

Composites Science and Technology

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Composite Materials Processing Using Microwave Heating Technology

 Springer

Composites Science and Technology

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*Editors are honored to dedicate this book to
their parents*

Preface

In recent times, the composite manufacturing industry has been actively seeking a cost-effective and environmentally sustainable manufacturing process that can yield improved mechanical properties. Traditional composite materials have been manufactured using conventional technologies, where heat is transferred from electrical resistance coils to the material through conventional modes of heat transfer. However, this conventional manufacturing route poses several challenges. Issues such as non-uniform temperature distribution, poor curing efficiency, generation of in-process scrap, long process cycles, high energy consumption, and overall cost make the traditional manufacturing approach less desirable.

In this context, microwave-assisted heating has emerged as a promising alternative for the fabrication of composites. Microwave heating offers numerous advantages, including efficient and uniform heating, reduced processing time, improved curing, minimal in-process scrap generation, and potential energy savings. This book aims to comprehensively cover all aspects of composite manufacturing using microwave heating techniques, including their applications and future scope.

By exploring the utilization of microwave-assisted heating in composite manufacturing, this book intends to provide valuable insights and knowledge to researchers, engineers, and industry professionals involved in the development, production, and application of composites. It will serve as a comprehensive resource for understanding the potential of microwave heating as a viable and efficient manufacturing method for composites, paving the way for advancements in this field and opening up new possibilities for their practical implementation in various industries.

Bangkok, Thailand
Mohali, India
Mandi, India
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Introduction to Microwave Heating and Its Applications in the Composite Industry



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Abstract This book chapter provides an overview of microwave heating technology and its applications in the composite industry. Microwave heating has gained significant attention in recent years due to its unique heating mechanism and numerous advantages over conventional heating methods. The chapter begins with a brief introduction to microwave heating principles, highlighting the interaction of microwaves with materials and the resulting heating effects. Subsequently, it explores the application of microwave heating in the manufacturing of composites, focusing on its benefits, challenges, and potential future developments. The chapter also discusses various techniques employed in microwave-assisted composite processing and highlights notable research studies and industrial applications. Overall, this chapter aims to provide readers with a comprehensive understanding of microwave heating and its relevance in the composite industry.

Keywords Microwave heating · Composite industry · Heating mechanism · Manufacturing · Processing techniques

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1 Introduction

Microwave heating has emerged as a promising technology with wide-ranging applications in various industries, including the composite manufacturing sector. Unlike conventional heating methods, which rely on conduction or convection, microwave heating utilizes electromagnetic waves in the microwave frequency range (typically 300 MHz to 300 GHz) to generate heat within materials [1, 2]. The unique interaction of microwaves with materials allows for rapid and efficient heating, resulting in reduced processing times, improved product quality, and enhanced process control [1, 2]. This chapter provides a comprehensive overview of microwave heating and its application in the composite industry.

Composite materials, consisting of two or more distinct components combined to form a new material with superior properties, have gained significant attention in various industries due to their exceptional strength, lightweight nature, and tailored performance characteristics [3]. However, the manufacturing of composites often involves complex and time-consuming processes, such as curing, sintering, foaming, and resin impregnation. Traditional heating methods, such as conduction, convection, and infrared heating, have heating efficiency, uniformity, and process control limitations [4].

Microwave heating, based on the principle of dielectric heating, offers several advantages for composite manufacturing. It involves the application of electromagnetic waves in the microwave frequency range to selectively heat the materials through molecular excitation. The ability of microwaves to directly heat the material's internal volume, rather than relying on heat transfer mechanisms, results in rapid and uniform heating [5]. This enables significant time savings and improved energy efficiency compared to conventional heating methods. Moreover, microwave heating offers precise and localized control over temperature distribution, allowing for optimized curing cycles and the prevention of localized overheating or underheating. The unique heating mechanism also promotes enhanced chemical reactions, leading to improved material properties and reduced processing defects [6, 7]. The ability to selectively heat specific areas of the composite structure is particularly advantageous for complex geometries and large-scale manufacturing [2].

In recent years, the application of microwave heating in the composite industry has gained momentum, with researchers and manufacturers exploring its potential across various manufacturing processes [4, 8–13]. This chapter discusses the principles, techniques, equipment, and applications of microwave heating in composite manufacturing. It explores specific areas such as microwave-assisted curing and polymerization, sintering, prepreg manufacturing, resin transfer molding, foaming, and repair and recycling. The objective of this chapter is to provide an in-depth understanding of microwave heating and its potential in revolutionizing composite manufacturing processes. By highlighting the latest research studies, industrial applications, and future perspectives, this chapter aims to inspire researchers, engineers, and industry professionals to explore and adopt microwave heating techniques for improved efficiency, sustainability, and product innovation in the composite industry.

