Composites: Part A 156 (2022) 106870

Contents lists available at ScienceDirect

Composites Part A

journal homepage: www.elsevier.com/locate/compositesa

Processing of polymer matrix composites using microwave energy: A review

Tejas Pramod Naik, Inderdeep Singh *, Apurbba Kumar Sharma

Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee, Roorkee 247667, Uttarakhand, India

ARTICLE INFO

Keywords:
A: Polymer-matrix composites (PMCs)
A: Thermosetting resin
A: Thermoplastic resin
Microwave processing

ABSTRACT

Search for novel energy-efficient, eco-friendly, and time-saving manufacturing techniques has gained momentum in the recent times. Polymer composites have been increasingly adapted for variety of industrial applications, however, their efficient processing remains challenging. Microwave curing technique has been employed to process thermoset-based composites since 1980, however, processing of thermoplastic-based composites with natural-fibers as reinforcement, calls for additional data and hence investigations. The current work presents an overview of the basics of microwave heating and the physics behind the microwave processing of polymer composites. A state-of-the-art on microwave processing of thermoset and thermoplastic-based composites and developments in microwave joining has been reviewed. The major constraints in adopting microwave technology for curing composites at the industry scale are highlighted. The article also highlights the challenges during microwave processing of sustainable thermoplastic-based polymer composites. Future scope of work to 3D print the polymer matrix composite parts, through microwave scanning route has been indicated.

1. Introduction

Conventional materials have been an integral part of human life in the form of various products. Substitution of these materials is difficult, yet rapid developments in the field of composite materials have revolutionized the field of materials science and engineering. The advancements in polymer composites, leading to their improved characteristics, have opened a plethora of opportunities for researchers and engineers. Advanced polymer composites, reinforced with synthetic fibers like carbon, aramid, glass etc. [1,2] are being preferentially utilized in many applications requiring lightweight, high quality, strength, erosion, and chemical resistance. Engineered synthetic fiber-reinforced polymer composites have demonstrated the basic durability in a wide range of indoor and outdoor applications. Although these composites have incredible mechanical properties, they do exhibit many concerns including poor machinability and non-biodegradable nature of the fibers/polymers. In the current situation, the significant challenge for the researchers and specialists is to replace the oil based non-biodegradable polymers and synthetic fibers with completely biodegradable biopolymers and naturally occurring fibers. The stringent ecological policies, rules, and guidelines for development of eco-friendly materials have prompted the advancement of natural fiber-reinforced polymer composites [3]. Over the past two decades, the use of natural fibers as the reinforcement, like coir, kenaf, jute, sisal etc. [4-6] for thermoplastic and thermoset polymers has been aggressively investigated and now these sustainable composites are being effectively adopted by different car producers [4]. The broad classification of the polymers and fibers has already been reported [5]. Various manufacturing techniques like hand layup, injection moulding, pultrusion, extrusion, compression moulding, etc. are being commercially employed for processing of these materials [2,7]. In conventional heating-based material processing techniques, external heat is supplied, which affects the material properties. The temperature gradient which exists in conventional heating affects the material characteristics, thus tends to change the microstructure and mechanical properties. Changes in microstructure and hence mechanical properties vis-à-vis temperature gradient during heating/cooling cycles are well known. In conventional heating, heat flows basically through conduction, convection, and radiation. Thus, material properties and heating rate influence the change in temperature of the material. While there is a possibility of getting the area/volume of the material overheated/damaged when the heat is applied; during cooling, the volume of the material which remains heated for a longer period of time might exhibit coarse grain structure. These phenomena affect the crystallization/microstructure of the material and

* Corresponding author.
E-mail addresses: tejas.naik@me.iitr.ac.in (T.P. Naik), inderdeep.singh@me.iitr.ac.in (I. Singh), aks@me.iitr.ac.in (A.K. Sharma).

https://doi.org/10.1016/j.compositesa.2022.106870
Received 20 July 2021; Received in revised form 4 February 2022; Accepted 6 February 2022
Available online 9 February 2022
1359-835X/© 2022 Elsevier Ltd. All rights reserved.

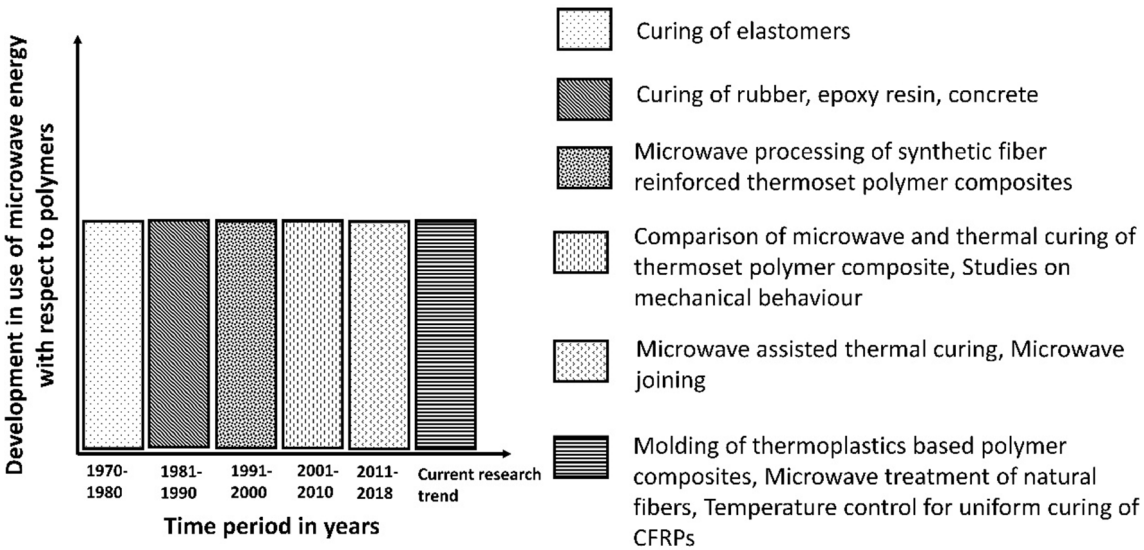


Fig. 1. Development in use of microwave energy with respect to polymers.(**Source:** Web of science, clarivate analytics).

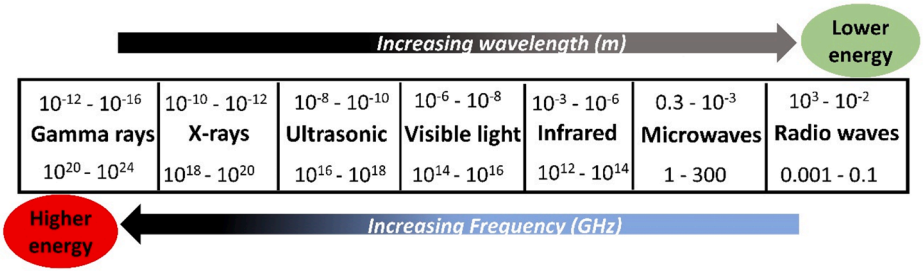


Fig. 2. Electromagnetic spectrum indicating energy content. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

hence the corresponding material properties. Specially in polymers (thermoplastic) as the crystallization of polymer is complex and is sensitive to cooling rate. Higher cooling rate results in lower crystallinity which results in lesser transformation in molecular chains and thus affects the material properties [8,9]. Fiber burning, non-uniform distribution of temperature, fiber damage, longer curing time, thermal gradients, poor efficiency, high energy consumption, waste generation and costly equipment are some of the drawbacks related to conventional techniques used for fabrication of polymeric composites [10,11]. These processing constraints of the conventional heating methods, therefore, require development of novel procedures to process advanced materials, adequately and productively. One such approach is the invention of microwave processing of materials that provides benefits such as less power consumption, faster processing and eco-friendly. Material processing using microwave energy has shown to be a potential manufacturing route for sintering [12,13], joining [14,15], cladding [16,17] casting [18,19] and drilling [20-22]. The use of microwave energy with respect to polymer processing for the past 5 decades is shown in Fig. 1. The use of microwave energy started with the curing of elastomers between the years 1970–1980. Microwave curing of thermoset polymer composites was reported subsequently [23]. Since then, processing of the thermoset-based polymer composites using microwaves has increased and today the process is well developed. The current research trend is focused on moulding and joining of thermoplastic-based polymer composites (both synthetic/natural). In the recent work, the application envelop of microwave processing has been found to extend to other processes beyond curing. A comprehensive summary of the processes, the parameters, the physics involved and the major challenges specific to the processing of polymer composites (PMCs) using microwave was reported in [24]. Therefore, the present work is focussed on the essentials of microwave energy, its basic characteristics with respect to material processing and its application in the field of polymeric composites. The progress made in the area has been reviewed and the opportunities have been identified.

