino, S., Liu, G., Sakaliyska, M., Surreddi, K. B., & Eckert, J. (2009). Powder metallurgy of Al-based metal matrix composites reinforced with β -Al₃Mg₂ intermetallic particles: Analysis and modeling of mechanical properties. *Acta Materialia*, 57(15), 4529-4538.
12. Nishino, K. (2017). Development of fuel economy regulations and impact on automakers. Mitsui global strategic studies institute monthly report.
13. IHS, Light vehicle production from 2016 to 2024, by major market (in million units), Statista (2017).
14. Rawal SP (2001) Metal-matrix composites for space applications. *JOM* 53(4):14–17
15. Miracle DB, and Hunt WH (2004) "Automotive applications of metal matrix composites." *Aluminium Consultant Group Inc*: 1029–1032. (<https://dl.asminternational.org/handbooks/edited-volume/60/chapter-abstract/702992/Automotive-Applications-of-Metal-Matrix-Composites?redirectedFrom=PDF>)

16. Nash P, Zhao N (2020) 1000 at 1000: particulate-reinforced metal matrix composites. *J Mater Sci* 55(34):16059–16062
17. Taub A, De Emmanuel M, Luo A, Matlock DK, Speer JG, Vaidya U (2019) *Materials for automotive lightweighting. Annu Rev Mater Res* 4:327–359
18. Lagneborg, R. (1991). *New steels and steel applications for vehicles. Materials & Design*, 12(1), 3-14.
19. Olhan, S., Khatkar, V., & Behera, B. K. (2021). *Textile-based natural fibre-reinforced polymeric composites in automotive lightweighting. Journal of Materials Science*, 56(34), 18867-18910.
20. Gurunathan, T., Mohanty, S., & Nayak, S. K. (2015). *A review of the recent developments in biocomposites based on natural fibres and their application perspectives. Composites Part A: Applied Science and Manufacturing*, 77, 1-25.
21. Sanjay, M. R., Madhu, P., Jawaaid, M., Senthamaraiannan, P., Senthil, S., & Pradeep, S. (2018). *Characterization and properties of natural fiber polymer composites: A comprehensive review. Journal of Cleaner production*, 172, 566-581.
22. Li, Y., Liu, J., Huang, W., & Zhang, S. (2022). *Microstructure related analysis of tensile and fatigue properties for sand casting aluminum alloy cylinder head. Engineering Failure Analysis*, 136, 106210.
23. González, R., González, A., Talamantes-Silva, J., Valtierra, S., Mercado-Solís, R. D., Garza-Montes-de-Oca, N. F., & Colás, R. (2013). *Fatigue of an aluminium cast alloy used in the manufacture of automotive engine blocks. International Journal of Fatigue*, 54, 118-126.

24. Sajadifar, S. V., Scharifi, E., Wegener, T., Krochmal, M., Lotz, S., Steinhoff, K., & Niendorf, T. (2022). *On the low-cycle fatigue behavior of thermo-mechanically processed high-strength aluminum alloys. International Journal of Fatigue*, 156, 106676.
25. Al-Alimi, S., Yusuf, N. K., Ghaleb, A. M., Lajis, M. A., Shamsudin, S., Zhou, W. & Adam, A. (2024). *Recycling aluminium for sustainable development: A review of different processing technologies in green manufacturing. Results in engineering*, 23, 102566.
26. Rohatgi P (1991) *Cast aluminum-matrix composites for automotive applications. JOM* 43(4):10–15
27. Efthymiou, E., Cöcen, Ö. N., & Ermolli, S. R. (2010). *Sustainable aluminium systems. Sustainability*, 2(9), 3100-3109.
28. Gopalakrishnan S, Murugan N (2012) *Production and wear characterisation of AA 6061 matrix titanium carbide particulate reinforced composite by enhanced stir casting method. Compos B Eng* 43(2):302–308
29. Kala H, Mer KKS, Kumar S (2014) *A review on mechanical and tribological behaviors of stir cast aluminum matrix composites. Procedia Mater Sci* 6:1951–1960
30. Kumar, A., Singh, V. P., Singh, R. C., Chaudhary, R., Kumar, D., & Mourad, A. H. I. (2024). *A review of aluminum metal matrix composites: fabrication route, reinforcements, microstructural, mechanical, and corrosion properties. Journal of Materials Science*, 59(7), 2644-2711.
31. Chawla, K. K. (2012). *Composite materials: science and engineering. Springer Science & Business Media*.

- 32 Hashim, J., Looney, L., & Hashmi, M. S. J. (1999). *Metal matrix composites: production by the stir casting method. Journal of materials processing technology*, 92, 1-7.
- 33 Callister Jr, W. D., & Rethwisch, D. G. (2020). *Materials science and engineering: an introduction. John wiley & sons.*
- 34 Gök, D. A., Bayraktar, C., & Hoşkun, M. (2024). *A review on processing, mechanical and wear properties of Al matrix composites reinforced with Al₂O₃, SiC, B₄C and MgO by powder metallurgy method. Journal of Materials Research and Technology*, 31, 1132-1150.
- 35 Channar, H. R., Ullah, B., Naseem, M. S., Akhter, J., Mehmood, A., & Aamir, M. (2024). *Mechanical properties and microstructural investigation of AA2024-T6 reinforced with Al₂O₃ and SiC metal matrix composites. Eng*, 5(4), 3023–3032.
36. Subramanya Reddy, P., Kesavan, R., & Vijaya Ramnath, B. (2017). *Evaluation of mechanical properties of aluminum alloy (Al2024) reinforced with silicon carbide (SiC) metal matrix Composites. Solid state phenomena*, 263, 184-188.
37. Işıtan, A., Aytekin, S., & Onar, V. (2024). *Enhancing the microstructure and mechanical properties of cast aluminum matrix composites through nano-al₂o₃ reinforcement via CMT and PMC welding. International Journal of Metal casting*, 18(4), 3166-3179.
38. Lee, K. B., Nayak, K. C., Shim, C. H., Lee, H. I., Kim, S. H., Choi, H. J., & Ahn, J. P. (2023). *Tensile properties of aluminum matrix composites produced via a nitrogen-induced self-forming process. Journal of Composites Science*, 7(11), 457.

