

ADVANCES IN PRODUCTION ENGINEERING

FUNCTIONAL COMPOSITES

Role in Modern Engineering

Edited By

Sandip Kumar, Pranav Charkha,
Santosh Jaju and Harish Tiwari

 Scrivener
Publishing

WILEY

Functional Composites

Scrivener Publishing
100 Cummings Center, Suite 541J
Beverly, MA 01915-6106

Advances in Production Engineering

Series Editor: Dr. Sandip Kumar (sandip.sandip.kumar@gmail.com)

“Advances in Production Engineering” addresses recent developments and research issues related to the production engineering which necessitates the development of new materials and manufacturing processes in order to produce high-quality products at lower prices and in less time. This series aims to provide a scientific platform for researchers, practitioners, professionals, and academicians to discuss the most recent technological developments in metals, polymers, ceramics, composites, biomaterials, nanomaterials, special materials, metals, micro-forming, powder metallurgy, ceramics processing, non-traditional machining, high speed machining, micro and nanomachining, and laser processing. Tribological analysis, friction behavior, modelling, and optimization techniques in materials, machining, and manufacturing are also covered in the series.

Publishers at Scrivener

Martin Scrivener (martin@scrivenerpublishing.com)
Phillip Carmical (pcarmical@scrivenerpublishing.com)

Functional Composites

Role in Modern Engineering

Edited by

Sandip Kumar

*Department of Mechanical Engineering, Aditya University, Surampalem,
Andhra Pradesh, India*

Pranav Charkha

*School of Engineering & Technology, Pimpri Chinchwad University,
Pune, Maharashtra, India*

Santosh Jaju

*Department of Mechanical Engineering, G. H. Rasoni College of Engineering,
Nagpur, Maharashtra, India*

and

Harish Tiwari

Pimpri Chinchwad College of Engineering & Research, Ravet, Pune, India



WILEY

This edition first published 2025 by John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA and Scrivener Publishing LLC, 100 Cummings Center, Suite 541J, Beverly, MA 01915, USA

© 2025 Scrivener Publishing LLC

For more information about Scrivener publications please visit www.scrivenerpublishing.com.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, except as permitted by law. Advice on how to obtain permission to reuse material from this title is available at <http://www.wiley.com/go/permissions>.

Wiley Global Headquarters

111 River Street, Hoboken, NJ 07030, USA

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

The manufacturer's authorized representative according to the EU General Product Safety Regulation is Wiley-VCH GmbH, Boschstr. 12, 69469 Weinheim, Germany, e-mail: Product_Safety@wiley.com.

Limit of Liability/Disclaimer of Warranty

While the publisher and authors have used their best efforts in preparing this work, they make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives, written sales materials, or promotional statements for this work. The fact that an organization, website, or product is referred to in this work as a citation and/or potential source of further information does not mean that the publisher and authors endorse the information or services the organization, website, or product may provide or recommendations it may make. This work is sold with the understanding that the publisher is not engaged in rendering professional services. The advice and strategies contained herein may not be suitable for your situation. You should consult with a specialist where appropriate. Neither the publisher nor authors shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages. Further, readers should be aware that websites listed in this work may have changed or disappeared between when this work was written and when it is read.

Library of Congress Cataloging-in-Publication Data

ISBN 978-1-394-24200-9

Cover image: Generated with AI using Adobe Firefly
Cover design by Russell Richardson

Set in size of 11pt and Minion Pro by Manila Typesetting Company, Makati, Philippines

Printed in the USA

10 9 8 7 6 5 4 3 2 1

Contents

Preface	xv
1 Introduction to Functional Composite Materials	1
<i>Sandip Kumar, Gurudas Mandal, Jagadeesha T. and Pranav Charkha</i>	
1.1 Introduction	1
1.2 Overview	3
1.3 Characteristics of Composites	7
1.4 A Fundamental Method for Choosing Materials	8
1.5 Polymer Matrix	9
1.6 Reinforcements	11
1.7 Techniques for Producing Composites	12
1.7.1 Molding Using Open Contact	13
1.7.2 Resin Infusion Method	13
1.7.3 Injection Molding	14
1.7.4 Filament Winding	14
1.7.5 Pultrusion Process	14
1.7.6 Additive Manufacturing	15
1.8 Composite Properties	15
1.9 Latest Developments	16
1.10 Applications	17
1.11 Conclusion	17
References	17
2 Shape Memory Alloys as Functional Composites	21
<i>Param Singh, Yatin Khanna, Roopak Varshney and Yajush Walia</i>	
2.1 Introduction	22
2.1.1 Exploration and Attempts at Development	22