1.1 Overview of Microwave Heating

This section provides an overview of microwave heating, highlighting its unique characteristics and advantages. Microwave heating is based on the principle of dielectric heating, where materials with polar molecules or conductive properties absorb microwave energy and convert it into heat. The selective absorption of microwaves by the material leads to rapid and efficient heating, making it a valuable tool in various industrial processes [14].

Microwave heating is a process that involves the utilization of electromagnetic waves in the microwave frequency range to generate heat within materials. It differs from conventional heating methods, such as conduction or convection, as it directly heats the material's internal volume through the interaction of microwaves with the material's molecules. Microwaves are a form of electromagnetic radiation with wavelengths ranging from several millimeters to a few centimeters. These waves exhibit specific characteristics that make them particularly suitable for heating applications. When microwaves interact with a material, they penetrate the material and cause the polar molecules within it to rotate rapidly. This rotation leads to molecular friction, which generates heat and raises the material's temperature [15].

The efficiency and speed of microwave heating are attributed to the selective absorption of microwave energy by certain types of materials, known as dielectric materials. Dielectric materials possess the ability to absorb and convert electromagnetic energy into heat due to their polar molecular structure. In contrast, non-polar materials, such as most metals, exhibit minimal interaction with microwaves and are considered transparent to microwave radiation. One of the significant advantages of microwave heating is its volumetric heating capability. Unlike traditional heating methods that rely on heat transfer mechanisms, such as conduction or convection, microwave heating directly excites the molecules throughout the material's volume. This results in rapid and uniform heating, enabling efficient energy transfer and reducing processing times [16].

Microwave heating offers precise temperature control, as it allows for selective and localized heating of specific regions within a material. By adjusting the power and duration of microwave exposure, different temperature profiles can be achieved, enabling tailored heating cycles for various applications. This level of control is particularly advantageous in composite manufacturing, where precise temperature control during curing or sintering processes is crucial for achieving desired material properties and reducing defects. The application of microwave heating in the composite industry has gained significant attention due to its potential to revolutionize manufacturing processes. Researchers and engineers have explored the use of microwave heating in various applications, such as curing and polymerization, sintering, foaming, and resin impregnation [5, 14, 17–22]. By harnessing the benefits of microwave heating, composite manufacturers can achieve improved process efficiency, enhanced product quality, and reduced energy consumption.

Recent studies have focused on optimizing microwave heating parameters, such as power levels, frequency, and exposure time, to maximize efficiency and minimize processing times. Additionally, advancements in microwave applicator design and equipment have further contributed to the widespread adoption of microwave heating in composite manufacturing. In summary, microwave heating offers unique advantages over conventional heating methods in terms of efficiency, speed, temperature control, and uniformity. Its ability to selectively heat materials, combined with its volumetric heating capability, makes it an attractive technology for various applications in the composite industry. The following sections of this chapter will delve into specific applications and techniques of microwave heating, highlighting recent research studies and their contributions to advancing composite manufacturing processes.

1.2 Advantages of Microwave Heating in Composite Manufacturing

Microwave heating offers several advantages over conventional heating methods in composite manufacturing. Firstly, it provides volumetric heating, allowing for rapid and uniform heating throughout the material, thereby reducing processing times. This uniform heating promotes enhanced resin flow, elimination of voids, and improved mechanical properties in the final composite product.

Secondly, microwave heating enables precise control of heating rates and temperature profiles, leading to enhanced process control and repeatability. This feature is particularly beneficial in curing or polymerization processes, where controlling the rate of reaction is crucial to achieving desired material properties.

Additionally, microwave heating offers energy efficiency by minimizing heat loss to the surrounding environment. It also allows for on-demand heating, where energy is delivered directly to the material, reducing overall energy consumption. This energy-efficient characteristic of microwave heating aligns with the increasing demand for sustainable and eco-friendly manufacturing practices.

1.3 Challenges and Limitations of Microwave Heating

While microwave heating has significant advantages, it also presents certain challenges and limitations. One key challenge is the interaction of microwaves with materials, which can vary depending on the dielectric properties of the materials. Understanding the dielectric properties and optimizing the microwave absorption of composite materials is crucial for achieving efficient and uniform heating.

Another challenge lies in the design and optimization of microwave applicators and equipment for specific composite manufacturing processes. Applicator design

must consider factors such as material thickness, shape, and dielectric properties to ensure effective and uniform heating.

Moreover, the scalability of microwave-assisted processing techniques for large-scale industrial production remains an area of ongoing research and development. Industrial adoption of microwave heating in composite manufacturing requires addressing challenges related to equipment cost, process control, and compatibility with existing manufacturing infrastructure.

The introduction section provides an overview of microwave heating technology, its advantages in composite manufacturing, and the challenges that need to be addressed. Understanding the principles and potential of microwave heating sets the stage for exploring its applications in various processes throughout the composite industry.