39. Chandla, N. K., Kant, S., & Goud, M. M. (2023). *A review on mechanical properties of stir cast Al-2024 metal matrix composites. Advances in Materials and Processing Technologies*, 9(3), 948-969.
40. Gaurav, S. K., Singh, V. K., & Chauhan, S. (2024). *Fabrication and Mechanical Strengthening of Aluminium Composite Material-A Review. J. Mater. Environ. Sci.*, 15 (11), 1526, 1548.
41. Hosseinzadeh, A., & Yapici, G. G. (2018). *High temperature characteristics of Al2024/SiC metal matrix composite fabricated by friction stir processing. Materials Science and Engineering: A*, 731, 487-494.
42. Rofman, O. V., Mikhaylovskaya, A. V., Kotov, A. D., Mochugovskiy, A. G., Mohamed, A. K., Cheverikin, V. V., & Short, M. P. (2020). *AA2024/SiC metal matrix composites simultaneously improve ductility and cracking resistance during elevated temperature deformation. Materials Science and Engineering: A*, 790, 139697.
43. Tiwari, J. K., Mandal, A., Rudra, A., Mukherjee, D., & Sathish, N. (2019). *Evaluation of mechanical and thermal properties of bilayer graphene reinforced aluminum matrix composite produced by hot accumulative roll bonding. Journal of Alloys and Compounds*, 801, 49-59.
44. Najar, F. A., Rathee, S., Srivastava, M., Kaushik, A., & Gautam, R. K. S. (2026). *Enhancement of Tribological, Mechanical and Fluidic characteristics of Al5059/B4C+ 5% Mg Surface Composites using Friction Stir Processing. Tribology International*, 111648.
45. Reddy, M. P., Shakoor, R. A., Parande, G., Manakari, V., Ubaid, F., Mohamed, A. M. A., & Gupta, M. (2017). *Enhanced performance of nano-sized*

SiC reinforced Al metal matrix nanocomposites synthesized through microwave sintering and hot extrusion techniques. Progress in natural science: materials international, 27(5), 606-614.

46. Kim, C. S., Cho, K., Manjili, M. H., & Nezafati, M. (2017). *Mechanical performance of particulate-reinforced Al metal-matrix composites (MMCs) and Al metal-matrix nano-composites (MMNCs). Journal of Materials Science, 52(23), 13319-13349.*

47. Yoo, S. C., Lee, D., Ryu, S. W., Kang, B., Ryu, H. J., & Hong, S. H. (2023). *Recent progress in low-dimensional nanomaterials filled multifunctional metal matrix nanocomposites. Progress in Materials Science, 132, 101034.*

48. Ujah, C. O., Popoola, A. P. I., Popoola, O. M., & Aigbodion, V. S. (2019). *Enhanced tribology, thermal and electrical properties of Al-CNT composite processed via spark plasma sintering for transmission conductor. Journal of Materials Science, 54(22), 14064-14073.*

49. Sun, H., Saba, F., Fan, G., Tan, Z., & Li, Z. (2022). *Micro/nano-reinforcements in bimodal-grained matrix: A heterostructure strategy for toughening particulate reinforced metal matrix composites. Scripta Materialia, 217, 114774.*

50. Sajjadi, S. A., Parizi, M. T., Ezatpour, H. R., & Sedghi, A. (2012). *Fabrication of A356 composite reinforced with micro and nano Al₂O₃ particles by a developed compo casting method and study of its properties. Journal of alloys and compounds, 511(1), 226-231.*

51. Chak, V., Chattopadhyay, H., & Dora, T. L. (2020). *A review on fabrication methods, reinforcements and mechanical properties of aluminum matrix composites. Journal of manufacturing processes*, 56, 1059-1074.
52. Singh, A. K., Soni, S., & Rana, R. S. (2020). *A critical review on synthesis of aluminum metallic composites through stir casting: challenges and opportunities. Advanced Engineering Materials*, 22(10), 2000322.
53. Sun, Z., Luo, Y., Chen, C., Dong, Z., Jiang, G., Chen, F., & Ma, P. (2024). *Mechanical enhancement of carbon fiber-reinforced polymers: From interfacial regulating strategies to advanced processing technologies. Progress in Materials Science*, 142, 101221.
54. Clyne, T. W., & Withers, P. J. (1993). *An introduction to metal matrix composites. Cambridge university press*.
55. Gupta, A., & Basu, B. (2019). *Sustainable primary aluminium production: technology status and future opportunities. Transactions of the Indian Institute of Metals*, 72(8), 2135-2150.
56. Ashby, M. F. (2012). *Materials and the environment: eco-informed material choice. Elsevier*.
57. Jagadeesh, G. V., & Gangi Setti, S. (2020). *A review on micromechanical methods for evaluation of mechanical behavior of particulate reinforced metal matrix composites. Journal of Materials Science*, 55(23), 9848-9882.
58. Heinz, A., Haszler, A., Keidel, C., Moldenhauer, S., Benedictus, R., & Miller, W. S. (2000). *Recent development in aluminium alloys for aerospace applications. Materials Science and Engineering: A*, 280(1), 102-107.

59. Surappa, M. K. (2003). *Aluminium matrix composites: Challenges and opportunities*. *Sadhana*, 28(1), 319-334.
60. Jayakumar, J., Raghunath, B. K., & Rao, T. H. (2012). *Recent development and challenges in synthesis of magnesium matrix nano composites—A Review*. *Int. J. Latest Res. Sci. Technol*, 1, 164-171.
61. Ye, H. Z., & Liu, X. Y. (2004). *Review of recent studies in magnesium matrix composites*. *Journal of materials science*, 39(20), 6153-6171.
62. Saravanan, R. A., & Surappa, M. K. (2000). *Fabrication and characterisation of pure magnesium-30 vol.% SiCP particle composite*. *Materials Science and Engineering: A*, 276(1-2), 108-116.
63. Alam, S. N., & Singh, H. (2014). *Development of copper-based metal matrix composites: An analysis by SEM, EDS and XRD*. *Microscopy and Analysis*, 28(4), 8-13.
64. Chaudhary, N., & Singh, S. (2023). *Experimental investigation on microstructural and mechanical properties of in situ SiC-reinforced friction stir spot weld of Al 6061-T6*. *Journal of Materials Science*, 58(4), 1849-1868.
65. Singh, M., Mondal, D. P., Jha, A. K., Das, S., & Yegneswaran, A. H. (2001). *Preparation and properties of cast aluminium alloy–sillimanite particle composite*. *Composites Part A: Applied Science and Manufacturing*, 32(6), 787-795.
66. Ramnath, B. V., Elanchezhian, C., Jaivignesh, M., Rajesh, S., Parswajinan, C., & Ghias, A. S. A. (2014). *Evaluation of mechanical properties of aluminium alloy–alumina–boron carbide metal matrix composites*. *Materials & Design*, 58, 332-338.

67. Reddy, P. S., Kesavan, R., & Vijaya Ramnath, B. (2018). *Investigation of mechanical properties of aluminium 6061-silicon carbide, boron carbide metal matrix composite. Silicon, 10(2), 495-502.*
68. Kurbet, R., Basavaraj, Amruth, C. M., & Jayasimha, S. L. N. (2021, October). *Effect of ceramic particles on AMMC through stir casting method—a review. In Proceedings of Fourth International Conference on Inventive Material Science Applications: ICIMA 2021 (pp. 373-388). Singapore: Springer Singapore.*
69. Ahmed, A., Neely, A. J., & Shankar, K. (2007, January). *Effect of ceramic reinforcements on the mechanical behaviour of 7xxx series Aluminium matrix composites. In Proceedings of the 5th Australasian Congress on Applied Mechanics (pp. 459-464). Brisbane,*
70. Dinaharan, I., Sathiskumar, R., & Murugan, N. (2016). *Effect of ceramic particulate type on microstructure and properties of copper matrix composites synthesized by friction stir processing. Journal of Materials Research and Technology, 5(4), 302-316.*
71. Alaneme, K. K., Akintunde, I. B., Olubambi, P. A., & Adewale, T. M. (2013). *Fabrication characteristics and mechanical behaviour of rice husk ash–Alumina reinforced Al-Mg-Si alloy matrix hybrid composites. journal of Materials Research and Technology, 2(1), 60-67.*
72. Hashim, H., Salleh, M. S., & Omar, M. Z. (2019). *Homogenous dispersion and interfacial bonding of carbon nanotube reinforced with aluminum matrix composite: a review. Rev Adv Mater Sci, 58(1), 295-303.*
73. Mishra, T. N., Kumar, A., & Prasad, S. B. (2025). *A recent innovation in stir-cast aluminium metal matrix composites to improve mechanical and wear*

properties with potential applications: a review: mishra, kumar, and prasad. Jom, 77(10), 7895-7924.