2. Microwave processing of materials

Initially, microwaves were utilized for communication purposes [25]. Percy Spencer's experiments in 1946 demonstrated the heating of surfaces using microwave energy [26]. However, in the year 1950, the microwave procedure was set up. The use of microwaves in material processing became more widespread in 1999 and is still in the research and development stage. The frequency band of 300 MHz–300 GHz (Fig. 2.) is dedicated for electromagnetic (EM) waves called microwaves. Microwaves consist of both electric and magnetic fields, orthogonal to one another, within the wavelength range from 1 to 1000 mm. Energy wise these waves are relatively weaker than other industrially popular forms of EM waves like ultrasonic waves or X-rays as illustrated in Fig. 2 [27-29]. It is interesting to note that all major material, such as metals, ceramics, polymers, and their composites have been processed by researchers using this less explored form of energy [30]. Microwave processing has been broadly classified into three groups – low-temperature processing, moderate temperature processing and high-temperature processing [31]. The properties of prime importance regarding microwave processing of non-metallic materials are loss tangent and complex relative permittivity of the dielectric (material). Low dielectric loss in case of the polymers leads to negligible heating, while low skin depth in metallic materials reflects the microwaves with negligible heating at

room temperature. Microwave curing includes volumetric energy absorption by the material [32]. This has a significant positive impact on processing time, energy-consumption, costs, time for complete curing, uniform curing, productivity and mechanical as well as thermal properties [33,34]. Microwave interaction depends on the relations of material properties (i.e., electric and magnetic) with electromagnetic characteristics of the microwave [27,28]. Heating mechanisms in microwave processing depends on the type of target material, for e.g., non-magnetic, or magnetic. In case of non-magnetic materials (like water (H_2O)) dipolar losses dominate in generation of heat and in case of metallic and high conductivity materials (like Aluminium (Al), Iron (Fe)), conduction losses dominate in heat generation. On the other hand, in case of magnetic material (like Fe) along with conduction losses, magnetic losses such as hysteresis loss, domain wall resonance loss, eddy current loss, residual loss, and electron spin loss generates heat [26]. Most of the polymeric materials also have low dielectric loss factor and they do not interact with microwaves. This is a major challenge in microwave processing of polymeric systems which calls for adding suitable phases, may be fibers as reinforcement or susceptors. The PMCs are processed (curing, joining, moulding) in the low-temperature region of microwave processing, having temperature less than 500 °C [31]. Uniform bulk heating is expected to occur during microwave processing of PMCs as compared to the conventional heating techniques due to its volumetric heating characteristics. To ensuring uniform microwave heating, temperature control in curing process is necessary. The major challenge in application of microwave curing technology is the uneven temperature distribution on the composite surface due to uneven EM field distribution inside the applicator [35,36]. The variation in temperature distribution is the result of hot spot formation inside the microwave applicator because of the areas of low and high intensity fields [37]. As a result, composite severely deforms and remains under treated. In this regard, many approaches for ensuring uniform microwave heating have been documented and classified into two methods–random compensation principle method and active temperature control method [38,39]. The different ways based on the random compensation principle method to control temperature are; Optimizing shape of the applicator [40], increasing the applicator dimensions [41], increasing the number of microwave sources [42], increase in the number electromagnetic modes within the cavity and providing the relative motion between the material and EM field [24]. These methods, relatively to a different extent improved the uniform heating in microwave process but the precise control of distribution of temperature on the heating surface cannot be realized. In the recent study, Sun [43] have presented a semi-direct neural network method to improve the microwave heating uniformity. In this method, surface temperature of the material was monitored and controlled by varying the power of different sources in real time. However, in case of advanced composite materials because of poor quality of temperature tracking and slow response use of this method was not ideal. In this context, an intelligent temperature control method based on online learning was proposed by Zhou et.al. [38]. The proposed method used convolutional neural network (CNN) to learn the real time dynamic relationship between the heating pattern and microwave control strategies. The results from this method were found to be better as compared with the previously existing control methods in terms of tracking error and temperature difference and thus can be proposed where high temperature uniformity is required. The polymeric composite product yielded by microwave processing is better as compared to conventionally cured one because of the uniform heating characteristics of the microwaves. Microwave hybrid heating (MHH), for example, has been shown to successfully process PMCs, resulting in improved mechanical properties and fiber–matrix bonding in both thermoset and thermoplastic polymer composites. Further, researchers in the past, have focused most of the microwaves at a specific location/area using silicon carbide (SiC) or charcoal powder as a susceptor materials. This approach is called as selective heating [44-46]. Only a specific area of the material is exposed to EM radiation during selective heating. Joining of PMCs (lap and butt configuration) using microwave energy has also been reported. Very few articles are available on microwave processing of natural fiber reinforced composites (NFRCs). The present article reviews the work done in curing/moulding the polymer (thermoset and thermoplastic) composites using microwave energy. The behaviour of the polymeric composites reinforced with natural/synthetic fibers is discussed in the following sections. The work carried out on joining of the composites using the microwave energy as a novel technique has also been discussed.

2.1. Theory of microwave material interaction in PMCs

Microwave heating of materials is characterized by rapid, volumetric, and uniform heating throughout the thickness of the material. The penetration of microwaves into a material (bulk or particle) is not similar for all materials. Microwaves may; (a) get absorbed inside the material, causing heating and other effects; (b) get reflected from; or (c) get transmitted through it without causing much effect. Therefore, the amount by which microwaves penetrate inside a material becomes an important indicator and is called skin depth (D_S) or penetration depth (D_P). Skin depth in microwave material processing is defined as the distance from the surface at which the magnitude of the field strength drops by a factor of 1/e (36.8%) [47]. At room temperature, the bulk metallic materials tend to reflect all the incident microwaves due to low D_S. The depth in case of different types of material is calculated using Eqs. (1) and (2) [26].

Metal (Skin Depth D_S)

$$D_S = \frac{1}{\sqrt{\pi \mu f \sigma}} = 0.029(\rho \lambda_0)^{0.5} \tag{1}$$

Non-metal (Penetration Depth D_P)

$$D_P = \frac{1}{\omega \sqrt{\left[0.5 \mu_0 \mu^{'} \varepsilon_0 \varepsilon^{'} \left\{ \sqrt{\left(1 + \left(\frac{\varepsilon^{''}_{eff}}{\varepsilon^{'}}\right)^2\right)} - 1 \right\}\right]}} \tag{2}$$

where f denotes frequency (Hz), ρ denotes electrical resistivity (Ω m), μ denotes magnetic permeability (Hm^{-1}), λ_0 denotes incident wavelength (mm), σ denotes electrical conductivity (Sm^{-1}), ω denotes angular frequency (s^{-1}), $\mu^{'}$ denotes magnetic constant (Hm^{-1}), μ_0 denotes magnetic permeability of air (Hm^{-1}), ε_0 denotes permittivity of free space, $\varepsilon^{''}_{eff}$ denotes effective dielectric loss vector and $\varepsilon^{'}$ denotes dielectric constant.

Further, it is crucial to know that the absorption of the microwave power by the material depends on its dielectric properties. The estimated power absorbed per unit volume of the exposed material can be determined using Eq. (3) [48].

$$P = \omega(\varepsilon_0 \varepsilon^{''} E^2_{rms} + \mu_0 \mu^{''} H^2_{rms}) \tag{3}$$

where P denotes applied power (W), μ_0 denotes magnetic permeability of air (Hm^{-1}), $\varepsilon^{''}$ denotes dielectric loss factor, $\mu^{''}$ denotes imaginary component of the magnetic permeability (Hm^{-1}), H^2_{rms} denotes root mean square of the magnetic field (Am^{-1}) and E^2_{rms} denotes root mean square of the electric field (Vm^{-1}).

For non-magnetic materials, $\mu^{''}$ is negligible, and hence contribution of the magnetic field in power absorption can be ignored and Eq. (3) diminishes to a solitary term, $P = \omega(\varepsilon_0 \varepsilon^{''} E^2_{rms})$. The amount of energy added to the target material is given by Eq. (4) [49].

$$E = \int_0^t p.dT \tag{4}$$

where E denotes total energy added to the target material (J), T denotes time for which total power is applied (s) and P denotes applied power (W).

The propagation of EM field in the target material is governed by

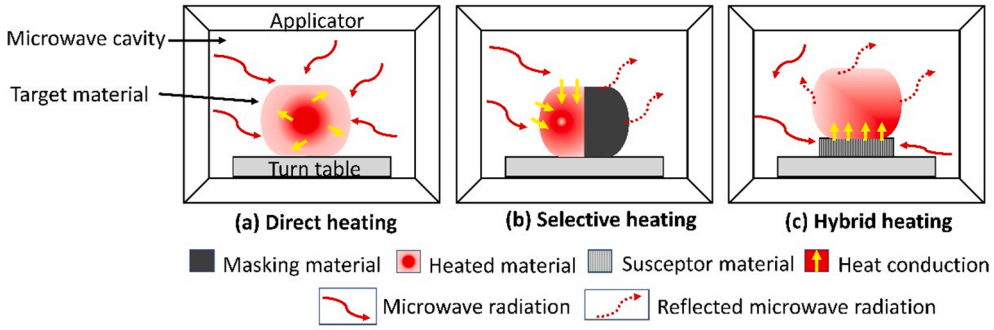


Fig. 3. Different types of microwave heating techniques. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

complex dielectric constant (ε^*) and loss tangent is also another term for expressing dielectric response of the target material. A lossy insulator material (absorber) gets heated more adequately than a low loss insulator material (transparent) and change in temperature (ΔT) with time (Δt) inside the material is given by Eq. (5) [48].

$$\frac{\Delta T}{\Delta t} = \frac{2\pi f \varepsilon''_{eff} E^2}{\rho C_p} \tag{5}$$

where Δt denotes time (s), ΔT denotes change in temperature (°C), and C_p denotes specific heat (J kg^{-1} K^{-1}).

2.2. Microwave heating techniques and heat transfer modes in PMCs

Materials absorb microwaves, depending on their properties and on the electric and magnetic field strength of the EM radiation throughout the material thickness. Based on the microwave-material interaction, materials are classified as– (a) absorber, (b) conductor, (c) transparent, (d) mixed absorber [26,30,50,51]. Different materials may require different types of heating techniques for their processing. There are three types of heating techniques generally used in microwave processing of the materials depending upon the microwave-material interaction characteristics. These are– Direct, Selective, and Hybrid heating as shown schematically in Fig. 3 (a-c). In addition to this, recently the use of novel indirect microwave heating is also proposed for processing of advance materials like CFRP composites [52,53].