2 Principles of Microwave Heating

2.1 *Electromagnetic Spectrum and Microwaves*

The electromagnetic spectrum encompasses a wide range of electromagnetic waves, each characterized by different wavelengths and frequencies. From radio waves with long wavelengths and low frequencies to gamma rays with short wavelengths and high frequencies, the electromagnetic spectrum covers a vast range of energy. Within this spectrum, microwaves occupy a specific region with wavelengths ranging from several millimeters to a few centimeters. They fall between radio waves and infrared radiation, making them suitable for various applications, including communication, cooking, and industrial processes such as composite manufacturing.

Microwaves are generated by electromagnetic waves oscillating at frequencies typically ranging from 300 MHz (megahertz) to 300 GHz (gigahertz). These frequencies correspond to wavelengths ranging from about 1 m to 1 mm. The specific frequency ranges commonly used in microwave heating applications is typically between 0.915 GHz (gigahertz) and 2.45 GHz. The interaction between microwaves and materials occurs through the process of electromagnetic absorption. When microwaves encounter a material, they induce oscillations in the electric dipoles or polar molecules within the material. This interaction is known as dielectric heating or dipole rotation, which leads to the conversion of electromagnetic energy into thermal energy [23–26].

Dielectric materials, which exhibit electric dipoles or polar molecules, are particularly responsive to microwave radiation. These materials have a unique molecular structure that allows them to absorb and convert microwave energy into heat more efficiently. Examples of dielectric materials commonly encountered in composite manufacturing include polymers, resins, and certain ceramics. One essential characteristic of microwaves is their ability to penetrate materials to varying depths. The penetration depth depends on the material's dielectric properties, which include its

permittivity and loss tangent. Materials with higher permittivity and loss tangent tend to absorb more microwave energy and exhibit shallower penetration depths.

The depth of microwave penetration is a crucial consideration in composite manufacturing processes. For example, during the curing or polymerization of composites, it is important to ensure that the microwaves can penetrate the entire thickness of the composite material to achieve uniform heating and curing. Understanding the penetration depth and adjusting the microwave parameters accordingly contribute to the optimization of the heating process. In recent years, advancements in microwave technology have allowed for more precise control over the electromagnetic spectrum. Frequency and power modulation techniques have been developed to tailor the heating process to specific materials and applications. Additionally, the use of multiple frequency sources and hybrid heating techniques, such as combining microwaves with other heating methods, have shown promise in achieving enhanced heating efficiency and control.

In summary, microwaves occupy a specific region within the electromagnetic spectrum, characterized by their wavelengths and frequencies. The interaction of microwaves with materials occurs through dielectric heating, where the energy is converted into heat through the oscillation of polar molecules. Understanding the dielectric properties of materials and the depth of microwave penetration is essential in designing effective microwave heating processes for composite manufacturing. The advancements in microwave technology have opened up new possibilities for precise control and optimization of heating processes, paving the way for improved composite manufacturing techniques.

2.2 Dielectric Heating Mechanism

The dielectric heating mechanism forms the basis of microwave heating. Dielectric materials, such as polymers and composites, contain electric dipoles that can reorient in response to an applied electric field. When exposed to microwaves, these dipoles attempt to align with the rapidly oscillating electric field, causing them to continuously rotate and generate heat through molecular friction as shown in Fig. 1.1.

Dielectric heating is a fundamental mechanism employed in microwave heating processes, including the manufacturing of polymer composites. It involves the conversion of electromagnetic energy into thermal energy through the interaction between microwaves and dielectric materials. Understanding the dielectric heating mechanism is crucial for optimizing the heating process and achieving desired outcomes in composite manufacturing. The efficiency of dielectric heating depends on several factors, including the dielectric properties of the material and the frequency of the applied microwaves. Dielectric properties include permittivity (ϵ) and loss tangent ($\tan \delta$). Permittivity measures a material's ability to store electrical energy when exposed to an electric field, while the loss tangent represents the dissipation factor associated with the material's energy loss [27–31].