74. Kok, M. (2005). *Production and mechanical properties of Al₂O₃ particle-reinforced 2024 aluminium alloy composites. Journal of materials processing technology, 161(3), 381-387.*

75. Vencl, A., Manić, N., Popovic, V., & Mrdak, M. (2010). *Possibility of the abrasive wear resistance determination with scratch tester. Tribology Letters, 37(3), 591-604.*

76. Prakash, B., Sivananthan, S., & Vijayan, V. (2021). *Investigation on mechanical properties of Al6061 alloy–Multiwall carbon nanotubes reinforced composites by powder metallurgy route. Materials Today: Proceedings, 37, 336-340.*

77. Chandio, A. D., Ansari, M. B., Hussain, S., & Siddiqui, M. A. (2019). *Silicon carbide effect as reinforcement on aluminium metal matrix composite. J. chem. soc. pak, 41(4), 650-654.*

78. Kumar, R., Jha, K., Sharma, S., Kumar, V., Li, C., Rajkumar, S., & Królczyk, G. (2022). *Effect of particle size and weight fraction of SiC on the mechanical, tribological, morphological, and structural properties of Al-5.6 Zn-2.2 Mg-1.3 Cu composites using RSM: fabrication, characterization, and modelling. Heliyon, 8(9).*

79. Alaneme, K., & Aluko, A. (2012). *Production and Age-Hardening Behaviour of SiC Reinforced Aluminium Composites Developed by Modified Stir-Casting Technique. West Indian Journal of Engineering.*

80. Suresh, S., Sudhakara, D., & Vinod, B. (2020). Investigation on mechanical, wear, and machining characteristics of Al 7075/MWCNTs using the liquid state method. *Advanced Composites and Hybrid Materials*, 3(2), 243-254.
81. Asthana, R., & Rohatgi, P. K. (1991). Solidification synthesis of pressure-infiltrated Al alloy 2014-SiC platelet composites. *Materials Science and Engineering: A*, 144(1-2), 169-178.
82. Beder, M., Varol, T., & Akçay, S. B. (2024). Impact of high Al₂O₃ content on the microstructure, mechanical properties, and wear behavior Al–Cu–Mg/Al₂O₃ composites prepared by mechanical milling. *Ceramics International*, 50(20), 38610-38631.
83. Yılmaz, O., & Buytoz, S. (2001). Abrasive wear of Al₂O₃-reinforced aluminium-based MMCs. *Composites Science and Technology*, 61(16), 2381-2392.
84. Manojkumar, S., & Mehta, K. K. (2023). Effect of TiB₂ on mechanical and corrosion properties of Al 7075/TiB₂/Gr composite prepared by stir casting. *Materials Today: Proceedings*, 91, 62-66.
85. Farooq, S. A., Mukhtar, S. H., Raina, A., Haq, M. I. U., Siddiqui, M. I. H., Naveed, N., & Dobrota, D. (2024). Effect of TiB₂ on the mechanical and tribological properties of marine grade Aluminum Alloy 5052: An experimental investigation. *Journal of Materials Research and Technology*, 29, 3749-3758.
86. Mohanavel, V., Rajan, K., & Senthil Kumar, K. R. (2015). Study on mechanical properties of AA6351 alloy reinforced with titanium di-boride (TiB₂) composite by in situ casting method. *Applied Mechanics and Materials*, 787, 583-587.

87. Loganathan, P., Gnanavelbabu, A., Rajkumar, K., & Ayyanar, S. (2020, April). *Microstructural characteristics and mechanical behaviour of AA7075/TiB₂ composite*. In *Materials Science Forum* (Vol. 979, pp. 40-46). Trans Tech Publications Ltd.
88. Paladugu, S. R. M., Aparna, N. D., & Sreekanth, P. R. (2022). *Mechanical and wear analysis of Al6061-SiC/Al₂O₃/B₄C hybrid metal matrix composites using stir casting process*. *Materials Today: Proceedings*, 56, 1091-1096.
89. Sangamaeswaran, R., Muhilan, S., Navin, J., Manuelraj, P. A., & Palaniappan, M. (2023). *Mechanical and wear properties of friction stir processing AA 6082-T6/B₄C aluminium matrix composites*. *Materials Today: Proceedings*.
90. Chakravarthy, M. P., & Rao, D. S. (2022). *Evaluation of mechanical properties of aluminium alloy (AA 6082) reinforced with rice husk ash (RHA) and boron carbide (B₄C) hybrid metal matrix composites using stir casting method*. *Materials Today: Proceedings*, 66, 580-586.
91. Balasubramanian, I., & Maheswaran, R. (2015). *Effect of inclusion of SiC particulates on the mechanical resistance behaviour of stir-cast AA6063/SiC composites*. *Materials & Design* (1980-2015), 65, 511-520.
92. Sharma, P., Dwivedi, S. P., Sharma, R., Dabra, V., & Sharma, N. (2020). *Microstructural and mechanical behavior of aluminium alloy reinforced with TiC*. *Materials Today: Proceedings*, 25, 934-937.
93. Kishore, T. V. (2019). *Al 7075 reinforced with WC metal matrix composites*. *Journal of Science and Technology*, 4, 45-50.

94. Satish Kumar, T., Suganya Priyadharshini, G., Shalini, S., Krishna Kumar, K., & Subramanian, R. (2019). Characterization of NbC-reinforced AA7075 alloy composites produced using friction stir processing. *Transactions of the Indian Institute of Metals*, 72(6), 1593-1596.
95. Lv, Z., Sha, J., Lin, G., Wang, J., Guo, Y., & Dong, S. (2023). Mechanical and thermal expansion behavior of hybrid aluminum matrix composites reinforced with SiC particles and short carbon fibers. *Journal of Alloys and Compounds*, 947, 169550.
96. Kumar, A., Ghosh, P. K., Yadav, K. L., & Kumar, K. (2017). Thermo-mechanical and anti-corrosive properties of MWCNT/epoxy nanocomposite fabricated by innovative dispersion technique. *Composites Part B: Engineering*, 113, 291-299.
97. Mokhayer, M. M., Kakroudi, M. G., Milani, S. S., Ghiasi, H., & Vafa, N. P. (2019). Investigation of AlN addition on the microstructure and mechanical properties of TiB₂ ceramics. *Ceramics International*, 45(13), 16577-16583.
98. Júnior, L. A. F., Tomaz, Í. V., Oliveira, M. P., Simão, L., & Monteiro, S. N. (2016). Development and evaluation of TiB₂-AlN ceramic composites sintered by spark plasma. *Ceramics International*, 42(16), 18718-18723.
99. Dinaharan, I., & Akinlabi, E. T. (2018). Low-cost metal matrix composites based on aluminum, magnesium and copper reinforced with fly ash prepared using friction stir processing. *Composites Communications*, 9, 22-26.
100. Vinothkumar, S., Karunakaran, S., Jayanthi, N., Bodkhe, M. G., Sadasivuni, H., & Hasane, S. A. (2023). Experimental investigation on the impact of

mechanical properties of SiC, Al₂O₃ and ZrSiO₄ particles on AA6063 composites. Materials Today: Proceedings.