2.2	Composition and Microstructure of Shape Memory Alloys' (SMAs') Composition	23
2.2.1	Microstructure	24
2.2.2	Characterization Techniques	26
2.2.3	Shape Memory Effect	26
2.2.4	Super Elasticity	28
2.3	Processing Techniques Used for Shape Memory Alloys	30
2.3.1	Casting	30
2.3.2	Powder Metallurgy	31
2.3.3	Thermomechanical Processing	32
2.4	Characterization Methods Employed to Evaluate the Microstructural and Mechanical Properties of SMAs	33
2.4.1	Microscopy	33
2.4.2	X-Ray Diffraction (XRD)	34
2.4.3	Tests of the Material's Mechanical Characteristics and Behavior	35
2.5	Applications of Shape Memory Alloys as Functional Composites	35
2.5.1	Aerospace	36
2.5.2	Automotive	36
2.5.3	Medical Applications	36
2.5.4	Consumer Electronics	37
2.6	Design Considerations and Challenges in Using SMAs for Specific Applications	38
2.6.1	Compatibility with the Prerequisites of the Application	38
2.6.2	Mechanisms of Actuation and Their Controls	38
2.7	The Choice of Materials and Their Compatibility	39
2.7.1	Fatigue and Durability	39
2.7.2	Manufacturing and Processing	40
2.7.3	Expense and the Possibility of Commercialization	40
2.8	Case Studies and Success Stories That Demonstrate the Practical Implementation of SMAs as Functional Composite Structures	41
2.8.1	The Use of Smart Morphing Adaptors in Aerospace	41
2.8.2	Self-Deployable Space Structures	41
2.8.3	Orthopedic Implants and Medical Devices	41
2.8.4	Adaptive Structures in the Automotive Sector	42
2.8.5	Wearable Technologies and Intelligent Textiles	42
2.9	Current State of Research in Shape Memory Alloys and Potential Areas for Future Exploration	42

2.10	Recent Advancements in the Development of Novel SMA Compositions, Processing, and Applications	44
2.10.1	Novel SMA Compositions	44
2.10.2	Advanced Processing Methods	45
2.10.3	SMA Application Advancements	45
2.10.4	Composite Hybrid Structures	46
2.11	Conclusions	46
	References	47
3	Characterization and Testing of Smart Functional Composites	49
	<i>Ranjita Swain, Sunita Routray and Rudra Narayan Mohapatro</i>	
3.1	Introduction	50
3.1.1	Shape Memory Composites (SMPs)	50
3.1.2	Self-Healing Composites	50
3.1.3	Piezoelectric Composites	51
3.1.4	Magnetostrictive Composites	51
3.1.5	Thermoelectric Composites	51
3.1.6	Conductive Composites	52
3.1.7	Light-Responsive Composites	52
3.1.8	Bio-Inspired Composites	52
3.1.9	Multi-Functional Composites	53
3.2	Mechanical Characterization	54
3.2.1	Overview of Mechanical Testing Methods	54
3.2.2	Discussion of Mechanical Properties	56
3.2.3	Mechanical Characterization of Smart Functional Composites	57
3.2.4	Electrical Characterization of Smart Functional Composites	58
3.2.4.1	Dielectric Strength	58
3.2.4.2	Insulation Resistance	58
3.2.4.3	Volume Resistivity and Surface Resistivity	58
3.2.5	Types of Smart Functional Composites	59
3.2.5.1	Structural Smart Composites	59
3.2.5.2	Composites for Actuation	59
3.2.5.3	Novel Functional Composites	60
3.2.5.4	Nanocomposites for Novel Functions	60
3.3	Thermal Characterization of Smart Functional Composites	60
3.3.1	Thermal Behavior of Smart Functional Composites	61
3.3.1.1	Thermal Characterization Techniques	62