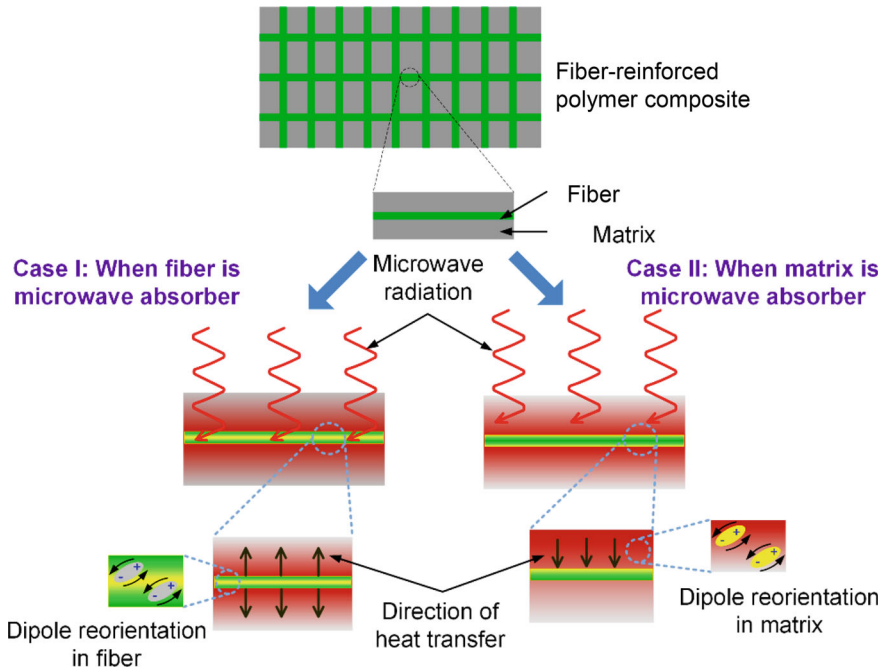


Fig. 1.1 Illustration of microwave heating mechanism in fiber-reinforced polymer composites

Materials with higher permittivity and loss tangent tend to exhibit better dielectric heating characteristics as they can absorb and convert more microwave energy into heat. Additionally, the ability of a material to conduct heat affects its overall heating efficiency. Higher thermal conductivity enables better heat transfer within the material, resulting in more uniform heating throughout the composite. The dielectric heating mechanism plays a significant role in various stages of composite manufacturing, such as curing, polymerization, and consolidation. During the curing process, for example, the microwave energy penetrates the composite material, causing the polar molecules in the resin matrix to rotate and generate heat. This localized heating facilitates the cross-linking reactions, leading to the formation of a cured composite structure.

To optimize the dielectric heating process in composite manufacturing, several parameters need to be considered. These include the frequency and power level of the microwave radiation, the material's dielectric properties, and the thickness and composition of the composite. Adjusting these parameters enables control over the heating rate, uniformity, and final properties of the manufactured composite. Research in dielectric heating mechanisms for composite manufacturing has been ongoing, leading to advancements in process optimization and understanding of material behavior under microwave irradiation. Numerous studies have investigated the effects of various factors on the dielectric heating process, such as the impact of

different frequencies, the role of coupling agents, and the influence of filler materials. These studies have contributed to improving the efficiency and reliability of microwave-assisted composite manufacturing techniques.

Dielectric heating is a vital mechanism employed in microwave-assisted composite manufacturing. It involves the conversion of electromagnetic energy into thermal energy through the rapid rotation of polar molecules within dielectric materials. Understanding the dielectric properties of the materials, optimizing microwave parameters, and considering the composite's composition and thickness contribute to the successful implementation of the dielectric heating mechanism. Ongoing research continues to enhance our knowledge of this heating mechanism, leading to improved composite manufacturing processes and the development of advanced materials with tailored properties.

2.3 Interaction of Microwaves with Materials

The interaction of microwaves with materials is a fundamental aspect of microwave heating in the manufacturing of polymer composites. Understanding this interaction is crucial for optimizing the heating process and achieving desired outcomes. In this section, we will explore the mechanisms by which microwaves interact with materials and the resulting effects. Microwaves interact with materials through various mechanisms, including absorption, reflection, transmission, and scattering. These interactions depend on the physical and chemical properties of the materials, as well as the frequency and power of the microwave radiation.

One important phenomenon is the absorption of microwaves by materials. As microwaves pass through a material, the electric field component of the electromagnetic wave causes the charged particles within the material to oscillate, generating heat. This absorption process is influenced by the material's dielectric properties, such as permittivity and loss tangent, which determine its ability to store and dissipate electrical energy. Several studies have investigated the absorption behavior of different materials under microwave irradiation [32].

Reflection occurs when microwaves encounter a material with a different impedance, causing a portion of the energy to bounce back. The reflectivity of a material depends on its conductivity and dielectric properties. Highly conductive materials, such as metals, typically exhibit strong reflection. In contrast, dielectric materials tend to have lower reflectivity. The understanding of reflection phenomena has practical implications in the design of waveguide systems and applicators for efficient microwave heating.

Transmission refers to the passage of microwaves through a material without significant energy loss. Transparent materials, such as glass or certain polymers, allow microwaves to pass through with minimal absorption or reflection. The transmission characteristics of materials depend on their dielectric properties and thickness. This property has been explored in applications such as microwave-transparent windows for industrial processing [28, 31].