In direct heating, the microwave absorbing materials (for example– food products, ceramics, water) couples with the microwaves and interacts with the molecules directly. The net energy absorbed produces heat inside the target (exposed) materials as shown in Fig. 3(a). The temperature gradient produced during microwave processing sometimes may cause overheating and generation of hotspots [54] which tends to overheat the localized material and may cause damage to the material. Hotspot formation is observed to be a major challenge while processing of PMCs, which needs to be overcome in order to get a good quality composite part. Actually, hotspot formation depends upon the type of the applicator used. Because of non-uniform electromagnetic field, a single hotspot is produced in single mode applicator while in multi-mode multiple hot spots are produced. The uniform curing of the polymer in microwave processing is based upon the EM field being uniform and which is difficult to achieve [35,55]. Different suggestions to overcome the non-uniform curing caused by the non-uniform EM fields within the applicator includes (a) use of hexagonal applicator (HEPHAISTOS) [35,56]. This is currently used in industry for curing of CFRPs, and it makes use of hexagonal applicator which produces a uniform magnetic field; (b) Combining microwave heating with conventional heating using heated tooling (less effective for thick components) [57]; (c) Rotating the target material with the help of turntable [57]; (d) Changing the distribution of the EM field inside the applicator by rotating the reflectors. These methods attempt to reduce the non-uniform distribution of the EM fields which would assists in a lesser number of hot spots formation as the microwave energy is not concentrated at a particular spot and thus helps to average out the power distribution. In selective heating, the desired portion of the material is heated, and rest of the material is covered using a masking material which do not absorb the microwaves as illustrated in Fig. 3(b). Microwave joining is one such application area in which selective heating mode is used to generate heat at the desired location (joint area) without affecting the properties of the rest of the target material volume. In order to solve the problems encountered in direct and selective heating techniques, hybrid heating was developed [58,59]. Microwave hybrid heating technique is used when the target material is non-microwave absorbing or for bulk metals which predominantly reflects microwaves at room temperature [15,60-64] (Fig. 3(c)). In this case, a susceptor material which couples with the microwaves at the room temperature and gets heated rapidly, is used. The heated susceptor subsequently transfers heat to target material through conduction and convection. Microwave moulding of thermoplastic-based PMCs is the application area in which hybrid heating mode is used.

3. Heating mechanisms in fiber reinforced PMCs

Microwave heating is volumetric in nature and is not confined to the exposed surface area. Accordingly, PMCs can be processed quickly utilizing microwave radiations [65]. The known mechanism of heat generation in the polymers is dipoles reorientation [26]. Dipoles realign themselves with the oscillating electric field in order to be in phase with the field. These frequent orientations of the dipoles are resisted by the inertial, frictional, elastic, molecular interaction force which generates heat and results in uniform heating throughout the material [26]. The PMCs fall under the category of mixed absorbers. In general PMCs consists of two phases-matrix and reinforcement. The material having high dielectric constant absorbs more microwaves on irradiation and gets heated; the heat is then transferred to the material of low dielectric constant by conduction mode of heating [66]. The selective mode of heating was distinguished as a proficient method for processing of the composite materials because of its special characteristics of volumetric and uniform heating as compared to traditional processing techniques. On the other hand, if neither of the constituents present in the composite possess required dielectric properties (like opaque materials), in such cases, conducting material additives can be added to the material. It has been reported that with the increase in volume fraction of reinforcement, fillers or additives, the microwave absorbing properties of the materials are influenced significantly [67-69]. Processing of PMCs relies upon different factors, for example, structure of dipole, working temperature, conductivity, frequency, and dielectric properties of the material constituents [26]. The reinforcements having low dielectric properties, for example, glass, aramid do not absorb microwave radiation significantly; in such cases microwaves are absorbed by the matrix polymer and it gets heated. Subsequently, this heat is partially

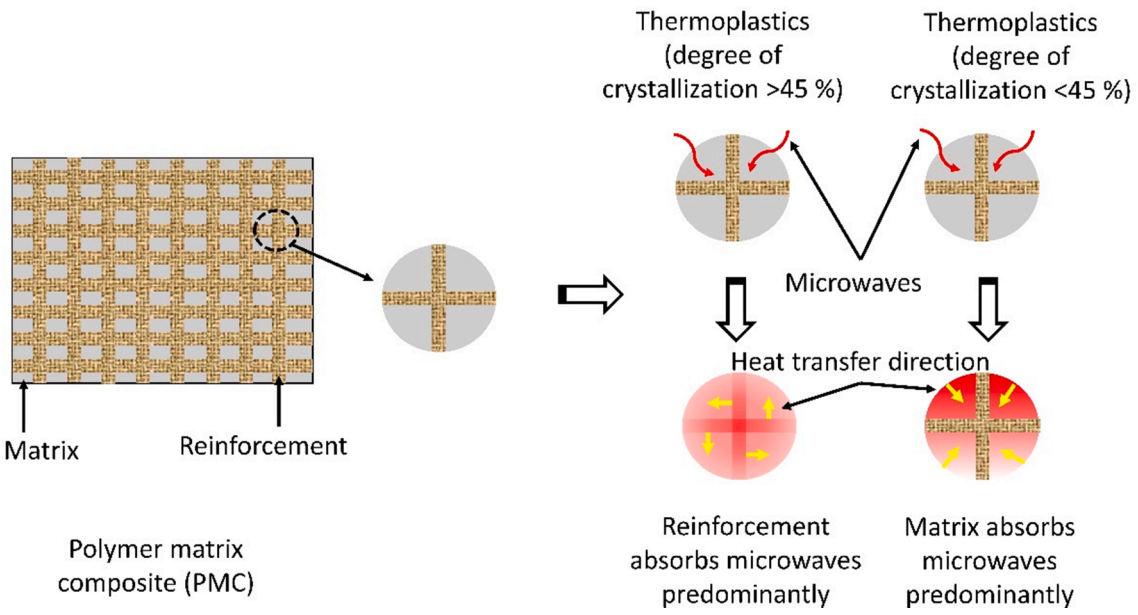


Fig. 4. Heat generation in polymeric composites under microwave irradiation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

transferred to the reinforcement. On the other hand, in case of reinforcement having high dielectric constant as compared to matrix, for example natural fibers reinforced thermoplastic polymers composites, microwaves are absorbed by the reinforcement phase and then the heat is transferred to the matrix through conduction. While in case of carbon fibers reinforced composites, the absorption of the microwave energy largely depends on the angle between the fiber axis and the electric component of EM waves [70]. The dielectric constant of most of the natural fibers is in the range of 3– 6, whereas for the polymer it's in the range of 2.26– 2.4 [71,72].

In thermoset-based PMCs, microwave processing affects the dielectric properties of the matrix material due to change in chemical structure. The thermoset matrix undergoes cross linking during microwave processing which changes the viscosity and thus the dielectric properties of the matrix. Generally, at room temperature, all the thermoset polymers are available in liquid state which solidify on adding hardener to it over a time. On microwave irradiation at room temperature, the matrix absorbs the microwaves effectively, but as it starts to solidify due to heavy cross linking, its viscosity increases which restricts the change in orientation of the dipoles in an oscillating electric field. Over time, this diminishes microwave absorption in thermoset materials [73-75]. At room temperature, the curing of thermoset PMCs is dominated by the matrix material. However, at high temperature, due to crosslinking of thermoset polymer, energy absorption depends on the conductivity of the reinforcing fibers [26].

Microwave processing of thermoplastic-based polymer composites is very difficult and predominantly depends upon three boundaries: degree of crystallinity, temperature, and conductivity of the fibers. It has been reported that thermoplastic with higher degree of crystallinity (greater than 45%), are microwaves transparent due to restriction of dipole reorientations. Therefore, only fibers will absorb microwaves and then heat is conducted to the matrix material through conduction [76]. Once the matrix reaches above critical temperature (T_C), the matrix will also contribute to absorbing the microwaves for the uniform heating to take place. On the other hand, for the thermoplastic having lower degree of crystallinity, both matrix and reinforcement absorbs microwave energy. The percentage absorbed by both the constituents depends on the dielectric loss factor of each of the constituent. In spite of several processing challenges, microwave processing of polymer composites is advantageous as compared to traditional processing techniques [76]. The energy absorption mechanism by the thermoplastic-based polymer composites is schematically explained in Fig. 4.

4. Processing of fiber reinforced PMCs using microwave energy

4.1. Thermoset-based PMCs

Thermosetting polymer resins are widely accepted matrix materials for composites, and epoxy resins are the popular choices for many of these composites owing to their relatively good mechanical and physical properties. Epoxy composites exhibit several improved properties as compared to the individual constituent and the resultant properties majorly depend on the curing process adopted. The curing refers to the transformation of a liquid polymer having low molecular weight into a 3-dimensional highly cross-linked solid [77]. The addition of heat along with pressure, speeds up the chemical reaction of polymerization in thermosetting polymer. The physical and chemical properties achieved for a polymer depend mainly upon curing method, the decision of curing agent, and the curing conditions (temperature and time). There are several techniques of curing like room temperature curing, thermal curing inside a furnace, heated moulds, hot press, autoclave, electron beam heating, etc. [78]. Due to increasing demand for PMCs various curing techniques, like ultraviolet light, gamma rays, electron beams, and microwave radiation have emerged [33]. Out of the mentioned techniques, the microwave curing technique is found to be more significant [79]. Carbon fiber-reinforced polymers (CFRPs) have received a lot of attention in recent decades and are now widely employed in the aerospace sector. There have been substantial amount of investigations exploring the use of microwaves to cure CFRPs [57]. Microwaves heat dielectric materials (thermosetting polymers) by interacting with them on a molecular level via an EM field and generating heat via the polarization process. There are several types of polarization, but only dipolar and interfacial polarization are important mechanisms for energy transfer [29]. Ultimately the level of polarization is governed by the dielectric properties of a material. Materials with high dielectric loss factor, have a low microwave D_P [35], such materials are referred to act as microwave reflectors. Materials having a low dielectric loss factor, on the other hand, have a high D_P which implies they absorb less energy from microwaves. In case of carbon fibers reinforced composites, the absorption of the microwave energy largely depends on the angle

Table 1
Processing of thermoset-based PMCs using microwave and thermal curing technique.