3.3.1.2	Thermal Properties of Key Smart Functional Composites	62
3.3.1.3	Challenges and Future Directions	63
3.4	Environmental and Durability Testing of Functional Smart Materials	63
3.4.1	Thermal Cycling and Temperature Testing	64
3.4.2	Moisture and Humidity Testing	64
3.4.3	UV and Radiation Exposure	65
3.4.4	Mechanical and Vibration Testing	65
3.4.5	Electromagnetic Interference (EMI) Testing	65
3.5	Durability Testing Methodologies for Smart Functional Composites	66
3.5.1	Accelerated Aging Testing	66
3.5.2	Self-Healing and Damage Detection	66
3.5.3	Field Testing and Real-World Simulations	67
3.6	Recent Advances in Smart Functional Composite Testing	67
3.6.1	Integration of Smart Sensors for Real-Time Monitoring	67
3.6.2	Nanomaterial Enhancements	67
3.7	Conclusion	67
	References	68
4	Piezoelectric Nanocomposites	71
	<i>Param Singh, Srijal Mishra, Roopak Varshney and Yajush Walia</i>	
4.1	Introduction	72
4.1.1	The Piezoelectric Effect	72
4.1.1.1	Direct Piezoelectric Effect	73
4.1.1.2	Reverse Piezoelectric Effect	73
4.2	Variables and Constants That Have an Impact on the Performance of Piezoelectric Materials	74
4.2.1	Electro-Mechanical Coupling Factors (k)	74
4.2.2	Piezoelectric Strain (Charge) Constant (d)	75
4.2.3	Piezoelectric Voltage Constants (g)	76
4.2.4	Mechanical Quality Factor (Q _m)	77
4.2.5	Electrical Loss (tanδ)	77
4.2.6	Dielectric Constant (ε)	77
4.3	Piezoelectric Nanocomposites	78
4.3.1	Piezoelectric Nanocomposite Materials—Polymer-Based	79
4.3.2	Poling	81

4.3.3	Preparation of a Nano-Polymeric Piezoelectric Composite	83
4.3.4	Piezoelectric Nanoparticle Polymer Composite Foam (PNPF)	84
4.3.5	Reverse Effect of PNPF	84
4.4	Piezoelectric Polymer Materials	85
4.4.1	Polyvinylidene Fluoride (PVDF)	85
4.4.2	Polyvinylidene Fluoride Trifluoro Ethylene (PVDF-TrFE)	86
4.4.3	Polyvinylidene Cyanide-Vinyl Acetate	86
4.4.4	Polyamide 11 (Nylon 11)	86
4.4.5	Cellular Polypropylene (PP)	86
4.4.6	Poly-Organo-Phosphazenes (POPh)	87
4.5	Piezoelectric Nanocomposite Materials—Ceramic-Based	87
4.5.1	Lead Zirconate Titanate (PZT)	87
4.5.2	Potassium Sodium Niobate (KNN)	88
4.5.3	Bismuth Sodium Titanate (BNT)	88
4.5.4	Aluminum Nitride (AlN)	88
4.5.5	Lithium Niobate	89
4.6	Improvements to Piezoelectric Ceramics	89
4.7	Applications of Piezoelectric Nanocomposites	89
4.7.1	Bio-Medical	89
4.7.2	Piezoelectric Tactile Sensors	89
4.7.3	Piezoelectric Vibrational Energy Harvestors Using Polymer Nanocomposite	90
4.7.4	Piezoelectric Nano-Generator (PENG)	90
4.7.4.1	Force Applied Perpendicular to the Nanowire's Axis	91
4.7.4.2	Force Applied Parallel to the Nanowire's Axis	92
4.7.5	Nanocomposite Electrical Generators (NEG)	93
	References	94
5	Modulation of Waveform Effect on Ni/Nano-ZrO₂-TiO₂ Composite Coating on Mild Steel	99
	<i>Koona Bhavani, VSN Venkata Ramana, Chitrada Prasad, A. Ramesh and Marana Lalitha</i>	
5.1	Introduction	100
5.2	Procedure	101
5.2.1	Materials and Synthesis of Nanocomposites	101
5.2.2	Electrodeposition	102
5.2.3	Characterization	104

5.3	Results and Discussions	104
5.3.1	Microscopic Structure Analysis	104
5.3.2	X-Ray Diffraction	106
5.3.3	Microhardness	108
5.3.4	Pitting Corrosion Studies	109
5.4	Conclusions	111
	References	111
6	Smart Composite Materials for Aerospace Applications	115
	<i>Ibrahim Momoh-Bello Omiogbemi, Emmanuel Imhanote Awode, Mohammed Habib Muhammad, Adegoke Adesanmi and Ishaya Musa Dagwa</i>	
6.1	Introduction	116
6.1.1	Importance of Composite Materials in Aerospace	118
6.1.1.1	Weight Reduction	119
6.1.1.2	High Strength-to-Weight Ratio	119
6.1.1.3	Corrosion Resistance	119
6.1.1.4	Design Flexibility	120
6.1.1.5	Heat Resistance and Thermal Stability	120
6.1.1.6	Structural Health Monitoring	121
6.1.1.7	Reduction in Production Costs	121
6.1.1.8	Sustainability	122
6.1.2	Overview of Smart Functional Composite Polymer Materials	122
6.1.2.1	Key Characteristics	122
6.1.2.2	Manufacturing Techniques	123
6.1.2.3	Applications	124
6.2	Types of Smart Functional Composite Polymer Materials	124
6.2.1	Polymer Matrix Composites (PMCs)	125
6.2.2	Carbon Fiber Reinforced Polymers (CFRP)	125
6.2.3	Glass Fiber Reinforced Polymers (GFRP)	126
6.2.4	Shape Memory Polymers (SMPs)	127
6.2.5	Self-Healing Polymers (SHPs)	129
6.2.6	Conductive Polymer Composites (CPCs)	130
6.3	Properties and Characteristics	131
6.3.1	Mechanical Properties	131
6.3.1.1	Strength	132
6.3.1.2	Stiffness	132
6.3.1.3	Toughness	133