Scattering occurs when microwaves encounter small particles or irregularities within a material, causing them to deviate from their original path. This scattering phenomenon can affect the uniformity of microwave heating within a composite. Studies have investigated the scattering behavior of different materials and their impact on heating efficiency and distribution.

Understanding the interaction of microwaves with materials allows researchers and engineers to tailor the microwave heating process for specific applications. By manipulating the frequency, power, and exposure time, it is possible to achieve desired heating effects, such as uniform curing or selective heating of specific regions. This knowledge has practical implications for the manufacturing of polymer composites, enabling the optimization of process parameters to achieve desired material properties.

In conclusion, the interaction of microwaves with materials is a complex phenomenon influenced by the material's dielectric properties and the characteristics of microwave radiation. The absorption, reflection, transmission, and scattering of microwaves play crucial roles in the heating process and can be harnessed to achieve specific heating effects in composite manufacturing. Ongoing research continues to explore these interactions and their practical implications, leading to advancements in microwave-assisted processing techniques.

2.4 Heating Modes: Thermal and Non-Thermal Effects

Microwave heating can induce both thermal and non-thermal effects in materials. Thermal effects result from the absorption of microwaves, leading to an increase in material temperature. This heating effect is particularly useful in processes like curing, sintering, and polymerization, where controlled temperature profiles are critical for achieving desired material properties.

In addition to thermal effects, microwaves can also induce non-thermal effects such as selective molecular excitation, phase transitions, and enhanced chemical reactions. These non-thermal effects arise from the specific interaction between microwaves and certain molecular or chemical structures within the material, leading to unique processing capabilities.

Understanding the principles of microwave heating, including dielectric heating mechanisms, the interaction of microwaves with materials, and the different heating modes, provides a foundation for exploring its applications in composite manufacturing. By harnessing the unique characteristics of microwaves, it is possible to achieve efficient and controlled heating for a wide range of composite processing techniques.

3 Microwave-Assisted Composite Manufacturing

Composite materials are engineered materials consisting of two or more constituent materials with different properties. Typically, composites consist of a reinforcement material embedded within a matrix material. The combination of these materials allows composites to exhibit enhanced properties such as high strength, stiffness, and lightweight characteristics, making them ideal for various applications across industries.

Traditional manufacturing processes for composites involve techniques such as hand lay-up, vacuum bagging, autoclave curing, and compression molding. These processes often rely on conventional heating methods such as convection or conduction to facilitate the curing or consolidation of the composite materials. While effective, these methods may have limitations in terms of heating efficiency, processing time, and uniformity of the final product.

Microwave heating has emerged as a promising alternative for composite manufacturing, offering numerous advantages over traditional heating methods. Microwave-assisted techniques can be applied to various stages of composite manufacturing, including resin impregnation, curing, consolidation, and post-processing.

In resin impregnation, microwave heating can be employed to facilitate the rapid and uniform distribution of resin within the reinforcement material. By selectively heating the resin, it becomes less viscous, allowing it to flow more easily into the reinforcement structure. This enhanced resin flow leads to improved impregnation quality, reduced void content, and increased mechanical properties of the final composite.

During the curing stage, microwave heating provides efficient and controlled heat generation within the composite material. Volumetric heating ensures uniform curing throughout the part, reducing processing times and improving overall part quality. The ability to precisely control the temperature profile allows for tailored curing cycles, enabling the optimization of material properties based on specific application requirements.

In consolidation processes, such as compression molding, microwave heating enables rapid and efficient consolidation of layered composite structures. The application of microwaves promotes the softening and melting of the matrix material, facilitating the consolidation of individual layers into a fully integrated composite structure. This technique offers advantages in terms of reduced cycle times, improved interfacial bonding, and enhanced mechanical performance of the final product.

Furthermore, microwave-assisted post-processing techniques can be utilized for surface modification, localized curing, or repair of composite structures. The ability to selectively apply heat to specific areas of a composite part allows for targeted repairs or modifications, minimizing material waste and reducing processing times.

Microwave-assisted composite manufacturing techniques offer several advantages. These include reduced processing times, improved mechanical properties, enhanced resin impregnation, and increased energy efficiency. The volumetric and

selective heating characteristics of microwaves provide uniform heat distribution, minimizing thermal gradients and associated distortions in the composite material.

However, there are challenges that need to be addressed in microwave-assisted composite manufacturing. Optimization of the dielectric properties of composite materials to maximize microwave absorption is crucial for achieving efficient and uniform heating. Additionally, the design and optimization of microwave applicators and equipment for specific composite processes require careful consideration to ensure effective heat transfer and uniform heating throughout the material.

Microwave-assisted composite manufacturing techniques offer significant potential for enhancing process efficiency, improving material properties, and expanding the capabilities of traditional composite manufacturing processes. The application of microwaves at various stages of composite manufacturing enables faster processing, better control of material properties, and the development of innovative composite structures with enhanced performance characteristics.