101. Khanna, V., Kumar, V., & Bansal, S. A. (2021). *Mechanical properties of aluminium-graphene/carbon nanotubes (CNTs) metal matrix composites: Advancement, opportunities and perspective. Materials Research Bulletin, 138, 111224.*

102. Shinde, S. S., & Barve, S. B. (2024). *Advances in hybrid aluminium metal matrix composite produced by stir casting route: A review on applications and fabrication characteristics. Materials Today: Proceedings.*

103. Khalid, M. Y., Umer, R., & Khan, K. A. (2023). *Review of recent trends and developments in aluminium 7075 alloy and its metal matrix composites (MMCs) for aircraft applications. Results in Engineering, 20, 101372.*

104. Qadir, J., Lewis, A. S., Wessley, G. J. J., & Samuel, G. D. (2023). *Influence of nanoparticles in reinforced aluminium metal matrix composites in aerospace applications—A review. Materials Today: Proceedings.*

105. Dixit, P., & Suhane, A. (2022). *Aluminum metal matrix composites reinforced with rice husk ash: A review. Materials Today: Proceedings, 62, 4194-4201.*

106. Kumar, T. S., Shalini, S., Petru, J., & Kalita, K. (2025). *Effect Of Particulate Reinforcement On The Aging Behavior of Aluminium Metal Matrix Composites- A Review. Journal of Materials Research and Technology.*

107. Ahmaruzzaman, M. (2010). *A review on the utilization of fly ash. Progress in energy and combustion science, 36(3), 327-363.*

108. Mathapati, M., Amate, K., Prasad, C. D., Jayavardhana, M. L., & Raju, T. H. (2022). *A review on fly ash utilization. Materials Today: Proceedings*, 50, 1535-1540.
109. Selvam, J. D. R., Smart, D. R., & Dinaharan, I. (2013). *Microstructure and some mechanical properties of fly ash particulate reinforced AA6061 aluminum alloy composites prepared by compocasting. Materials & Design*, 49, 28-34.
110. Surappa, M. K. (2008). *Dry sliding wear of fly ash particle reinforced A356 Al composites. Wear*, 265(3-4), 349-360.
111. Prasad, R., Kumar, H., Sinha, N. K., Tewari, S. P., Singh, J. K., Yadav, S., & Deo, M. (2021). *Characterization of A356/(fly ash+ red mud) surface hybrid composite fabricated by friction stir processing. Materials Today: Proceedings*, 46, 1476-1480.
112. Yuan, W., Li, H., Zhang, D., Pan, T., Li, Y., Yan, Z., & Chang, N. (2025). *Effects of Red Mud Incorporation on the High-Temperature Performance of Alkali-Activated Fly Ash. Journal of Environmental Chemical Engineering*, 120061.
113. Chinta, N. D., Selvaraj, N., & Mahesh, V. (2018). *Mechanical characterization of aluminium–red mud metal matrix composites. Materials Today: Proceedings*, 5(13), 26911-26917.
114. Mishra, P., Mishra, P., & Rana, R. S. (2018). *Effect of rice husk ash reinforcements on mechanical properties of aluminium alloy (LM6) matrix composites. Materials today: proceedings*, 5(2), 6018-6022.

115. Alaneme, K. K., & Olubambi, P. A. (2013). Corrosion and wear behaviour of rice husk ash—Alumina reinforced Al–Mg–Si alloy matrix hybrid composites. *Journal of Materials Research and Technology*, 2(2), 188-194.
116. Balogun, O. A., Akinwande, A. A., Adediran, A. A., Ogunsanya, O. A., Ademati, A. O., Kumar, M. S., ... & Akinlabi, E. T. (2022). Microstructure and particle size effects on selected mechanical properties of waste glass-reinforced aluminium matrix composites. *Materials Today: Proceedings*, 62, 4589-4598.
117. Sinshaw, Y., & Palani, S. (2022). Mechanical property analysis of glass particulates reinforced Aluminum matrix composites. *Materials Today: Proceedings*, 62, 488-494.
118. Tejyan, S., Lal, C., Ror, C. K., & Singh, V. (2025). Influence of marble waste reinforcement on mechanical properties and sliding wear behavior of an aluminium alloy metal matrix composite. *Journal of Engineering Research*, 13(1), 131-141.
119. Al-Naib, U. M. B. (2026). Industrial and Agro-Waste Reinforcements in Aluminum Matrix Composites: Toward Sustainable Materials Development. *Total Environment Engineering*, 100064.
120. Mahan, H.M., Konovalov, S.V., Najm, S.M. et al(2024). Experimental and Numerical Investigations of the Fatigue Life of AA2024 Aluminium Alloy-Based Nanocomposite Reinforced by TiO₂ Nanoparticles Under the Effect of Heat Treatment. *Int. J. Precis. Eng. Manuf.* 25, 141–153.
121. Dutta, I., & Bourell, D. L. (1989). A theoretical and experimental study of aluminum alloy 6061-SiC metal matrix composite to identify the operative

mechanism for accelerated aging. Materials Science and Engineering: A, 112, 67-77.

122. Dhar, A. K., & Sutradhar, G. (2021, November). *Experimental analysis of microstructure and mechanical characteristics of LM6 & fly ash composite through stir casting method. In Journal of Physics: Conference Series (Vol. 2070, No. 1, p. 012177). IOP Publishing.*

123. Boobalan, V., & Sathish, T. (2022). *A comprehensive study on boron carbide reinforcement in Aluminum-and its alloy composites. Materials Today: Proceedings, 69, 1238-1241.*

124. Ben, F., & Olubambi, P. A. (2024). *Agro waste reinforcement of metal matrix composites, a veritable sustainable engineering achievement, or an effort in futility? A critical review. Materials research express, 11(6), 062004.*

125. Channi, A. S., & Channi, M. K. (2025). *Advances in AMC: A Review of Processing Techniques, Mechanical Performance and Wear Properties. International Journal of Innovations in Science, Engineering And Management, 256-261.*