6.3.2	Thermal Properties	133
6.3.2.1	Thermal Conductivity	133
6.3.2.2	Thermal Stability	135
6.3.3	Electrical Properties	136
6.3.3.1	Conductivity	136
6.3.3.2	Resistivity	136
6.3.4	Multifunctional Properties	137
6.3.4.1	Self-Sensing	137
6.3.4.2	Self-Healing	137
6.4	Aerospace Applications	138
6.4.1	Structural Components	138
6.4.1.1	Wings	138
6.4.1.2	Fuselage	139
6.4.1.3	Control Surfaces	139
6.4.2	Functional Components	139
6.4.2.1	Actuators	139
6.4.2.2	Sensors	139
6.4.2.3	Energy	140
6.4.2.4	Storage	140
6.4.3	Thermal Management Systems	140
6.4.4	Self-Healing Coatings and Materials	141
6.5	Manufacturing Techniques	141
6.5.1	Conventional Methods	142
6.5.1.1	Hand Layup	142
6.5.1.2	Resin Transfer Molding (RTM)	142
6.5.1.3	Compression Molding	143
6.5.2	Advanced Methods	144
6.5.2.1	Additive Manufacturing (AM)	144
6.5.2.2	Electrospinning	145
6.5.2.3	Automated Fiber Placement (AFP)	145
6.5.3	Nanotechnology-Enabled Manufacturing	146
6.6	Challenges	147
6.6.1	Interfacial Properties and Bonding	147
6.6.2	Scalability and Cost-Effectiveness	148
6.6.3	Integration with Existing Aerospace Systems	148
6.6.4	Future Research Directions	148
6.7	Conclusion	149
	References	150

7 Behavioral Study of Tribological Coating of Smart Functional Composites for High Wear Applications	169
<i>M. Sasi Kumar, N. Venkatesh, M. Makesh Kumar, S.L. Pradeep Kumar, D. Santhosh Kumar and B. Deeban</i>	
7.1 Introduction	170
7.2 Principle of Tribology and Mechanisms of Wear	171
7.2.1 Wear Types	171
7.2.2 Significance of Coating in Enhancing Wear Resistance	172
7.3 Intelligent Multifunctional Composites	172
7.3.1 Categories of Functional Composites	173
7.3.2 Applications in High-Wear Environments	173
7.4 Tribological Coatings	173
7.5 Techniques for the Design and Fabrication of Materials	175
7.6 Development of Performance	176
7.7 Obstacles and Constraints	179
7.7.1 Material Compatibility Challenges	179
7.7.2 Considerations Regarding Expenses and the Ability to Scale	179
7.7.3 Constraints Related to Environmental and Operational Factors	179
7.8 Emerging Trends and Research Pathways	180
7.9 Conclusion	182
References	183
8 Applications to Dynamic Behavior: Free Vibration Analysis of Functional Composites	189
<i>Debarupam Gogoi, Pramod Kumar Parida, Md. Irquam Alam, Mihir Kumar Pandit and Arun Kumar Pradhan</i>	
8.1 Introduction	190
8.1.1 Advantages of FGM Over Traditional Composites	191
8.2 Recent Advances in the Development and Application of Functionally Graded Materials	194
8.3 Challenges and Future Directions	196
8.4 Free Vibration Analysis of Functional Composite Materials	197
8.4.1 Geometry and Property	197
8.4.2 Mathematical Modeling	200
8.5 Conclusion	210
References	211