Composite	Thermal curing conditions	Microwave curing conditions	Results/Major findings	Ref.
Glass/Epoxy	10 h at 110 °C and then post-cured 4 h at 125 °C	P: 1.2–0.2 kW	• The curing of thermosetting composites involves two transformations: gelation and vitrification. • If gelation is not fully achieved before vitrification it results in less strength of specimens. • Maximum gelation was achieved faster at a higher power rating for both exposed and sandwiched specimens.	[122]
E-glass /Epoxy	–	–	• More voids exist in MCCs than in TCCs because of shorter time for curing and less pressure application. • MCCs showed stronger matrix-fiber interface as compared to TCCs.	[85]
Epoxy resin	140 °C for 900 s	P: 200 W T: 900 s	• Due to greater homogeneity microwave cured resin (MCR) has a little higher young's modulus and tensile strength. • After ageing in water, the MCR maintained its mechanical properties over the thermally cured samples.	[123]
Glass/Epoxy	12 hr at 130 °C	–	• TCCs showed high strength as compared to MCCs.	[124]
Di-glycidyl ether of bisphenol-A (DGEBA) with three types of curing agents: 4,4′-diamino-di-phenyl-sulfone (DDS), 4,4′diamino-diphenyl-methane (DDM) and *meta*-phenylene-diamine (mPDA).	–	P: 200–600 W	• In DDS system, at lower power level, 100% curing was not achieved. • Full cure was obtained in DDM and mPDA systems at all power levels.	[125]
DGEBA with three types of curing agents: DDS, DDM, mPDA	–	P: 200–600 W	• Due to the sluggish reaction of DDS with epoxy, the maximum value of percentage cure and glass transition temperature (T_g) achieved was found to be lower than those achieved through thermal curing. • Overall, cure time for the mPDA system was found to be reduced through microwave curing.	[126]
Carbon/Epoxy	–	–	• Flexural and Interlaminar shear strength (ILSS) properties of the MCCs were found to be less as compared to the autoclave cured composites. • Partially cured composites showed poor flexural and ILSS properties. • Void content in MCCs as compared to partially and fully autoclave cured composites was reported to be high because of low pressure application in microwave. • Mechanical properties of the MCCs were found to be better.	[127]
Glass/Epoxy	24 hr room temperature curing followed by step-post cure to 85 °C	P: 2.4 kW	• Mechanical properties, of MCCs compared well with the TCCs. • The T_g obtained for MCCs was found to be more than the TCCs.	[128]
Hemp, Flax, Kenaf, Henequen, Glass/Epoxy	145 °C	T: 180 s	• Compared to oven, MCCs achieved larger extent of cure as was revealed by the differential scanning calorimetry (DSC) plot. • Dielectric loss for the natural and glass composites was found to be same.	[65]
Phenol formaldehyde/ Ceramic microsphere	–	P: 160 W T: 2400 s	• Fracture toughness of MCCs was found to be 37% higher than TCCs inside the oven.	[129]
Vinyl ester/Fly ash	ambient	(i) P: 180 and 360 W, for T: 60, 70, and 80 s, (ii) P: 540 and 720 W, for T: 15, 20, and 25 s, respectively	• Vinyl ester resins absorb microwaves readily. • Low shrinkage and improved fracture toughness were found in MCCs.	[130]
Fly ash/Vinyl ester	–	P: 180 and 360 W T: 20–50 s.	• Tensile strength increased. • Resin shrinkage reduced. • Production cost of composites reduced.	[131]
Aluminium/Polyester and Carbon-black/Polyester	–	–	• Modeling results showed that for polyester/aluminium there was better control of temperature compared to other composites while on the other hand, the degree of cure was found to be same for both the composite systems.	[132]
Carbon/Polymer prepregs	120–135 °C, for 2 hr	P: 510–610 W T: 1800 s	• Compared to autoclave, microwave-thermal curing process was found to be time and energy efficient.	[105]
Basalt/Furan	90 °C for 8 hr	–	• Lower residual stresses and homogeneous crosslinking due to volumetric heating in microwave curing showed better impact performance as compared to TCCs. • ILSS failure is a resin dependent property, higher ILSS means good quality of the resin with less voids.	[133]
Carbon/Epoxy	80 °C for 3 h	T: 1200 s	• Flexural strain of the microwave irradiated composites was found to be more as compared to TCCs because of the increase in the fiber–matrix interlocking.	[134]

(*continued on next page*)

Table 1 (*continued*)

Composite	Thermal curing conditions	Microwave curing conditions	Results/Major findings	Ref.
Carbon fiber reinforced polymer	–	P: 5 kW	• MCCs showed better interfacial adhesion than TCCs. • Fast heating rate has a bad effect on the performance of the MCCs. • Compressive strength was found to be insignificantly affected by the curing rates and holding time. • Reducing curing time by increasing heating rate showed moderate decrease in the ILSS because of change in resin viscosity.	[135]
Silicon Carbide/ Epoxy	Room temperature (RT) for 7 h	P: 300 W T: 1200 s	• Increased interfacial polarization owing to the presence of SiC fillers, resulted in improved dielectric properties. • T_g, flexural properties increase with increase in SiC content.	[136]
Plantain /Epoxy	–	P: 550 and 750 W T: 120 s	• Treatment of fibers at higher power level and time decreases the mechanical properties because of the degradation and rupturing of the fiber surface. • Interfacial adhesion between the matrix and fiber increased due to microwave treatment which increased its mechanical properties.	[137]
Fly ash/Epoxy	50 °C for 1200 s	P: 2.5 kW T: 300 s	• Microwave curing route was found to be successful for 99% degree of crosslinking. • The mechanical properties of specimens containing 10% fly ash combined for 30 min and cured in microwave revealed the best results when compared to oven and ambiently cured composites.	[138]
Jute/Vinyl ester	–	P: 800 W T: 900 s	• The deposition of Mg^{+2} ions on the fiber surface was confirmed through field emission scanning electron microscope (FESEM), energy-dispersive X-ray spectroscopy (EDS) and fourier transform infrared spectroscopy (FTIR) analysis. • Flame retardancy improved due to doping with Mg^{+2} ions.	[139]
Bamboo/Cement	–	P: 300 W T: 3600 s	• Microwave assisted alkali treatment improved the mechanical bonding between the constituents due to improvement in the fiber roughness, ductility, and toughness.	[140]
Carbon fiber reinforced polymer (CFRP)	–	P: 180 W T: 30 s	• Wettability was found to be better because microwave irradiation has "co-irradiation grafting" effect on fiber which increases the roughness and energy of the fiber. • The Interfacial shear strength (IFSS) and ILSS properties of the prepregs were found to increase post microwave pre-treatment.	[141]
Glass fiber reinforced multi walled carbon nanotubes (MWCNT)-PANi/Epoxy	RT for 24 h	–	• With increase in the fraction of MWCNT/PANi wt.% in the epoxy, microwave absorption increased.	[142]

**P: Microwave power and T: Microwave exposure time.*

between the fiber axis and the electric component of EM waves. For example, in a recent study Zhou et al. [70], experimentally determined the effect of different ply angles on microwave absorption. Vector network analyzer (VNA) was used to determine the scattering parameters. It was reported that in unidirectional CFRPs laminates with 0° ply angles, fibers aligned parallel to electric field do not absorb microwave energy and behave as a reflective material. Whereas for 90° ply angle, maximum microwave energy is absorbed by the perpendicularly aligned carbon fibers to electric field and it mainly comes from conduction loss in the carbon fibers. Microwaves, according to some studies, do not affect the curing reaction, but rather enhance the rate of reaction by volumetric heating [80]. Few researchers have compared thermal and microwave curing process in terms of mechanisms and rate of reactions for different epoxies, bismaleimides and polyimides [81,82]. The microwave field was found to have no significant effect on the kinetics of the curing process, while the temperature distribution generated by EM field was linked to the variation in curing time observed in both the curing processes. It has also been reported that microwave curing of CFRPs can improve the adherence at the fiber–matrix interface [83]. This, according to Drzal et al. [84] is due to carbon fibers selective heating. The microwaves preferentially are absorbed by the fibers, which then is transferred to surrounding polymer via conduction, resulting in better interfacial properties. Microwave curing of glass fiber polymer composites has also been reported to have similar effect [85]. When compared to other traditional processing methods such as autoclave curing, the reduction in processing time and energy savings have the potential to result in considerable cost reduction in manufacturing of CFRP products [57]. Carbon nanotube-reinforced polymers may also be processed more efficiently and in less time [86,87]. Despite the potential benefits of employing microwaves in the curing of polymer composites, the technique has not yet gained widespread acceptance in the industry. This may be attributed to various scaling issues reported by the researchers; these include – (a) lack of tools (microwave transparent) for use in the process [88], (b) high initial investment on industrial microwave applicators [57], (c) process requires costlier consumable materials as compared to conventional processes [57], (d) size of the applicators is usually significantly smaller unless customized, (e) heating behaviour of complicated tool geometries is often required to be verified before commercial use, stressing the importance of process monitoring and simulation tools [89,90], (f) hot spots and electrical arcing can result from selective microwave coupling to fibers [24], (g) close monitoring and process parameters control is required to produce a uniformly cured laminate [38], (h) difficult to achieve uniform electromagnetic field inside the cavity [24,38,57], (i) less pressure application during fabrication of the composites [57] and (j) concern on the leakage of microwaves during microwave processing.