126. Mohapatra, S. K., Maity, K., Bhuyan, S. K., & Satpathy, M. P. (2018, March). *Mechanical and Tribological Characteristics of the AMC, Prepared by P/M Route along with Thermo-Mechanical Treatment. In IOP Conference Series: Materials Science and Engineering (Vol. 338, No. 1, p. 012023). IOP Publishing.*

127. Roy, P., Singh, S., & Pal, K. (2019). *Enhancement of mechanical and tribological properties of SiC-and CB-reinforced aluminium 7075 hybrid composites through friction stir processing. Advanced Composite Materials, 28(sup1), 1-18.*

128. Kumar, K. R., Mohanasundaram, K. M., Arumaikkannu, G., & Subramanian, R. (2012). *Effect of particle size on mechanical properties and tribological behaviour of aluminium/fly ash composites*. *Science and Engineering of Composite Materials*, 19(3), 247-253.
129. Mubarok, F., & Espallargas, N. (2015). *Tribological behaviour of thermally sprayed silicon carbide coatings*. *Tribology International*, 85, 56-65.
130. Uvaraja, V. C., Natarajan, N., Rajendran, I., & Sivakumar, K. (2013). *Tribological behavior of novel hybrid composite materials using Taguchi technique*. *Journal of tribology*, 135(2), 021101.
131. Stojanovic, B., Tomović, R., Gajević, S., Petrović, J., & Miladinovic, S. (2022). *Tribological behavior of aluminum composites using Taguchi design and ANN*.
132. Kalel, N., Jadhav, D. T., Limaye, P. K., Patil, S. R., & Khare, N. (2016, December). *Application of Taguchi technique and ANOVA to experimental study of tribological behaviour of material pairs with case study*. In *Proceedings of the Conference "NTC2016", Varanasi, India (pp. 8-10)*.
133. Zhao, L., Tang, J., Zhou, M., & Shen, K. (2022). *A review of the coefficient of thermal expansion and thermal conductivity of graphite*. *New Carbon Materials*, 37(3), 544-555.
134. Sharma, N. K., Misra, R. K., & Sharma, S. (2016). *Modeling of thermal expansion behavior of densely packed Al/SiC composites*. *International journal of solids and structures*, 102, 77-88.

135. Okumus, S. C., Aslan, S., Karslioglu, R., Gultekin, D., & Akbulut, H. (2012). *Thermal expansion and thermal conductivity behaviors of Al-Si/SiC/graphite hybrid metal matrix composites (MMCs)*. *Materials Science*, 18(4), 341-346.
136. Esmati, M., Sharifi, H., Raeissi, M., Atrian, A., & Rajaei, A. (2019). *Investigation into thermal expansion coefficient, thermal conductivity and thermal stability of Al-graphite composite prepared by powder metallurgy*. *Journal of Alloys and Compounds*, 773, 503-510.
137. Safi, M., Hassanzadeh-Aghdam, M. K., & Mahmoodi, M. J. (2019). *Effects of nano-sized ceramic particles on the coefficients of thermal expansion of short SiC fiber-aluminum hybrid composites*. *Journal of Alloys and Compounds*, 803, 554-564.
138. Hiremath, A., & Hemanth, J. (2017). *Experimental evaluation of the coefficient of thermal expansion of chilled aluminum alloy-borosilicate glass (P) composite*. *Journal of Materials and Environmental Sciences*, 8(12), 4246-4252.
139. Mohan Krishna, S. A., Vinay, K. B., Ashok, B. C., Naveen Prakash, G. V., & Nithyananda, B. S. (2021). *Experimental and numerical investigations on thermal expansion and thermal conductivity properties of Al 6061-SiC-GR hybrid metal matrix composites*. *International Journal of Computational Materials Science and Engineering*, 10(01), 2150002.
140. Xue, C., Yu, J. K., & Zhu, X. M. (2011). *Thermal properties of diamond/SiC/Al composites with high volume fractions*. *Materials & Design*, 32(8-9), 4225-4229.

141. Fathy, A., & El-Kady, O. (2013). Thermal expansion and thermal conductivity characteristics of Cu–Al₂O₃ nanocomposites. *Materials & Design* (1980-2015), 46, 355-359.
142. Li, M., Ghosh, S., & Richmond, O. (1999). An experimental–computational approach to the investigation of damage evolution in discontinuously reinforced aluminum matrix composite. *Acta materialia*, 47(12), 3515-3532.
143. Aghdam, M. M., Smith, D. J., & Pavier, M. J. (2000). Finite element micromechanical modelling of yield and collapse behaviour of metal matrix composites. *Journal of the Mechanics and Physics of Solids*, 48(3), 499-528.
144. Xia, Z. H., & Curtin, W. A. (2001). Multiscale modeling of damage and failure in aluminum-matrix composites. *Composites science and technology*, 61(15), 2247-2257.
145. Cannillo, V., Pellacani, G. C., Leonelli, C., & Boccaccini, A. R. (2003). Numerical modelling of the fracture behaviour of a glass matrix composite reinforced with alumina platelets. *Composites Part A: Applied Science and Manufacturing*, 34(1), 43-51.
146. Ilie, D. E., O'Donnell, B. P., McGarry, J. P., & McHugh, P. E. (2007). Computational modelling of the extrusion of an Al-SiC metal matrix composite using macroscale and microscale methods. *The Journal of Strain Analysis for Engineering Design*, 42(4), 237-252.
147. Tay, T. E., Liu, G., Tan, V. B. C., Sun, X. S., & Pham, D. C. (2008). Progressive failure analysis of composites. *Journal of Composite Materials*, 42(18), 1921-1966.

148. Prabu, S. B., & Karunamoorthy, L. (2008). *Microstructure-based finite element analysis of failure prediction in particle-reinforced metal-matrix composite*. *Journal of materials processing technology*, 207(1-3), 53-62.
149. Umer, U., Ashfaq, M., Qudeiri, J. A., Hussein, H. M. A., Danish, S. N., & Al-Ahmari, A. R. (2015). *Modeling machining of particle-reinforced aluminum-based metal matrix composites using cohesive zone elements*. *The International Journal of Advanced Manufacturing Technology*, 78(5), 1171-1179.
150. Kurşun, A., Bayraktar, E., & Enginsoy, H. M. (2016). *Experimental and numerical study of alumina reinforced aluminum matrix composites: Processing, microstructural aspects and properties*. *Composites Part B: Engineering*, 90, 302-314.
151. Abidin, N. M., Sultan, M. T., Hua, L. S., Basri, A. A., Md Shah, A. U., & Safri, S. N. (2019). *A brief review of computational analysis and experimental models of composite materials for aerospace applications*. *Journal of Reinforced Plastics and Composites*, 38(23-24), 1031-1039.
152. Talreja, R. (2022). *Damage and failure of composite materials*. In *Advanced theories for deformation, damage and failure in materials* (pp. 235-280). Cham: Springer International Publishing.
153. Biswas, P., Mandal, D., & Mondal, M. K. (2023). *Compressive failure analysis of in-situ Al-Mg₂Si composites: experiment and finite element modelling*. *Engineering Fracture Mechanics*, 277, 108986.
154. Balokhonov, R., Zemlianov, A., Gatiyatullina, D., & Romanova, V. (2023). *Computational analysis of the influence of residual stress on the strength of*

composites with different aluminum matrices and carbide particles. *Metals*, 13(4), 724.