9	Structural Health Monitoring of Composite Structures: Utility, Challenges, Sensor Technologies, and Advanced Methods	215
	<i>Sumanta Banerjee and Anindita Kundu</i>	
9.1	Introduction	216
9.1.1	Traditional Composites: Overview and Advantages	216
9.1.2	Smart Composites: Characterization and Application Potential	218
9.1.3	Structural Health Monitoring: Why the Need?	219
9.1.4	What This Chapter is All About?	219
9.2	Composite Materials: Problems and Challenges	220
9.3	Structural Health Monitoring for Composites: Benefits and Challenges	221
9.4	Sensors Employed in SHM: A Review	222
9.4.1	Fiber Optic Sensors (FOSs)	222
9.4.2	Resistance Strain Gauges	224
9.4.3	Piezoelectric Sensors	225
9.4.4	Eddy Current Sensors	225
9.4.5	Micro-Electromechanical (MEMS) Sensors	226
9.5	Overview of Typical SHM Methods for Composite Materials	229
9.5.1	Lamb Wave Method (LWM)-Based SHM	229
9.5.2	The Electromechanical (E/M) Impedance Method	232
9.5.3	Active Vibration-Based Method (AVBM)	234
9.5.4	Acoustic Emission “Passive” Methods for SHM	236
9.5.5	Strain-Based Methods for SHM	238
9.5.6	The Comparative Vacuum Monitoring (CVM) “Passive” Method	240
9.6	Conclusions and Future Scope	240
	References	241
	Index	247

Preface

Continuous fiber-reinforced composites is a novel class of materials with characteristics such as high modulus, tolerance, strength, damage resistance, and safety. The aerospace industry now relies heavily on them, and they are increasingly used in consumer goods, recreational products, and other industries. Polymer matrix composites are widely used across many industries. In the field of materials science and engineering, they represent a vital subject for undergraduate students. Due to the dominance of traditional composite materials in structural applications (such as aerospace), their use has largely focused on mechanical and fabrication characteristics. However, driven by the demands of the battery, biomedical, and electronic industries, non-structural applications are becoming increasingly significant. Since functional and structural composites have different performance and cost requirements, the scientific principles guiding their design also differ considerably. This book's focus on functional composite materials sets it apart from other related works.

In addition to discussing the creation, composition, characteristics, and applications of relevant composite materials, the book presents the fundamental concepts underlying each function. While cement-matrix composites are commonly used for structural purposes, ceramic and metal-matrix composites are becoming increasingly important. This book covers composite materials across all matrix types.

Classifying composite materials by their matrix type is a less common approach in books on composites. In contrast, this book adopts a novel functional approach, organizing materials according to their applications. This helps readers understand how composites are designed to meet the needs of various industries. Such insight benefits both professionals across sectors and students preparing for industry roles. Moreover, the functional approach allows for the systematic exploration of a broad range of scientific topics beyond just mechanical behavior.

The book contains nine chapters. Chapter 1 provides an overview of composite materials, covering the properties of polymer matrices and reinforcements, material selection basics, production methods, composite properties, and applications. Chapter 2 focuses on the synthesis and processing of Shape Memory Alloys (SMAs) within composites. It addresses scalability, manufacturing techniques, performance optimization, and the challenges and potential of SMA-based composites. The chapter highlights the transformative potential of SMAs in driving advanced technological developments and offers a comprehensive analysis of their interaction with composite materials, including insights into their synthesis, applications, and future prospects.

Chapter 3 introduces key types of smart composites, including those embedded with piezoelectric, thermochromic, and magnetostrictive elements, highlighting their unique ability to enhance structural performance. It also explores challenges in their development, such as material compatibility, processing methods, and long-term durability. The chapter concludes by identifying emerging trends, such as the use of sustainable materials and the integration of artificial intelligence (AI) for real-time monitoring and adaptive response.

Chapter 4 covers the fundamentals of piezoelectric materials, offering a detailed discussion on piezoelectric nanocomposites, their properties, and the fabrication of select examples. These materials have broad applications, including nano-transformers, portable nano-generators, energy harvesters, and biomedical devices—though most are used in sensor manufacturing. Chapter 5 explores the electrodeposition process using periodic modulation of rectangular and triangular waveforms, examining their effect on the conventional electroplating of Ni/ZrO₂-TiO₂ coatings on mild steel.

Chapter 6 explores the evolving field of smart functional composite polymer materials for aerospace applications. It examines their use in structural components, functional devices, thermal management systems, and self-healing coatings. Chapter 7 focuses on the friction and wear resistance behavior of advanced coatings, highlighting their ability to enhance mechanical performance under extreme conditions. The chapter illustrates how these coatings can extend component lifespan, reduce maintenance needs, and offer sustainable engineering solutions for high-demand sectors such as aerospace, automotive, and energy.