It was suggested that reduction in cost is important for microwave curing to be adopted by the industry. Microwave curing must create components with equivalent or better mechanical properties in order to be a viable replacement for a traditional method. The mechanical performance of microwave cured CFRPs depends on both process and material-related factors [24]. Compression, interlaminar shear, interlaminar fracture toughness, tensile, and flexural properties of microwave cured CFRPs have been investigated and reported by researchers. The results obtained with the microwave cured composites (MCCs) as compared to thermally cured composites (TCCs) reveal that the properties of the MCCs are either comparable or better than the properties obtained from the TCCs [52,91-100]. Recently for uniform curing of composites a novel method of indirect microwave heating was proposed. Rao et al. [53] investigated the microwave indirect curing process for glass epoxy composite laminates. Microwave susceptive mould (silica-based) was used to improve the EM energy absorption and uniform curing of composites. Li et al. [52] studied the vacuum assisted microwave indirect curing process of multidirectional CFRP composites. Short carbon/epoxy composite was used as microwave susceptive mould to improve energy absorption for uniform curing of the composites. The CFRP laminates for load-bearing applications always consists of orthogonal plies. The multidirectional carbon fibers give metal-like electromagnetic properties in-plane to CFRP laminates and reflects the microwaves without heating. A unique solution was proposed by Zhou et al. recently to address this problem by introducing ultrathin and flexible metallic resonance structure supported by a dielectric spacer, on the highly reflective CFRP laminates, forming a metal–insulator-CFRP laminates which can couple to magnetic field of the microwave. The arrangement is effective in inducing strong current inside the CFRP laminates which converts microwave energy into joule heating. A patterned heating process has also been demonstrated by altering the layout of resonance structures. [101]. The vertical penetrating microwave (VPM) was also proposed as a solution to heat multidirectional CFRP [102]. There is a need to devote attention towards controlling temperature uniformity for better mechanical properties of CFRP laminates fabricated using microwave curing as compared to its autoclave counterpart. Application of ultrathin and flexible resonance structure for manipulating the temperature distribution at particular regions on the CFRP laminate have also been reported in the recent time, also known as zone-regulated microwave heating through frequency-selective absorption [103]. Also, application of resonance structure with dielectric-variable spacer periodically for limiting the absorption of hot areas during microwave curing of CFRP has also been reported [104]. The research on the new technology recently developed high electromagnetic power heating autoclave inset oven system (HEPHAISTOS) microwave applicator (industrial scale), which has the potential for adoption by industry has been found to be limited. More investigations are necessary, for microwave applicator that can produce large scale real-world components with precise process control and process optimization ensuring repeatability [57]. A brief review of the research work reported on the curing of thermoset based polymer composites is presented in Table 1. However, a handful of articles are only available which focus on use of natural fibers as reinforcement with epoxy matrix.

4.2. Thermoplastic-based PMCs

The current research trend is focused on fabrication of the thermoplastic-based PMCs using microwave energy. This may be attributed to the fact that the thermoplastic is mouldable on application of heat and are recyclable. The increasing burden on the environment and the strict laws and policies by the governments has motivated the researchers to come up with the solutions, such as, development of materials which are reusable and recyclable. Almost all thermoplastic polymers are reusable and recyclable, also the domestic applications are more for thermoplastic polymers. Hence, it becomes necessary that the processing of thermoplastic polymers is easy and economical. In this regard, microwave processing is found to be one of the solutions. However, the major challenge in processing of the thermoplastic-based polymers and polymer composites is that they are transparent to microwaves [26]. Dielectric constant for most of the thermoplastic polymer pellets like polypropylene (PP) and high-density polyethylene (HDPE) is less [72]. However, MHH is a solution for melting of thermoplastic polymers. In MHH technique, a material having high dielectric constant, called susceptor (charcoal, silicon carbide, graphite, clay ceramic brick, etc), is used for melting the polymer. The susceptor material absorbs most of the microwaves and gets heated quickly, thereafter, it transfers the heat to the polymer pellets through conduction mode of heating; simultaneously suitable pressure may be applied as shown in Fig. 5a. to attain better uniformity. Many researchers have proposed use of teflon fixture for the application of the pressure inside the microwave cavity [105-107]. Teflon being microwave transparent would not absorb any microwaves. This solution for the in-situ pressure application appears workable but measurement of pressure is challenging and needs further investigations. Globally, researchers have used natural fibers like jute, coir, kenaf, hemp, sugar palm, sisal, etc. for fabrication of composites with microwave energy. The key findings are summarized in Table 2. The two important microwave parameters, power and exposure time significantly influence the mechanical properties of the developed composites and hence needs to be optimized for different polymers. In one such study, investigation of the role of microwave power on mechanical properties of the developed HDPE composites has been reported [108]. Carbon nanotubes (CNTs) were used as the reinforcements, and it has been reported that the CNTs results in faster and efficient coupling with microwaves [109-111]. Further research was focused on increasing the properties of the microwave moulded composites by fiber treatment. Various researchers have used sodium hydroxide (NaOH) for treatment of fibers and reported that the hemicellulose, lignin, pectin, and waxes remove due the treatment. The treatment creates the craters on the fiber surface which results in better fiber–matrix interlocking and hence enhancement in the mechanical properties [112-117]. Motivated by the results that microwave energy can be used for processing of the thermoplastic-based polymers, researchers have extended this technique for the practical application like fabrication of scaffold which finds its application in medical field [61]. A brief review of the work carried out globally on curing of thermoplastic-based composites with microwave energy are summarized in Table 2. It can be noted from Table 2 that microwave processing of thermoplastic based polymer composites is getting popular recently and has opened ample scope to explore this new area. Extensive research is required towards; (a) utilization of short fibers for manufacturing of composites using microwave moulding technique, (b) in-situ process temperature measurement and its control, (c) simulation studies to determine the effect of time and temperature on resultant material properties, (d) secondary processing of the microwave moulded thermoplastic composites, (e) microwaves processing of carbon fiber reinforced thermoplastic composites, (f) modification of natural fibers using microwave treatment which can thereafter be use as a raw material of green composite products fabrication [114].

4.3. Microwave joining

Microwave joining is fusion bonding technique which comes under the category of EM heating. In microwave assisted joining process, the joint area is exposed to the microwaves and rest of the specimen is masked with a material which reflects the microwaves [44]. Masking is essential to prevent the entire sample from heating. The primary goal is to heat only the joint region where joint is to be formed. As a result, it is also known as selective microwave heating [26]. The dielectric properties of thermoplastic influence microwave joining of thermoplastic composites [118]. Thermoplastic with a high dielectric loss factor create a significant quantity of heat at the joint junction. Furthermore, the dielectric properties of thermoplastic are affected by crystallinity of

polymer [30]. Polymers having a crystallinity greater than 45% are basically transparent to microwaves owing to dipole orientation confinement. Addition of conductive fillers or fibers called as susceptor material can have a significant impact on dielectric loss factor of the thermoplastic polymers [119]. Some common examples of susceptor material used are charcoal powder, silicon carbide, carbon fibers, and metal powder. The two adherends which are to be joined are kept in lap configuration having a joint area of 25 mm × 25 mm. The susceptor material is placed at top and bottom of the joint area as shown in Fig. 5 (b). As the microwave is turned on, the susceptor material starts absorbing microwaves at a faster rate and its temperature increases rapidly. Once the susceptor material gets heated up, it transfers heat by conduction to the joint interface thus softening the polymer material at the joint interface. Molten polymer is formed only at the joint area as rest of the specimen is masked. One of the advantages of microwave joining is it takes less time than other joining methods. Owing to a faster heating rate being experienced during the exposure of the microwave, joining is accomplished in a shorter processing time. This is attributed to the uniform and volumetric heating in the targeted joint area. Yarlagadda and Chai [120] examined thermoplastic joining using concentrated microwave energy. Two approaches were used in the thermoplastic joining procedure. In the first situation, microwave energy was directly induced at the specimen joint interface, whereas in the second situation, primers in the form of epoxy-based resin were used to encourage material joining through microwave radiation. Under room temperature settings, experiments were carried out using (ultra-high molecular weight polyethylene) UHMWPE, polycarbonate (PC), and acrylonitrile–butadienestyrene (ABS) polymers. In the recent times, considerable work is going on the natural fiber-based polymer composites and their joining for industrial applications. A brief review of the relevant work reported on joining of NFRCs using microwave energy is presented in Table 3. In one of the investigations, biodegradable composite made of PLA/Sisal was fabricated using compression moulding technique with variable fiber content; the composite was then joined using microwave energy with charcoal as the susceptor. It was reported that the bio composites with lower fiber content took less time for bond formation [44]. In another investigation, comparative analysis of the joint strength between adhesively bonded joint and microwave-based joint was carried out and it was reported that the samples joined using microwave energy showed better joint strength in contrast to the adhesive bonding technique [45]. Input power, location of specimen inside the microwave cavity, exposure time, type of susceptor used, were found to have fundamental role in defining the joining process. The PP and (polylactic acid) PLA based natural fiber composites were fabricated and joined with the assistance of microwave energy. PLA-based composites were reported to have higher joint strength than PP-based composites [46]. In one of the investigations, Nylon/Grewia optiva composites were joined in lap configuration utilizing araldite as a sticky material. The joining of the composites was achieved utilizing variable and fixed frequency microwave applicators and the outcomes were compared. It was observed that the composites joined by variable frequency microwave applicator showed better results [121]. Thus, it can be concluded that microwave processing is an effective and time saving technique for the joining of polymer composites.

5. Challenges in processing of PMCs using microwave energy

The various challenges encountered during processing of polymer-based composites are summarized in Table 4. Also, the challenges faced during fabrication of the thermoplastic-based NFRCs in a domestic applicator are tabulated in Table 5.