155. Thomas, L. C., Kumar, V., Gangwar, A., Pisupati, M., Gupta, C., & Panda, S. K. (2024). Computational modelling and experimental techniques for fibre metal laminate structural analysis: a comprehensive review. *Archives of Computational Methods in Engineering*, 31(1), 351-369.

156. Farid, W., Li, H., Wang, Z., Cui, H., Kong, C., & Yu, H. (2024). Integrating experimental and computational analyses for mechanical characterization of titanium carbide/aluminum metal matrix composites. *Materials*, 17(9), 2093.

157. Bhuvaneswari, V., Arulmurugan, B., Balaji, D., Aravindh, M., & Rajeshkumar, L. (2024). An overview of stress analysis of composites through computational modelling and simulation with the aid of patent landscape analysis. *Archives of Computational Methods in Engineering*, 31(6), 3473-3495.

158. Shaquib, O., Kaur, R., & Parbhakar, D. (2025). Multiscale Computational Design And Structural-Functional Optimization Of Fly Ash-Reinforced Aluminum Matrix Composites. *Lex Localis: Journal of Local Self-Government*, 23.

159. Kumar, R. H., & Venkatachalapathy, V. S. K. (2025). Experimental and Numerical Wear Behavior Analysis of Piston Made of Hybrid Aluminum Metal Matrix Composite. *Korean Journal of Materials Research*, 35(7), 247-265.

160. Votarikari, N. K. (2025). Behavioural analysis of particle reinforcement in Al-MMC on mechanical and thermal properties using DIGIMAT. *Advances in Materials and Processing Technologies*, 1-18.

161. Naplocha, K., & Kaczmar, J. W. (2011). *Wear mechanisms of fibre reinforced composite materials based on 2024 and 7075 aluminum alloys. Journal of Achievements in Materials and Manufacturing Engineering*, 49(2), 180-187.
162. Rao, J. B., Rao, D. V., Murthy, I. N., & Bhargava, N. R. M. R. (2012). *Mechanical properties and corrosion behaviour of fly ash particles reinforced AA 2024 composites. Journal of composite materials*, 46(12), 1393-1404.
163. Shabani, M. O., & Mazahery, A. (2013). *Computational modeling of cast aluminum 2024 alloy matrix composites: Adapting the classical algorithms for optimal results in finding multiple optima. Powder technology*, 249, 77-81.
164. Fallahnezhad, K., Steele, A., & Oskouei, R. H. (2015). *Failure mode analysis of aluminium alloy 2024-T3 in double-lap bolted joints with single and double fasteners; A numerical and experimental study. Materials*, 8(6), 3195-3209.
165. Daneshmand, S., & Masoudi, B. (2018). *Investigation and optimization of the electro-discharge machining parameters of 2024 aluminum alloy and Al/7.5% Al₂O₃ particulate-reinforced metal matrix composite. Science and Engineering of Composite Materials*, 25(1), 159-172.
166. Wisner, B., & Kontsos, A. (2018). *Investigation of particle fracture during fatigue of aluminum 2024. International journal of fatigue*, 111, 33-43.
167. Shin, S. E., & Bae, D. H. (2018). *Fatigue behavior of Al2024 alloy-matrix nanocomposites reinforced with multi-walled carbon nanotubes. Composites Part B: Engineering*, 134, 61-68.

168. Mazlan, S., Yidris, N., Koloor, S. S. R., & Petru, M. (2020). *Experimental and numerical analysis of fatigue life of aluminum Al 2024-T351 at elevated temperature. Metals, 10(12), 1581.*
169. Gara, N., Ramachandran, V., & Rengaswamy, J. (2021). *Analytical and FEM analyses of high-speed impact behaviour of Al 2024 alloy. Aerospace, 8(10), 281.*
170. Balokhonov, R., Romanova, V., Zinovieva, O., & Dymnich, E. (2022). *A computational study of the effects of polycrystalline structure on residual stress-strain concentrations and fracture in metal-matrix composites. Engineering Failure Analysis, 138, 106379.*
171. Gara, N., Jayaganthan, R., & Velmurugan, R. (2023). *Failure analysis through fragmentation behaviour of Al 2024 alloy subjected to high strain Rates-experimental and numerical studies. Engineering Failure Analysis, 149, 107258.*
172. Gairola, S., Jayaganthan, R., Singh, R. K., Kumar, N., & Ajay, J. (2024). *An investigation on damage tolerant design parameter of additively manufactured Al 2024: Fatigue crack growth rate and fracture toughness. Materials Today Communications, 38, 108480.*
173. Mahan, H. M., Sergey, K., Al-Nedawi, N. M., & Ali, A. H. (2024). *Effect of Aging Treatment and TiO₂ Nano Particles Addition on the Microstructure and Mechanical Properties of 2024 Aluminum Alloy. International Journal of Integrated Engineering, 16(1), 35-44.*
174. Kaverinsky, V. V., Bagliuk, G. A., & Sukhenko, Z. P. (2024). *Numerical simulation of in situ reaction synthesis of TiC reinforced aluminum matrix composite from elemental Al-Ti-C powders. Journal of Materials Engineering and Performance, 33(19), 9976-9986.*

175. MK, S., A, P., R, A. S. P., & George, J. (2025). *Analytical modeling of the ballistic performance of single and multilayered 2024 aluminum alloy through experimental and numerical investigations. Mechanics Based Design of Structures and Machines*, 1-21.
176. Singh, J., & Chauhan, A. (2016). *Characterization of hybrid aluminum matrix composites for advanced applications—a review. Journal of Materials Research and Technology*, 5(2), 159-169.
177. Venkatesh, R., Sharma, A., Karthik, K., Kumar, R., Vivekananda, P. K. K., Vinayagam, M., & Alharbi, S. A. (2025). *Hybrid reinforcement actions on microstructural, physical and mechanical properties of magnesium alloy composite by two-step stir casting process. International Journal of Metalcasting*, 1-12.
178. Nehra, R. K., Sahni, M., Badheka, V., & Mehta, K. (2025). *Schematic review of manufacturing methods, process parameters and existing challenges for metal matrix composites. International Journal of Cast Metals Research*, 38(2-3), 121-142.
179. Srivastava, V. S., Gupta, T. K., & Nigam, A. (2021). *Study of stirrer speed and preheat temperature on stir cast aluminium matrix composite materials—a review. Materials Today: Proceedings*, 47, 4114-4120.
180. Sahu, M., Patnaik, A., & Banerjee, M. K. *Mechanical and Tribological Characteristics of Industrial Waste-Filled Polymer Composites. In Sustainable*

Utilization of Industrial Wastes as Reinforcement in Composite Materials (pp. 62-71). CRC Press.

181. Pandey, M., Negi, A., Pandey, M., Mudila, H., Kumar, A., & Kumar, D. (2026). Agro, municipal, and forest waste-derived active materials for supercapacitors. *Sustainable Materials in Supercapacitors*, 227-246.