Chapter 8 discusses recent developments in composite materials, highlighting their advantages and limitations, trends in advanced and functionally graded materials (FGMs), various FGM structures and their applications, and the dynamic behavior of FGM plate structures. Chapter 9 provides a comprehensive review of structural health monitoring (SHM)

techniques for composites, outlining both their benefits and implementation challenges. It examines various sensor technologies—including Fiber Optic Sensors (FOSs), Resistance Strain Gauges, Eddy Current Sensors, Piezoelectric Sensors, and MEMS Sensors—for their applicability in SHM. The chapter also categorizes key SHM methodologies into ‘active’ and ‘passive’ approaches, covering techniques such as Lamb waves, electro-mechanical impedance, active vibration monitoring, strain-based methods, acoustic emission, and Comparative Vacuum Monitoring (CVM).

This book can serve as a reference for undergraduate and postgraduate students, as well as engineers, technicians, technology managers, and marketing staff. It will be especially helpful for thermal, electrical, industrial, and chemical engineers, thanks to the broad scientific scope enabled by the functional approach. Finally, we extend our gratitude to Martin Scrivener and Scrivener Publishing for their work in bringing this book to publication.

Dr. Sandip Kumar

June 2025

Introduction to Functional Composite Materials

Sandip Kumar^{1*}, Gurudas Mandal², Jagadeesha T.³ and Pranav Charkha⁴

¹*Department of Mechanical Engineering, Aditya University, Surampalem, Andhra Pradesh, India*

²*Department of Metallurgical Engineering, Kazi Nazrul University, Asansol, India*

³*Department of Mechanical Engineering, National Institute of Technology, Calicut, India*

⁴*School of Engineering & Technology, Pimpri Chinchwad University, Pune, India*

Abstract

Composite materials are vital for everything, from supporting modern nations to facilitating new inventions. The main benefits are their strength, durability, light weight, flexibility in design, and resistance to corrosion. These materials are utilized in modern industries including building, medicine, oil and gas, sports, transportation, and aerospace. This chapter covers an overview of composite materials, including the properties of polymer matrix, reinforcements, a basic approach to material selection, composite production procedures, composite properties, and applications.

Keywords: Natural fiber, biopolymer, thermoset, thermoplastic, fiber, matrix, composite

1.1 Introduction

Nature contains composites. The long cellulose fibers that make up wood are joined by lignin to form a composite substance. It is formed by joining two or more materials that do not dissolve concurrently and have quite discrete qualities. The composite's distinctive qualities are a result

*Corresponding author: sandip.sandip.kumar@gmail.com

of the interaction of its various constituent components. These materials have been applied by people in various contexts from a long time ago. To construct sturdy and long-lasting structures, early Mesopotamian and Egyptians settlers exploited the blending of straw and mud at around 1500 BC, which is when these materials were first applied. A block of brick has a strong confrontation to bending, ripping, and squeezing because of the mixture of straw and mud. The ancient composite materials such as ceramics and boats were reinforced by straw [1]. In 1200 AD, the first composite bow was produced by combining wood, bone, and animal glue during the Mongols period. Birch bark was used to wrap and press the bows. These bows were accurate and strong. The supremacy of Genghis Khan's military was ensured in part by composite Mongolian bows. Many of the biggest developments were brought about by wartime requirements because of their advantages, which include strength and light load. Various materials were created during World War II and transitioned from research and development to real manufacturing [2].

The fiber-reinforced polymers (FRP) are a direct result of the advancement and demand for composite materials. Over 7.5 million pounds of glass fibers had been utilized in 1945 for a variety of goods, mostly for military uses. The composite materials gained popularity and expanded quickly into the 1950s. The pioneers of composites made a bold attempt to expand the use of composites into other industries, including transportation, construction, and aircraft. The public sectors acquired the idea about the benefits of FRP composites, particularly no corrosion of composite materials. In 1946, the first composite boat hull was issued for commercial use. In 1947, an entire car body was made of composite and put through testing. As a result, Chevrolet Corvette was created in 1953. Several innovative molding techniques, including compression molding and sheet molding, emerged with the onset of the automotive age. The two methods became the most widely used molding procedures in the automotive and other sectors. Manufacturing techniques like vacuum bag molding, pultrusion, and large-scale filament winding were created in the early 1950s. The greatest market for composite materials in the 1960s was the marine industry. The first carbon fiber was patented in 1961 and frequently accessible after a few years. The industry commenced to manufacture the composites in the 1970s. During this time, numerous new resins and reinforcing fibers were created for use in composite applications. The automobile industry overtook the maritime industry as the largest market in the 1970s, and it still retains that position presently. Composites were initially employed in infrastructure applications in Asia and Europe in the late 1970s and early 1980s. In the 1990s, Aberfeldy, Scotland, saw the installation of the first