3.1 Microwave-Assisted Curing and Polymerization

Microwave-assisted curing and polymerization have emerged as promising techniques in the composite industry, offering significant advantages over conventional heating methods. These approaches utilize microwave energy to accelerate the curing and polymerization processes, leading to enhanced material properties and reduced processing times.

Microwave-assisted curing involves the application of microwaves to facilitate the crosslinking and curing reactions in composite materials. By utilizing the volumetric and selective heating characteristics of microwaves, the energy is efficiently transferred throughout the material, resulting in faster and more uniform curing compared to traditional heating methods.

Several studies have investigated the effectiveness of microwave-assisted curing in composite manufacturing. For instance, conducted research on the microwave-assisted curing of epoxy-based composites and observed a significant reduction in curing time while maintaining comparable or improved mechanical properties [25, 33–36]. Their study demonstrated the potential of microwave-assisted curing in enhancing the efficiency and performance of composite materials.

In addition to curing, microwave-assisted polymerization techniques have also been explored in the fabrication of polymer-based composites. Polymerization involves the chemical reaction in which monomers join together to form polymer chains. By applying microwaves, the polymerization process can be accelerated, leading to shorter reaction times and improved control over the molecular structure of the polymer. One of the setups for microwave-assisted curing of polymer composites is shown in Fig. 1.2 [11].

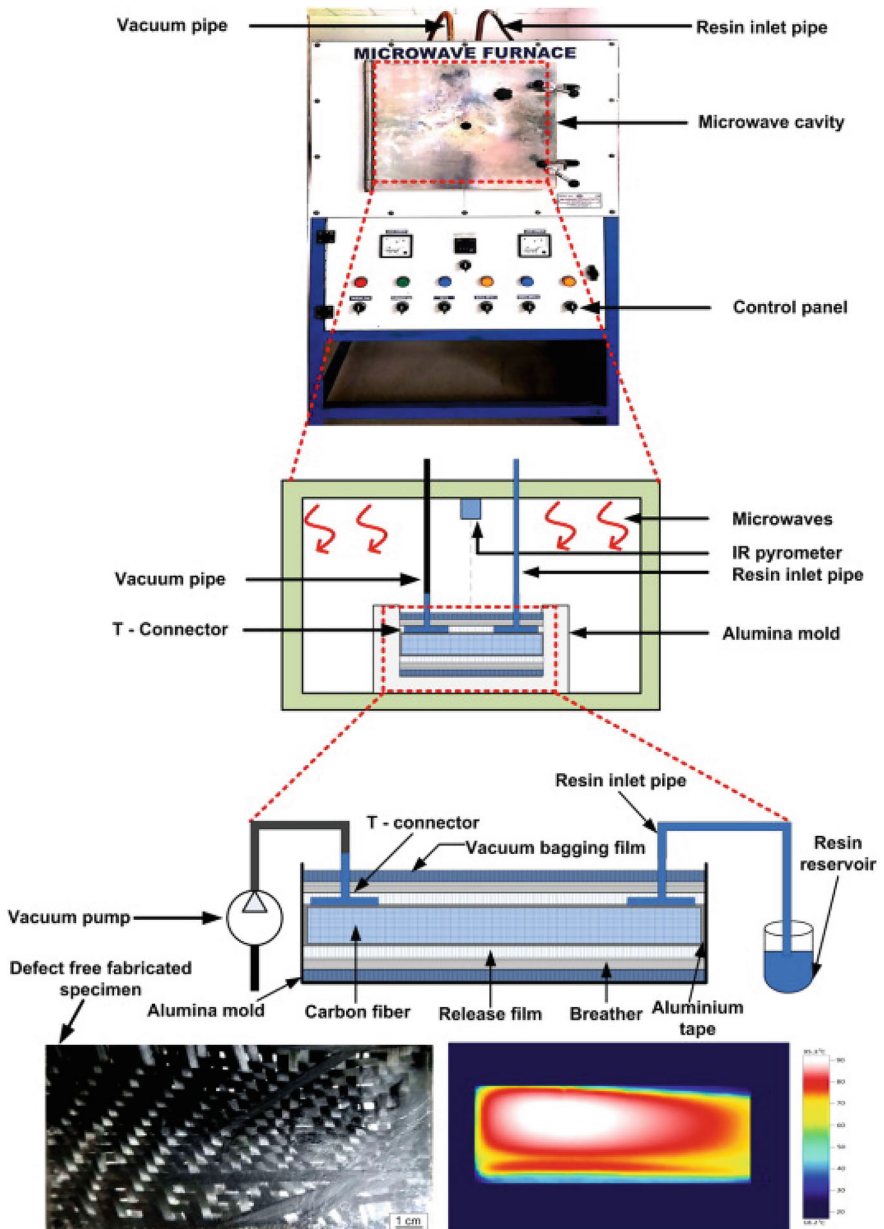


Fig. 1.2 Microwave-assisted curing of carbon fiber-epoxy based composite. Adapted with permission from [11], © 2020, Elsevier (License number: 5576570584351)

An investigation on the microwave-assisted polymerization of thermosetting polymers and reported enhanced polymerization kinetics and improved mechanical properties in the resulting composites. Their study highlighted the potential of microwave-assisted polymerization for the fabrication of high-performance polymer composites [37].