182. Sanjuan-Navarro, L., Sanchis-Angulo, P., Moliner-Martínez, Y., & Campíns-Falcó, P. (2026). Size assessing of different silica-based materials by asymmetrical flow field flow fractionation: from nanometers to micrometers. *Analytica Chimica Acta*, 345162.

183. Alem, S. A. A., Sabzvand, M. H., Govahi, P., Poormehrabi, P., Hasanzadeh Azar, M., Salehi Siouki, S., & Bagherifard, S. (2025). Advancing the next generation of high-performance metal matrix composites through metal particle reinforcement. *Advanced composites and hybrid materials*, 8(1), 3.

184. Al Njjar, A., Mazloun, K., & Sata, A. (2025). A review on fabrication of hybrid AA7075 aluminum-based matrix composites (HAMCS) using powder metallurgy for aerospace applications. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, 09544089251342691.

185. Singhal, V., Kandpal, B. C., Kumar, N., & Raman, R. S. (2025). *Advancements in Aluminum Metal Matrix Composites: Fabrication Techniques and Application Potentials-A Review*. *International Journal of Maritime Engineering*, 167(A3 (S)), 1-8.

186. Budapanahalli, S. H., Dhaduti, S. C., Kumar, R., Beemkumar, N., Mahapatro, A., Karun Kumar, Y., & Patil, A. Y. (2025). *A review on aluminium metal matrix composite for tribological study on gear applications. Discover Applied Sciences*, 8(1), 16.
187. Kumar, A., & Moeed, K. M. (2025). *Hybrid composites materials of reinforced aluminium alloy and its tribological analysis: a review: A. Kumar, KM Moeed. Discover Applied Sciences*, 7(10), 1159.
188. Omiogbemi, I. M. B., Awode, E. I., Muhammad, M. H., Adesanmi, A., & Dagwa, I. M. (2025). *Smart Composite Materials for Aerospace Applications. Functional Composites: Role in Modern Engineering*, 115-168.
189. Zhang, X., Sun, M., Chen, T., & Xiao, B. L. (2025). *Strong and ductile heterostructured aluminum matrix composites with multiscale and dual-structured reinforcing particulates. Composites Part B: Engineering*, 113358.
190. Gupta, M. K., Rajput, N. S., Kulshreshtha, S., Gangil, B., Patel, V. K., Mahto, J. N., & Gupta, T. K. (2024). *Fabrication and investigation of mechanical behaviors of TiB₂ reinforced AMCs. Transactions of the Indian Institute of Metals*, 77(2), 563-570.
191. Tang, J., Omar, M. Z., Jiang, R., Mohamed, I. F., & Li, A. (2025). *Effect of different ultrasonic power on microstructure and mechanical properties of ZL205A/TiB₂ composite materials. Metals and Materials International*, 31(3), 890-906.

192. Reddy, P. V., Kumar, G. S., Krishnudu, D. M., & Rao, H. R. (2020). *Mechanical and wear performances of aluminium-based metal matrix composites: a review. Journal of Bio-and Tribo-Corrosion*, 6(3), 83.
193. Pal, B. R., Ghosh, S., & Sahoo, P. (2021). *Aluminium hybrid composites reinforced with SiC and fly ash particles—recent developments. Recent advances in layered materials and structures*, 133-170.
194. Alade, O. E., Okiye, S. E., Emekwisia, C. C., Emejulu, E. C., Aruya, G. A., Afolabi, S. O., & Okoye, J. C. (2024). *Exploratory Analysis on the Physical and Microstructural Properties of Aluminium/Fly Ash Composite. American Journal of Bioscience and Bioinformatics (AJBB)*, 3(1).
195. Hadad, M., Babazade, A., & Safarabadi, M. (2020). *Investigation and comparison of the effect of graphene nanoplates and carbon nanotubes on the improvement of mechanical properties in the stir casting process of aluminum matrix nanocomposites. The International Journal of Advanced Manufacturing Technology*, 109(9), 2535-2547.
196. Liu, J., Zhang, Y., Zhang, Y., Kitipornchai, S., & Yang, J. (2022). *Machine learning assisted prediction of mechanical properties of graphene/aluminium nanocomposite based on molecular dynamics simulation. Materials & Design*, 213, 110334.
197. Tee, K. L., Lu, L., & Lai, M. O. (1999). *Synthesis of in situ Al–TiB₂ composites using stir cast route. Composite Structures*, 47(1-4), 589-593.

198. Beemaraj, R. K., Ramesh, M., Subramaniyan, G. G., & Kamatchi, T. (2024). *A study on mechanical and tribological properties of AMMC through stir casting process. Interactions*, 245(1), 334.
199. Chandla, N. K., Kant, S., & Goud, M. M. (2021). *Mechanical, tribological and microstructural characterization of stir cast Al-6061 metal/matrix composites—a comprehensive review. Sādhanā*, 46(1), 47.
200. Balcioğlu, H. E. (2019). *An investigation on the mechanical strength, impact resistance and hardness of SiC filled natural jute fiber reinforced composites. Res Eng Struct Mater*, 5(3), 213-31.
201. Muhammad, F., & Jalal, S. (2021). *A comparative study of the impact of the stirrer design in the stir casting route to produce metal matrix composites. Advances in Materials Science and Engineering*, 2021(1), 4311743.
202. Kasar, A. K., Gupta, N., Rohatgi, P. K., & Menezes, P. L. (2020). *A Brief Review of Fly Ash as Reinforcement for Composites with Improved Mechanical and Tribological Properties: Kasar, Gupta, Rohatgi, and Menezes. Jom*, 72(6), 2340-2351.
203. Shahbahrami, B., Bastami, H., & Shahbahrami, N. (2010). *Studies on oxidation behaviour of TiB₂ powder. Materials research innovations*, 14(1), 107-109.
204. Singh, R., & Singh, G. (2015). *Investigations of Al–SiC AMC prepared by vacuum moulding assisted stir casting. Journal of Manufacturing Processes*, 19, 142-147.

205. Kannan, C., & Ramanujam, R. (2017). *Comparative study on the mechanical and microstructural characterisation of AA 7075 nano and hybrid nanocomposites produced by stir and squeeze casting. Journal of advanced research*, 8(4), 309-319.
206. Malomo, B. O., Owolabi, H. A., Ibitoye, S. A., & Adekoya, L. O. (2016). *The Effect of Production Process Parameters on the Tensile Strength of Squeeze Cast Al₂O₃+ SiC/Al6061 Hybrid Composites. Materials Performance and Characterization*, 5(1), 330-346.
207. Bembalge, O. B., & Panigrahi, S. K. (2018). *Development and strengthening mechanisms of bulk ultrafine grained AA6063/SiC composite sheets with varying reinforcement size ranging from nano to micro domain. Journal of Alloys and Compounds*, 766, 355-372
208. Sambathkumar, M., Gukendran, R., Mohanraj, T., Karupannasamy, D. K., Natarajan, N., & Christopher, D. S. (2023). *A systematic review on the mechanical, tribological, and corrosion properties of Al 7075 metal matrix composites fabricated through stir casting process. Advances in Materials Science and Engineering*, 2023(1), 5442809.
209. Pazhouhanfar, Y., & Eghbali, B. (2018). *Microstructural characterization and mechanical properties of TiB₂ reinforced Al6061 matrix composites produced using stir casting process. Materials Science and Engineering: A*, 710, 172-180.
210. Yigezu, B. S., Jha, P. K., & Mahapatra, M. M. (2013). *The key attributes of synthesizing ceramic particulate reinforced Al-based matrix composites through*

stir casting process: a review. Materials and Manufacturing Processes, 28(9), 969-979.