pedestrian bridge made entirely of composite materials. During this time, the first all-composite vehicle bridge deck was built in Russell and Kansas, while the first FRP-reinforced concrete bridge deck was built in McKinleyville, West Virginia. Applications for composites are still being found today. New composites are created by combining nanomaterials with enhanced fibers and resins. In the early 2000s, nanotechnology started to appear in business goods. To enhance the electrical and mechanical characteristics of polymers, bulk carbon nanotube is utilized as composite reinforcement [3].

This material sector is advancing continuously with a large portion. For instance, engineers can modify the design of composite components based on the performance requirements, where more strength is required in the component. Wind turbine blades are always modifying the design of blade size and demand smart composite materials. By choosing the proper matrix material, the engineers can also decide the attributes like corrosion resistance, resistance to chemicals, etc. The use of natural fibers as reinforcements in composites to surrogate the synthetic fibers has acquired popularity recently owing to more environmental awareness and the requirement for sustainable development [4–7]. An overview of composite material, characteristics of polymer matrix, reinforcements, the fundamental method for choosing materials, techniques for producing composites, composite properties, and application are covered in this chapter.

1.2 Overview

As the most used word, composite materials are made up of two or more components, each of which exhibits a wide range of physical and/or chemical properties. A new material having features distinct from the individual component is fabricated by combining two or more fundamental materials. Blending two or more elementary materials produces a new substance with different properties from the constituent parts. Because the principal components remain discrete and the formation of structure is separate, composites must be appropriately separated from the solutions of solids and material mixtures [8].

Individual basic components, sometimes known as constituent materials, make up composite materials. The matrix, often known as the “binder,” and the reinforcement are the two elementary types of basic materials that are identified. To make a composite, at least one substance from each category is needed. By maintaining the relative positions of the reinforcements, the matrix phase surrounds, envelops, and supports them. By adding their unique mechanical and physical resources, the reinforcements improve the

4 FUNCTIONAL COMPOSITES

matrix's qualities. While the infinite variety of reinforcements and binders allows the designer to create the best possible combinations, resulting in custom-made composites, the synergism between the two phases produces the quality materials [9].

The following are familiar instances of composite materials:

- Wood (cellulose fibers encased in lignin and hemicellulose)
- Bones (apatite, a hard mineral, collagen, and a soft protein)
- Pearlite is a mixture of cementite and ferrite [10, 11]

The following composite materials are categorized as follows:

- The matrix (binder) component serves as the basis for the first classification criterion. Ceramic matrix composites (CMCs), organic matrix composites (OMCs), and metal matrix composites (MMCs) are the three primary composite groups. In general, OMC refers to polymer matrix composites (PMCs) and carbon-carbon composites.
- Fiber-reinforced composites (FRCs), laminar composites, and particle composites are differentiated based on the second categorization criterion, which relates to the reinforcing phases. FRC can be further divided into types with reinforcements that are continuous or discontinuous fibers, respectively.
- FRC is made up of fibers encased in matrix materials. If the composite's characteristics rely on the fiber length, it is referred to as a discontinuous fiber composite or a short fiber composite. However, the composite is contemplated "continuous fiber reinforced" when the fiber length expansion does not cause the elastic modulus of the composite to grow further. Despite often having good tensile qualities, fibers are typically tiny in diameter and readily twist when compressed axially. The fibers must be reinforced for resisting the buckling.
- The particulate composites are made of particles, which can be powdered or flakes, that are dispersed in a binding matrix. Particle boards are fabricated of wood and concrete is good example of this form [12].

There are numerous further categories of composite materials, including the following:

(a) Grouping based on the kind of matrix materials:

- Composites made of metal (MMCs)

Despite having a relatively high specific mass, metal fibers are typically inexpensive. They are used for metal matrix reinforcement. This material has not more requirement because of their high density. The excellent fiber-matrix compatibility allows for the primary function in the metal-metal composite preparation. Metal matrices are reinforced with carbon steel fibers to endure temperatures up to 300°C. Fibers are composed of heat-resistant metals such as tungsten or molybdenum, are used to strengthen metal matrices. So they can tolerate higher temperature. The following fibers are used generally.