6. Processing economy

Technoeconomic aspects of microwave processing technique have been analyzed in earlier work. Results showed that the overall processing time and energy/power consumed for microwave sintering [160-164] and microwave casting [165-167] are reasonably less as compared to conventional methods. Similar trend can be seen while processing with polymer composite using microwave energy. Data presented by GKN aerospace [168] for specific microwave cured CFRP aircraft components showed 80% reduction in energy and 40% reduction of the total cycle time compared to conventional autoclave process. Joshi and Bhudolia [105] reported that in microwave curing, energy consumption is 1/12th of the autoclave curing, and the process is six times and five times faster than the autoclave and oven curing respectively. Also, for indirect microwave curing process used for curing multidirectional CFRPs, the energy consumption and cure cycle was found to be 24.1% and 57.9% of the traditional thermal curing method, respectively [52]. Further, a research group reported that the fabrication time of thermoplastic based composites in microwave assisted compression moulding setup was 5.71 times lower than in convention

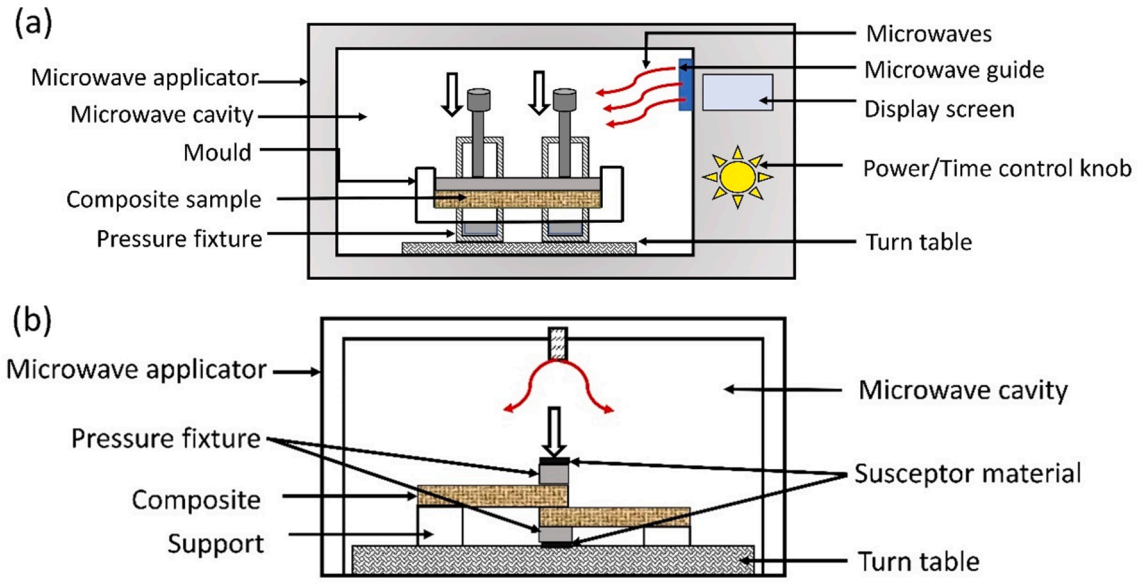


Fig. 5. Setup diagrams for microwave processing of thermoplastic based PMCs (a) Moulding, and (b) Joining. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Processing of thermoplastic-based PMCs using microwave energy.

Matrix	Fiber	Microwave power (W), and time (s)	Results/ Major findings	Ref.
PP and Ethylene vinyl acetate	Sisal and Grewia optiva	P: 900 W T: 570–390 s	• Flexural behaviour revealed that due to microwave curing, there is better interfacial bonding between fiber and matrix. • Simulation results revealed that microwave parameters like power and time play vital role during the process.	[143]
PP	Hemp	P: 700 W T: 480 s	• Blowholes were found in MCCs which decrease the properties of the composites as compared to compression moulded composites. • Power requirement is less in microwave as compared to compression moulding machine.	[107]
PP	Sisal	P: 700 W T: 400 s	• Compared to compression moulding technique, microwave processing led to an increase in the mechanical properties of the composites with added benefits, such as less processing time, energy efficiency. • MCCs showed more porosity as compared to compression moulded samples.	[106]
PP	Rattan, Bamboo and Coir	P: 600 W T: 720 s	• Strength of the processed polymers was found to be less due to lack of application of pressure.	[144]
Polyurethane	Sugar palm	P: 340 W T: 5400 s	• Microwave technique gives excellent tensile properties for both treated and untreated composites.	[145]
PP and PE	Jute and Kenaf	P: 900 W T: 1500–1200 s	• Possible to develop NFRCs using microwave energy. • Mechanical properties of microwave moulded composites were comparable with the conventionally processed composites.	[71]
Poly-L-lactic acid (PLLA)	Nano-hydroxyapatite (nHA)	P: 900 W T: 1200 s	• PLLA/nHA bio-composite scaffolds were successfully developed. • Homogeneously interconnected pores were seen through the FESEM analysis.	[61]
PLA	Nano-hydroxyapatite	P: 900 W T: 1220, 1190 and 1140 s	• Successfully developed porous polymeric foam. • As nHA percentage increases, the T_g also increases. • The foam's compressive strength improves as the reinforcement (nHA) wt.% increases, but its flexural strength declines.	[146]
HDPE and PP	Carbon nanotube	P: 180 W T: 180–240 s	• CNTs resulted in efficient and faster coupling with microwaves. • Fractured surface revealed the uniform dispersion of CNTs. • Agglomeration of the CNTs caused reduced tensile strength. • Crystallinity of the composites increased as peak of X ray diffraction (XRD) intensified.	[109]
Cement	Coir	P: 260 W T: 1200 s	• Microwave curing enhanced the tensile strength. • Improved adhesion between matrix and fiber due to microwaves. • Reduced water absorption of the composite board due to coating on the matrix which inhibit the penetration of the moisture inside the board.	[147]
PP	Coir	P: 720, 640, and 560 W T: 960, 1080, and 1200 s	• Mechanical properties depend on the fiber strength. • According to the analysis of variance (ANOVA), operating time is a major variable that influences ultimate tensile strength, followed by power and fiber size.	[148]
HDPE	Sisal	P: 900 W T: 273–317 s	• Good interfacial bonding between matrix and reinforcement was observed.	[149]
UHMWPE	nHA	P: 540, 720 and 900 W T: 1600, 1400 and 1000 s	• Porosity in composites reduced on application of pressure. • For better mechanical properties, 20 wt% of nHA was found to be optimum.	[150]
HDPE	MWCNT and Kenaf	P: 180 and 900 W T:180 and 420 s	• Ultimate stress and flexural modulus for HDPE/MWCNT is more as compared to HDPE/Kenaf composites. • Tensile modulus and Impact strength was found to be more for HDPE/Kenaf composites. • As strain rate increases, tensile modulus also increases. • HDPE/Kenaf composite is suitable for manufacturing of automobile parts as compared to HDPE/MWCNT because of the ductile nature of natural fiber.	[110,111]
PLLA	Coir	P: 900 W T: 720 s	• Parametric optimization was performed using design expert V.10 software. • Flexural strength depends on the percentage of reinforcing fibers.	[151]
HDPE	Kenaf	P: 900 W T: 1200 s	• Alkali-treated natural fibers improve the interfacial bonding. • Wear reduced due to tribofilm generated. • The tribological performance of NFRCs is better at the lower load and sliding speed. • For higher load and sliding speed, ceramics particle can be added to NFRCs.	[152]
HDPE	Hybrid Jute/Kenaf	P: 900 W T: 1500 s	• Effect of hybridization is helpful in increasing the properties of the composite as compared to single fiber reinforced composite.	[153]
Polycaprolactone (PCL)	nHA	P: 180, 540 and 900 W T: 850, 650 and 450 s	• Composite foam was successfully fabricated using microwave energy. • PCL/nHA composite foams may be used as bone scaffolds after bio-compatibility examinations.	[154]
HDPE	Kenaf	P: 900 W T: 420 s	• Hole drilling in developed composite is possible using CO_2 laser. • Power and cutting speed affects heat-affected zone (HAZ), kerf taper angle and surface roughness Thickness of composite significantly affects the width of HAZ and taper angle.	[155]
UHMWPE	Kevlar	P: 720 W T: 1310–1104 s	• With increase in reinforcement percentage, tensile, flexural, impact, hardness properties were found to increase.	[156]
PE	Coir	P: 360, 540, 720 and 900 W T: 1080, 840, 600 and 480 s	• It is possible to fabricate short fiber reinforced polymer composites. • Mechanical properties were found to be maximum at low power because of increase in time required for relaxing the oscillating molecules.	[108]
Recycled HDPE (rHDPE)	Pinecone	P: 540 W T: 800–900 s	• Microwave-assisted compression moulding (MACM) is an emerging and novel technique to fabricate composites. • Addition of optimum filler percentage is necessary to get desirable properties.	[157]

(*continued on next page*)

Table 2 (*continued*)

Matrix	Fiber	Microwave power (W), and time (s)	Results/ Major findings	Ref.
HDPE	Kenaf	P: 900 W T: 1200 s	• rHDPE composites showed 7%–10% reduction in mechanical properties as compared to virgin HDPE. • MACM took 5.71 times lesser time to fabricate than conventionally compression moulding (CCM). • The CCM approach had a 4.72 times larger mean temperature difference than the MACM technique. • Addition of fibers was found to be advantageous in case of MACM and disadvantageous in CCM in terms of mechanical properties and fabrication time. • The temperature results from thermocouples were close to results from thermal camera.	[158]

**P: Microwave power and T: Microwave exposure time.*

Table 3
Microwave joining of natural fiber reinforced PMCs.

Matrix	Fiber	Susceptor used	Fixture used for applying pressure	Microwave power (W)	Bond formation time (s)	Ref.
PLA	Sisal	Charcoal	Teflon Tape	360–900	250–100	[44]
PLA and PP	Nettle, Grewia optiva	Charcoal	Teflon Tape	900	200–250	[46]
PP	Jute	SiC	Aluminium fixture	900	60–90	[159]

compression moulding [158]. It is important to note that microwave processing technique is energy and time efficient. In addition to the technoeconomic feature of this technique, it offers ecofriendly processing of materials.