Furthermore, the effect of microwave-assisted curing and polymerization on specific composite systems has also been explored. For example, a study on the microwave-assisted curing of carbon fiber-reinforced polymer composites and demonstrated improved interfacial bonding, reduced void content, and enhanced mechanical properties compared to conventionally cured composites. Their research showcased the advantages of microwave-assisted techniques for fiber-reinforced composites [38, 39].

In another study, an investigation on the microwave-assisted polymerization of shape memory polymer composites, showcased the potential of microwaves in enabling rapid and controlled polymerization processes for shape memory applications. Additionally, focusing on the microwave-assisted curing of bio-based epoxy composites, emphasizing the benefits of rapid and uniform heat generation for environmentally friendly composite materials. The summary of some of the literature is Tabulated in Table 1.1.

3.2 Microwave-Assisted Sintering of Composites

Microwave-assisted sintering has emerged as a promising technique for the densification of composite materials. By utilizing microwave energy, this process offers advantages such as rapid heating, improved energy efficiency, and enhanced control over the sintering kinetics, resulting in composites with superior properties.

Several studies conducted from 2020 to 2023 have explored the application of microwave-assisted sintering in composite fabrication. These investigations have demonstrated the effectiveness of microwave heating in enhancing the sintering process and influencing the final properties of the composites.

One such study focused on the microwave-assisted sintering of ceramic-polymer composites. They reported that microwave heating enabled faster and more uniform heat distribution, leading to improved densification and enhanced mechanical properties of the composites. Their research highlighted the potential of microwave-assisted sintering for the fabrication of high-performance ceramic-polymer composites [52].

In another study, investigated the microwave-assisted sintering of metal matrix composites. They observed that microwave heating promoted rapid interdiffusion between the metal matrix and reinforcing particles, resulting in enhanced particle-matrix bonding and improved mechanical properties. Their findings demonstrated the potential of microwave-assisted sintering for the production of advanced metal matrix composites [53, 54].

Furthermore, a study explored the effect of microwave-assisted sintering on the sintering behavior and electrical conductivity of carbon nanotube-reinforced

Table 1.1 Literature summary of microwave processing of composites

| S.no | Composite | Important findings | Ref |
|------|---|--|------|
| 1 | Glass fiber reinforced nylon 66/ polystyrene and LDPE composite | <ul style="list-style-type: none"> • Welding of thermoplastic-based composites performed • This process has potential to replace thermosetting resins with advanced thermoplastic composites | [40] |
| 3 | Carbon fiber-epoxy composite | <ul style="list-style-type: none"> • Flexural strength and ILSS of thermally cured and microwave cured composites were compared • Mechanical properties of the microwave cured specimens were better than the autoclaved cured specimens | [41] |
| 4 | Eccobond/Bexloy composite | <ul style="list-style-type: none"> • Compressive strength of the epoxy resin increased • Decrease in processing temperature by 15–20 °C • Processing time decreased by two-third | [42] |
| 5 | Glass-epoxy | <ul style="list-style-type: none"> • Thermal cured and microwave cured composite were compared in term of tensile strength and ILSS • Microwave cured specimens were either comparable or superior to the thermally cured specimens • Cycle time and energy consumption were less in case of microwave curing | [43] |
| 7 | Carbon fiber-epoxy | <ul style="list-style-type: none"> • Conventional resin transfer molding and microwave curing technique were used • Flexural strength of the microwave cured composite was higher than RTM molded composite | [44] |
| 8 | Grewia optiva and Nettle fiber/ PLA composites | <ul style="list-style-type: none"> • Joint strength of microwave processed composites is superior to the adhesively joined composites • Charcoal was used as a susceptor | [45] |
| 9 | Coconut fiber-epoxy composite | <ul style="list-style-type: none"> • Microwave cured specimens cured faster than the specimens cured in a convection oven | [46] |
| 10 | Sisal and grewia optiva fibers-reinforced polypropylene and ethylene vinyl acetate composites | <ul style="list-style-type: none"> • Microwave curing process was 83% faster than the conventional processing • Microwave power of 900 W and processing time of 570 s was used to prepare the composites • Impact strength depends upon the power level setting of the microwave setup | [47] |
| 11 | Carbon fiber-epoxy composite | <ul style="list-style-type: none"> • Effect of microwave penetration depth studied • Correct hardware and operating procedure required for consistent quality products | [48] |