- Steel: regularly contains alloys of strengthening aluminium.
 - Tungsten: used to reinforce materials that can withstand heat.
 - Boric: extremely light but solid and inflexible; manufacturing is not simple. Boric fibers should be mentioned as a typical example, where a thin SiC layer is first applied to the surface of a thin tungsten wire to protect it from oxidation and boron diffusion into the matrix, followed by a boron layer that is chemically deposited on the wire by BCl₃ vapor.
- Composite materials with an inorganic non-metallic matrix.
 - Polymer matrix composites (PMCs)

Because of their low compactness, easy manufacturing, and desired technical properties, these polymers exhibit appropriate matrix materials. Consequently, polymeric resins endure elevated temperature. Due to that it is commonly applied in aviation [13]. Two important categories of polymers are thermosets and thermoplastics. A well-bonded 3D molecular structure that forms after curing, is what distinguishes thermosets. At high temperatures, some substances break down rather than melt. To amend this circumstances for curing and determining other characteristics, the key composition of the resin only needs to be replaced. They are also retained for long periods of time in a partially healed state. Additionally, thermosets have a great extent of flexibility. Therefore, they make excellent matrix bases for FRC in sophisticated applications. To create chopped fiber composites, thermosets are frequently utilized, particularly when utilizing a molded solution with good quality fibers. Thermoplastics are molecules with 1D or 2D structure that dissolved at greater temperatures and usually

have inflated melting points. Another benefit is that their softening at high temperatures is reversible, meaning that cooling can return them to their previous characteristics. This makes it easier to apply well-established compression procedures for creating molded compounds. Thermoplastic-reinforced resins are currently a constant growing class of composites. These days, a lot of research efforts in this field are focused on improving the resins' main qualities and maximizing their performing benefits for certain applications. This includes attempts to use die-casting techniques to replace problematic metals. The reinforcement significantly alters the morphology of crystalline thermoplastics, causing the reinforcement to be stimulated to permit nucleation.

These resins can alter their creep characteristics across a wide temperature range, regardless of whether they are crystalline or amorphous. Reinforcement in such systems can improve the creep resistance and failure load, but this temperature range also covers the point at which resin usage is compromised [14, 15].

(b) Categorization based on the type of scattered phase:

- Continuous composites reinforced with fibers
- Textile fibers and woven-reinforced composites
- Composites reinforced with sheets
- Composites reinforced with very short fibers (sometimes known as “whiskers”)
- Composites reinforced with particles
- Composites enhanced with nanoparticles

(c) Categorization based on reinforcing fiber type:

Composite materials made of carbon and graphite fibers are common traits of various materials:

- Less elongation at break than glass fibers.
- Tensile strength is lower than glass fibers at normal temperature.
- It is steady, chemically inert and excellent thermal performance up to 1000°C, and stable up to 2000°C when oxidation protected.
- Minimal expansion of heat, occasionally even contraction of heat.
- Significantly more resilient to fatigue than glass.
- Conductive of electricity.
- One hundred times the price of glass.
- Anisotropy is high.

1.3 Characteristics of Composites

The fact that there are numerous varieties of composite materials is already known to us based on their classification. Generally, the performance of various composites varies. However, they also share certain traits. When compared to well-familiar materials such as metals, polymer matrix composites have the subsequent unique properties:

(i) High specific strength and high specific modulus

High specific strength and specific modulus are the two main advantages of polymer matrix composites. The ratio of strength to density is known as specific strength, and the ratio of modulus to density is known as specific modulus. Length is the suitable dimension for both cases. These attributes are essential for structural materials used in aircraft. Because glass fibers have a relatively low modulus and a high density, glass fiber resin matrix composites have a somewhat lower specific modulus than metallic materials.

(ii) High damage resistance and rapid fatigue resistance

Often, there is no obvious sign of the severity of damage before metallic materials fatigue. In composites, the fiber/matrix interaction can prevent the spread of cracks. Those fiber links that are prone to breaking are always where fatigue failure begins. There is a significant forerun before the start of the last destruction because crack growth or destruction spreads gradually over an extended period. The S-N curve of fatigue properties shows that the fatigue strength of most metallic materials is only 40–50% of tensile strength, whereas for carbon fiber/polyester composites, this value rises to 72–82% for glass fiber composites. The percentage falls between these two ranges.

(iii) Good damping properties

The inherent frequency of composites is high, and it is generally difficult to generate a resonance. Simultaneously, composites have a strong vibration damping because the fiber/matrix contact readily absorbs vibrational energy. It is simple to halt vibrations if they do occur [16].

(iv) Practical processing methods

Fiber matrix can be preferred based on the product's performance needs and usage circumstances. As a result, custom materials can be created upon request. Depending on the product's size, shape,