7. Conclusions and future scope

Microwaves are being used for the processing of materials since a long time, but due to limited understanding of the phenomena, commercial utilization of microwaves for material processing is confined to a few selected materials only. Over the last 60 years, microwaves are being used for material processing which is gaining significant interests among the researchers worldwide because of eco-friendliness, time and energy efficiency. The current article has highlighted the fundamentals of curing and joining of polymeric composites using microwave energy. The phenomena leading to heating in polymeric composites were discussed. The summary of the reviewed information confirmed that microwave curing of polymer-based composites justifies its preference over the (traditional) thermal curing processes. Microwave curing of thermoset and thermoplastic-based composites shows improved mechanical, thermal, physical, and electrical properties over the conventional curing processes. It can be concluded that although reasonable work has been reported on the microwave processing of thermoset-based polymer composites, microwave processing of thermoplastic-based polymer composites is yet to be investigated exhaustively. It can be concluded with a fair degree of confidence that in near future, it is going to be one of the established and environment friendly processing routes for polymer-based composites.

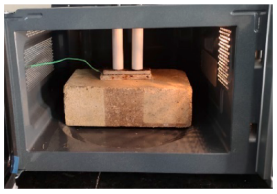
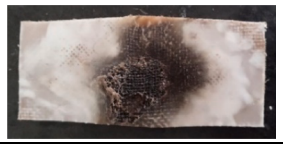
There are reasonable scopes for process improvement in the contexts of fixture design, mould design, process parameter optimization, use of different susceptor materials, etc. The trajectory of research endeavors in the field of microwave processing of polymeric composites will broadly cover the following domains:

- Design of tools and fixtures for new applications is a significant issue because microwave interaction is different for different materials. Design and development of new tools and fixtures affects repeatability of the process.

Table 4
Challenges in processing of polymers and polymer-based composites.

Challenges	Remarks
Non-uniform power distribution	• This is because of non-uniform EM fields in the cavity. • Uneven temperature over the target material surface because of hot spots formation. • Hot spot formation can be reduced by; rotating the turntable, rotating the EM reflectors, use of multiple magnetrons, use of multiple frequency microwave.
Thermal conductivity and physical properties of the matrix material	• Processing of polymeric composites is a challenging task as it is a two-phase system and anisotropic in nature, where each constituent exhibit different thermal behaviour at same processing conditions. • Due to the material's low thermal conductivity, heat accumulates at the centre of the specimen, forming the hot spot. • Optimization of the processing parameters is required for wide variety of polymers found in market as they have different density, melt flow index, melting point, and so forth.
Modeling and simulation of composites	• Microwave curing is a complex phenomenon as the constituents present in the composites show different behaviour with increase in temperature.
Temperature measurement	• Difficult to control temperature of different phases in composite • Non-contact pyrometer, optical fiber probe and shielded thermocouples are different techniques used to measure the temperature profile inside the microwave's cavity.
Poor repeatability of the process	• Limit the use of process for industrial application.
Selection of susceptor	• Improper selection of susceptor leads to non-uniform heating of the composites. • It may also lead to burning and degradation in properties of the composite materials.
Microwave arcing	• Both the composite and the equipment may suffer significant localized damage. • Mainly seen with carbon fiber used as reinforcement. • Leads to severe health and safety concerns.
Economics	• Design and development of customized microwave cavity is costly and time consuming. • Compromise with part size.

Table 5
Challenges faced in fabrication of natural fiber-based thermoplastic composites inside the domestic microwave applicator (Model: 20 L Grill microwave oven (20PG4S), Make: IFB).

Challenges	Typical image	Remark	Possible solutions
Removal of pressure plate (ceramic tile)		• Difficulty in removing the sample from the mould. • Material sticks to the pressure plate. • Breaking of pressure plate	• Use of polyester sheet. • Use of silicon spray. • Use of metal as a pressure plate instead of ceramic plate
Low pressure application		• Air entrapment • Poor interfacial bonding	• Use of teflon fixture to apply pressure
High pressure application		• Removal of excess material from the mould cavity	• Optimization of the pressure
Ceramic mould breakage (alumina)		• Excess temperature • Hot spot formation	• Optimization of the process parameters (power and exposure time)
Measurement of temperature profile (K-type thermocouple)		• Arcing inside cavity as thermocouple wire interacts with the microwave.	• Use of IR pyrometer to measure temperature • Shielding of the thermocouple wire
Non-uniform melting of polymer pellets		• Improper melting, • Poor bonding between polymer and fibers	• Selection of proper susceptor material • Optimization of the power and processing time
Thermal degradation of natural fibers		• Fiber burning. • Fiber degradation • Hot spot formation • Overheating	• Optimization of the input power and processing time • Fiber treatment

- Material specific simulation studies can be explored to develop understanding about the variation in the material properties with change in temperature and exposure time.
- Attempts can also be made towards increasing the process efficiency by coating high dielectric loss materials on either of the constituents present in composites for better microwave absorption.
- In-situ measurement and continuous monitoring of the temperature at different locations throughout the thickness of the sample on a rotating turntable is a challenge which needs to be addressed.
- The application spectrum of microwave processing of materials can be expanded in the direction of microwave machining (drilling) of PMCs and microwave joining.
- There is also a wide scope to hybridize the microwave heating process with the conventional process, for example, 3D printing in which microwave energy can be used to cure the polymer layer by layer to build a part [86,169]. Another technique, called LIRF (locally induced RF), for welding of 3D printed parts incorporating multi walled carbon nanotubes (MWCNTs) has been reported recently which carries ample scopes for exploring it in further [170].
- Research attempts can also be made in the direction of recycling of fibers in case of synthetic fiber reinforced PMCs in order to reduce burden of waste on environment. Recently a microwave-assisted chemical recycling method (sustainable) to recycle glass fibers from waste glass fiber reinforced polymer (GFRP) has been reported [171].
- Research attempts can be made to commercially fabricate intricate as well as near-net shaped polymer/polymer composite products directly inside the microwave applicator.

It is found that significant know-how has been developed regarding the successful application of microwave energy for processing of polymers and polymer-matrix composites. However, in order to realize the true potential of the process commercially, further efforts are required.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors would like to acknowledge the financial support provided by the Design Innovation Centre (DIC), Ministry of Education, Government of India through its Project No. DIC-1267-MID.

References

[1] Singh AP, Sharma M, Singh I. A review of modeling and control during drilling of fiber reinforced plastic composites. Compos Part B Eng 2013;47:118–25. https://doi.org/10.1016/j.compositesb.2012.10.038.

[2] Asim M, Jawaid M, Saba N, Ramengmawii NM, Sultan MTH. Processing of hybrid polymer composites-A review. Elsevier Ltd 2017. https://doi.org/10.1016/B978-0-08-100789-1.00001-0.

[3] Roux M, Eguémann N, Dransfeld C, Thiébaud F, Perreux D. Thermoplastic carbon fibre-reinforced polymer recycling with electrodynamical fragmentation: From cradle to cradle. J Thermoplast Compos Mater 2017;30(3):381–403. https://doi.org/10.1177/0892705715599431.

[4] Mohammed L, Ansari MNM, Pua G, Jawaid M, Islam MS. A review on natural fiber reinforced polymer composite and its applications. Int J Polym Sci 2015;2015:1–15. https://doi.org/10.1155/2015/243947.

[5] Ramamoorthy SK, Skrifvars M, Persson A. A review of natural fibers used in biocomposites: Plant, animal and regenerated cellulose fibers. Polym Rev 2015;55(1):107–62. https://doi.org/10.1080/15583724.2014.971124.

[6] Carruthers J. Technology overview biocomposites. Technol Strateg Board 2012:1–40.

[7] Oksman K, Skrifvars M, Selin J-F. Natural fibres as reinforcement in polylactic acid (PLA) composites. Compos Sci Technol 2003;63(9):1317–24. https://doi.org/10.1016/S0266-3538(03)00103-9.

[8] Chaitanya S, Singh I, Song JI. Recyclability analysis of PLA/Sisal fiber biocomposites. Compos Part B Eng 2019;173:106895. https://doi.org/10.1016/j.compositesb:2019.05.106.

[9] Lila MK, Komal UK, Singh I. Thermal post-processing of bagasse fiber reinforced polypropylene composites. Compos Commun 2021;23:100546. https://doi.org/10.1016/j.coco.2020.100546.

[10] Debnath K, Singh I. Primary and secondary manufacturing of polymer matrix composites. Taylor & Francis Group: CRC Press; 2018.

[11] Li N, Li Y, Jelonnek J, Link G, Gao J. A new process control method for microwave curing of carbon fibre reinforced composites in aerospace applications. Compos Part B Eng 2017;122:61–70. https://doi.org/10.1016/j.compositesb.2017.04.009.

[12] Matli P, Shakoor R, Amer Mohamed A, Gupta M. Microwave rapid sintering of Al-metal matrix composites: A review on the effect of reinforcements, microstructure and mechanical properties. Metals 2016;6(7):143. https://doi.org/10.3390/met6070143.

[13] Cheng J, Agrawal D, Zhang Y, Roy R. Microwave sintering of transparent alumina. Mater Lett 2002;56(4):587–92. https://doi.org/10.1016/S0167-577X(02)00557-8.

[14] Srinath MS, Sharma AK, Kumar P. A new approach to joining of bulk copper using microwave energy. Mater Des 2011;32(5):2685–94. https://doi.org/10.1016/j.matdes.2011.01.023.

[15] Srinath MS, Sharma AK, Kumar P. Investigation on microstructural and mechanical properties of microwave processed dissimilar joints. J Manuf Process 2011;13(2):141–6. https://doi.org/10.1016/j.jmapro.2011.03.001.

[16] Zafar S, Sharma AK. Development and characterisations of WC-12Co microwave clad. Mater Charact 2014;96:241–8. https://doi.org/10.1016/j.matchar.2014.08.015.

[17] Gupta D, Sharma AK. Development and microstructural characterization of microwave cladding on austenitic stainless steel. Surf Coatings Technol 2011;205(21-22):5147–55. https://doi.org/10.1016/j.surfcoat.2011.05.018.

[18] Mishra RR, Sharma AK. On mechanism of in-situ microwave casting of aluminium alloy 7039 and cast microstructure. Mater Des 2016;112:97–106. https://doi.org/10.1016/j.matdes.2016.09.041.