211. Kandpal, B. C., Kumar, J., & Singh, H. (2018). *Manufacturing and technological challenges in Stir casting of metal matrix composites–A Review. Materials Today: Proceedings, 5(1), 5-10.*

212. Prabu, S. B., Karunamoorthy, L., Kathiresan, S., & Mohan, B. (2006). *Influence of stirring speed and stirring time on distribution of particles in cast metal matrix composite. Journal of materials processing technology, 171(2), 268-273.*

213. Bhandare, R. G., & Sonawane, P. M. (2013). *Preparation of aluminium matrix composite by using stir casting method. International Journal of Engineering and Advanced Technology (IJEAT), 3(3), 61-65.*

214. Brabazon, D. J. B. D., Browne, D. J., & Carr, A. J. (2002). *Mechanical stir casting of aluminium alloys from the mushy state: process, microstructure and mechanical properties. Materials Science and Engineering: A, 326(2), 370-381.*

215. Krishnan, P. K., Arunachalam, R., Husain, A., & Al-Maharbi, M. (2021). *Studies on the influence of stirrer blade design on the microstructure and mechanical properties of a novel aluminum metal matrix composite. Journal of Manufacturing Science and Engineering, 143(2), 021008.*

216. Zulfia, A., Raga, K., Narottama, W., & Yunus, S. (2019). *Al6061 reinforced Al₂O₃ metal matrix composite produced by double blade stir*

casting. *International Journal on Advanced Science, Engineering and Information Technology*, 9(5), 1544-1549.

217 Saxena, A., Kumaraswamy, A., Dwivedi, S. P., Srivastava, A. K., Maurya, N. K., & Pandey, M. (2020). Experimental and numerical investigation of quasi-static (10^{-3} s^{-1}) fracture behavior of armor steel. *Arabian Journal for Science and Engineering*, 45(7), 5623-5629.

218. Gupta, T. K., & Saxena, A. The effect of reinforcement particles weight percentage on the mechanical properties and plastic flow behaviour of aluminum alloy 7075 matrix material. *Materialwiss. Werkstofftech*, 2024; 55(2), 194-203

219. Surya, M. S., & Gugulothu, S. K. Fabrication, mechanical and wear characterization of silicon carbide reinforced aluminium 7075 metal matrix composite. *Silicon*, 2022; 14(5), 2023-2032.

220. Msebawi, M. S., Leman, Z., Shamsudin, S., Tahir, S. M., Jaafar, C. N. A., Ariff, A. H. M., & Rady, M. H. The effects of CuO and SiO₂ on aluminium AA6061 hybrid nanocomposite as reinforcements: A Concise Review. *Coatings*, 2021; 11(8), 972

221. Maurya, M., Kumar, S., Bajpai, V. & Kumar Maurya, N. (2020). Process parameters, development and applications of stir cast composite: A review. *Materials Testing*, 62(2), 196-208

222. Chak, V., Chattopadhyay, H., & Dora, T. L. (2021). Application of solid processing routes for the synthesis of graphene-aluminum composites-a review. *Materials and Manufacturing Processes*, 36(11), 1219-1235.

223. Dwivedi, S. P., & Sahu, R. Development of aluminum-based composite material by using bagasse ash and eggshell as reinforcement along with nano-CuO particles. *J. Inst. Eng. India Ser. D*, 2023; 104(2), 489-502
224. Fono-Tamo, R. S., & Tien-Chien, J. (2018). Effect of reinforcement particles preheating on mechanical and microstructural properties of AMC. *Acta Metallurgica Slovaca*, 24(4), 337-346
225. Chen, T., Geng, L., Qin, H., & Gao, M. (2018). Core-shell-structured particle reinforced A356 matrix composite prepared by powder-thixoforming: effect of reheating temperature. *Materials*, 11(9), 1718
226. Standard, A.S.T.M., E8. Standard test method for tension testing of metallic materials. West Conshohocken (USA), 2004
227. Dhamodaran, S., Velukkudi Santhanam, S. K., & Kuppusamy, R. (2023, October). Testing and analysis of mechanical, and corrosion properties of 2024 aluminum alloy using Friction Stir Processing. In *ASME International Mechanical Engineering Congress and Exposition (Vol. 87615, p. V004T04A016)*. American Society of Mechanical Engineers.
228. Balakrishnan, M., & Raju, K. (2020). Friction weldability of Al 2024+ Li+ Si3N4 metal matrix composite. *Metallography, Microstructure, and Analysis*, 9(5), 641-650.
229. ASTM E290-14; Standard Test Methods for Bend Testing of Material for Ductility. ASTM International: West Conshohocken, PA, USA, 2014

230. Salguero, J., Iglesias, P., Vazquez-Martinez, J. M., Batista, M., & Del Sol, I. (2022, October). *A comparative study of disk wear volume evaluation of AL2024 based on ASTM G99. In ASME International Mechanical Engineering Congress and Exposition (Vol. 86717, p. V009T15A002). American Society of Mechanical Engineers.*

Research Paper (Journal and Conference)

1. Sahu R, Srinivas K, Agrawal AK. The effect of reinforcement particle weight percentage on the mechanical and microstructural properties of AA 2024-based metal matrix composite. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. 2025;239(13):5021-5033. doi:10.1177/09544062251324092
2. Sahu, R., Srinivas, K. & Agrawal, A.K. Experimental investigation of reinforcement TiB_2 , Waste glass powder, and CuO on the wear rate, coefficient of friction, and hardness of Al2024 matrix composites. Appl. Phys. A 131, 924 (2025). <https://doi.org/10.1007/s00339-025-08910-3>
3. Sahu, R., Srinivas, K., Agrawal, A.K. (2024). A Numerical Investigation on Estimation and Validation of Power Law Constants for TiB_2 Reinforced AA2024 Composite Material. Smart Innovation, Systems and Technologies, vol 390. Springer, Singapore. https://doi.org/10.1007/978-981-97-2716-2_3 (International Conference on Mechanical and Energy Technologies (ICMET-2023, 7–8 December 2023 Galgotias College of Engineering and Technology, Greater Noida, India)
4. Sahu, R., Srinivas, K., Agrawal, A.K “Fabrication and Analysis of Aluminium 2024 with Titanium Diboride (TiB_2) Composite Material (International Conference of Advance Research and Innovation (ICARI-2025) 2nd, February 2025. Delhi State Center, Institution of Engineers (India), New Delhi, India, on February 2nd, 2025.)