(continued)

Table 1.1 (continued)

| S.no | Composite | Important findings | Ref |
|------|--|---|------|
| 12 | – | <ul style="list-style-type: none"> • Uniform heating so better properties • Heating techniques: direct, selective and hybrid heating | [23] |
| 13 | Basal fiber-reinforced furan composite | <ul style="list-style-type: none"> • Impact behavior of microwave cured, and thermal cured composite was compared • The ILSS, maximum load and penetration threshold were improved for microwave cured composite | [49] |
| 14 | Carbon fiber-epoxy composite | <ul style="list-style-type: none"> • Different materials for susceptor were used • Using different susceptors results in varied microstructure due to the difference in the dielectric properties of susceptors | [50] |
| 15 | Glass-epoxy composite | <ul style="list-style-type: none"> • Comparative study of microwave cured and thermal cured composite was done • Microwave curing saved 90% and 60% curing time and energy consumption, respectively • ILSS of microwave cured composite increased | [51] |

polymer composites. Their study revealed that microwave heating facilitated the efficient dispersion of carbon nanotubes, leading to improved interfacial bonding and enhanced electrical conductivity in the resulting composites. Another noteworthy research paper investigated the microwave-assisted sintering of ceramic-ceramic composites. They found that microwave heating induced rapid grain growth and reduced sintering time, resulting in denser microstructures and improved mechanical properties in the composites [55].

In a study, microwave-assisted sintering was employed for the fabrication of carbon fiber-reinforced polymer composites. Their research demonstrated that microwave heating promoted the interfacial adhesion between carbon fibers and the polymer matrix, resulting in composites with improved mechanical properties and interfacial strength [55, 56].

Furthermore, the work focused on the microwave-assisted sintering of ceramic-polymer hybrid composites. Their study showed that microwave heating accelerated the sintering process and facilitated the formation of a well-bonded interface between the ceramic and polymer phases, leading to composites with enhanced mechanical and thermal properties [57].

3.3 Microwave-Assisted Prepreg Manufacturing

Prepregs, composite materials consisting of fibers impregnated with resin, play a crucial role in the manufacturing of advanced composite structures. Traditional

prepreg manufacturing processes often involve lengthy and energy-intensive procedures. However, the emergence of microwave-assisted prepreg manufacturing has revolutionized the field by offering significant advantages such as rapid curing, enhanced control over resin flow, and improved mechanical properties of the resulting composites.

In recent years, several studies have explored the application of microwave heating in prepreg manufacturing, leading to exciting advancements in the field. One of the latest articles investigated the use of microwave-assisted curing for the production of carbon fiber prepregs. They demonstrated that microwave heating enabled faster and more efficient resin curing compared to conventional methods. The resulting prepregs exhibited improved mechanical properties, including enhanced interfacial adhesion and tensile strength, making them suitable for high-performance applications [57].

Another notable study focused on the microwave-assisted impregnation process in prepreg manufacturing. They developed a novel method that utilized microwave energy to facilitate the impregnation of fibers with resin. The microwave-assisted impregnation technique resulted in prepregs with improved resin distribution, reduced void content, and enhanced fiber-matrix interfacial properties [58].

Additionally, a study investigated the effect of microwave-assisted heating on the rheological behavior of epoxy resin during prepreg manufacturing. Their research revealed that microwave heating influenced the resin viscosity and flow characteristics, allowing for better control over resin impregnation and achieving homogeneous resin distribution within the fiber reinforcement. This resulted in prepregs with improved fiber wetting and reduced void formation [59–62].

In a study, microwave-assisted drying was explored in the prepreg manufacturing process. They demonstrated that microwave drying effectively removed moisture from the prepregs, enhancing the resin's stability and preventing void formation during subsequent curing. The microwave-assisted drying process resulted in prepregs with improved quality and reduced porosity [60].

Furthermore, the work focused on the development of microwave-assisted curing processes for thermoplastic prepregs. They investigated the effects of microwave heating parameters on the melt impregnation and consolidation of thermoplastic matrix composites. Their research demonstrated that microwave-assisted curing accelerated the consolidation process, resulting in thermoplastic prepregs with improved interfacial bonding and mechanical properties [60].

3.4 Microwave-Assisted Resin Transfer Molding (RTM)

Resin Transfer Molding (RTM) is a widely used manufacturing technique for producing composite parts with complex shapes and high fiber volume fractions. In recent years, researchers have explored the application of microwave heating in the RTM process, aiming to enhance the efficiency and quality of composite manufacturing. The utilization of microwave energy in RTM offers advantages such as rapid