[19] Mishra RR, Sharma AK. A review of research trends in microwave processing of metal-based materials and opportunities in microwave metal casting. Crit Rev Solid State Mater Sci 2016;41(3):217–55. https://doi.org/10.1080/10408436.2016.1142421.

[20] Singh A, Sharma AK. On microwave drilling of metal-based materials at 2.45 GHz. Appl Phys A 2020;126:822. https://doi.org/10.1007/s00339-020-03994-5.

[21] Lautre NK, Sharma AK, Kumar P, Das S. Microwave drilling with litz wire using a domestic applicator. Bonfring Int J Ind Eng Manag Sci 2014;4(3):125–31. https://doi.org/10.9756/BIJIEMS.6053.

[22] George TJ, Sharma AK, Kumar P. Experimental study and simulation on microwave drilling of metals and glasses. J Exp Appl Mech 2014;5:10–9.

[23] Lee WI, Springer GS. Microwave curing of composites. J Compos Mater 1984;18:387–409. https://doi.org/10.1177/002199838401800405.

[24] Mgbemena CO, Li D, Lin M-F, Liddel PD, Katnam KB, Thakur VK, et al. Accelerated microwave curing of fibre-reinforced thermoset polymer composites for structural applications: A review of scientific challenges. Compos Part A Appl Sci Manuf 2018;115:88–103.

[25] Chandrasekaran S, Ramanathan S, Basak T. Microwave material processing—A review. Am Inst Chem Eng AIChE J 2012;58:330–63. https://doi.org/10.1002/aic.14002.

[26] Mishra RR, Sharma AK. Microwave–material interaction phenomena: Heating mechanisms, challenges and opportunities in material processing. Compos Part A Appl Sci Manuf 2016;81:78–97. https://doi.org/10.1016/j.compositesa.2015.10.035.

[27] Sutton WH. Microwave processing of materials. MRS Bull 1993;18:22–9. https://doi.org/10.1017/S0883769400038495.

[28] Sharma AK. Advanced manufacturing processes. NPTEL E-Learning Course 2013. https://doi.org/https://nptel.ac.in/courses/112/107/112107078/.

[29] Thostenson ET, Chou T-W. Microwave processing: Fundamentals and applications. Compos Part A Appl Sci Manuf 1999;30(9):1055–71. https://doi.org/10.1016/S1359-835X(99)00020-2.

[30] Clark DE, Folz DC, West JK. Processing materials with microwave energy. Mater Sci Eng A 2000;287(2):153–8.

[31] Agrawal D. Microwave sintering of ceramics, composites and metallic materials, and melting of glasses. Trans Indian Ceram Soc 2006;65(3):129–44. https://doi.org/10.1080/0371750X.2006.11012292.

[32] Jones L. Front Matter. My Curious Jocular Heroes. University of Illinois Press; 2017i–iv.

[33] Rao S, Rao R. Cure studies on bifunctional epoxy matrices using a domestic microwave oven. Polym Test 2008;27(5):645–52. https://doi.org/10.1016/j.polymertesting.2008.04.005.

[34] Soesatyo B, Blicblau A, Siores E. Effect of rapid curing doped epoxy adhesive between two polycarbonate substrates on the bond tensile strength 1999;90:451–6.

[35] Kwak M, Robinson P, Bismarck A, Wise R. Microwave curing of carbon–epoxy composites: Penetration depth and material characterisation. Compos Part A Appl Sci Manuf 2015;75:18–27. https://doi.org/10.1016/j.compositesa.2015.04.007.

[36] Sturm GSJ, Verweij MD, Stankiewicz AI, Stefanidis GD. Microwaves and microreactors: Design challenges and remedies. Chem Eng J 2014;243:147–58. https://doi.org/10.1016/j.cej.2013.12.088.

[37] Link G, Ramopoulos V. Simple analytical approach for industrial microwave applicator design. Chem Eng Process - Process Intensif 2018;125:334–42. https://doi.org/10.1016/j.cep.2017.12.015.

[38] Zhou J, Li Y, Li D, Wen Y. Online learning based intelligent temperature control during polymer composites microwave curing process. Chem Eng J 2019;370:455–65. https://doi.org/10.1016/j.cej.2019.03.204.

[39] Zhou J, Li Y, Li N, Liu S, Cheng L, Sui S, et al. A multi-pattern compensation method to ensure even temperature in composite materials during microwave curing process. Compos Part A Appl Sci Manuf 2018;107:10–20.

[40] Feher L, Thumm M. Microwave innovation for industrial composite fabrication—The HEPHAISTOS technology. IEEE Trans Plasma Sci 2004;32(1):73–9. https://doi.org/10.1109/TPS.2004.823983.

[41] Sturm GSJ, Stefanidis GD, Verweij MD, Van Gerven TDT, Stankiewicz AI. Design principles of microwave applicators for small-scale process equipment. Chem Eng Process Process Intensif 2010;49(9):912–22. https://doi.org/10.1016/j.cep.2010.07.017.

[42] Chen X, Zhan L, Huang M, Chang T, Li S, Peng W. A novel method for curing carbon fiber reinforced plastics by high-pressure microwave. Fibers Polym 2016;17(12):2143–52. https://doi.org/10.1007/s12221-016-6784-1.

[43] Sun Y. Adaptive and intelligent temperature control of microwave heating systems with multiple sources. KIT Scientific Publishing 2016.

[44] Singh I, Bajpai PK, Malik D, Sharma AK, Kumar P. Feasibility study on microwave joining of 'green' composites.' Akademeia 2011;1:ea0101.

[45] Singh I, Bajpai PK, Malik D, Madaan J, Bhatnagar N. Microwave joining of natural fiber reinforced green composites. Adv Mater Res 2012;410:102–5. https://doi.org/10.4028/www.scientific.net/AMR.410.102.

[46] Bajpai PK, Singh I, Madaan J. Joining of natural fiber reinforced composites using microwave energy: Experimental and finite element study. Mater Des 2012;35:596–602. https://doi.org/10.1016/j.matdes.2011.10.007.

[47] Mondal A, Shukla A, Upadhyaya A, Agrawal D. Effect of porosity and particle size on microwave heating of copper. Sci Sinter 2010;42(2):169–82. https://doi.org/10.2298/SOS1002169M.

[48] Leonelli C, Veronesi P, Denti L, Gatto A, Iuliano L. Microwave assisted sintering of green metal parts. J Mater Process Technol 2008;205(1-3):489–96. https://doi.org/10.1016/j.jmatprotec.2007.11.263.

[49] Roger JM. Engineers handbook of industrial microwave heating. The Institution of. Eng Technol 1998.

[50] Komal UK, Lila MK, Singh I. Microwave processing of natural fibre- reinforced polymer composites. In: Pramendra Kumar Bajpai, editor. Process. Nat. fibre Reinf. bio-composites, Woodhead publishing india in textiles; 2020, p. 137–54.

[51] Zafar S, Sharma AK. Microwave processing of polymer matrix composites. In: Kishore Debnath and Inderdeep Singh, editor. Prim. Second. Manuf. Polym. matrix Compos., CRC Press Taylor & Francis Group; 2018, p. 75–90.

[52] Li Y, Cheng L, Zhou J. Curing multidirectional carbon fiber reinforced polymer composites with indirect microwave heating. Int J Adv Manuf Technol 2018;97(1-4):1137–47. https://doi.org/10.1007/s00170-018-1974-1.

[53] Rao S, Chiranjeevi MC, Rajendra Prakash M. Vacuum-assisted microwave processing of glass-epoxy composite laminates using novel microwave absorbing molds. Polym Compos 2018;39(4):1152–60. https://doi.org/10.1002/pc.24044.

[54] Spotz MS, Skamser DJ, Johnson DL. Thermal stability of ceramic materials in microwave heating. J Am Ceram Soc 1995;78(4):1041–8.

[55] Thostenson ET, Chou T-W. Microwave and conventional curing of thick-section thermoset composite laminates: Experiment and simulation. Polym Compos 2001;22(2):197–212. https://doi.org/10.1002/pc.10531.

[56] Kwak M, Robinson P, Bismarck A, Wise R. Curing of composite materials using the recently developed HEPHAISTOS Microwave. ICCM Int Conf Compos Mater 2011:1–6.

[57] Galos J. Microwave processing of carbon fibre polymer composites: A review. Polym Polym Compos 2021;29(3):151–62. https://doi.org/10.1177/0967391120903894.

[58] Aravindan S, Krishnamurthy R. Joining of ceramic composites by microwave heating. Mater Lett 1999;38(4):245–9. https://doi.org/10.1016/S0167-577X(98)00166-9.

[59] Janney MA, Calhoun CL, Kimrey HD. Microwave sintering of solid oxide fuel cell materials: I, Zirconia-8 mol% Yttria. J Am Ceram Soc 1992;75(2):341–6. https://doi.org/10.1111/j.1151-2916.1992.tb08184.x.

[60] Verma N, Kumar R, Zafar S, Pathak H. Vacuum-assisted microwave curing of epoxy/carbon fiber composite: An attempt for defect reduction in processing. Manuf Lett 2020;24:127–31. https://doi.org/10.1016/j.mfglet.2020.04.010.

[61] Singh MK, Zafar S, Talha M. Development of porous bio-composites through microwave curing for bone tissue engineering. Mater Today Proc 2019;18:731–9. https://doi.org/10.1016/j.matpr.2019.06.478.

[62] Srinath MS, Sharma AK, Kumar P. A novel route for joining of austenitic stainless steel (SS-316) using microwave energy. Proc Inst Mech Eng Part B J Eng Manuf 2011;225(7):1083–91. https://doi.org/10.1177/2041297510393451.

[63] Singh S, Gupta D, Jain V, Sharma AK. Microwave processing of materials and applications in manufacturing industries: A review. Mater Manuf Process 2015;30 (1):1–29. https://doi.org/10.1080/10426914.2014.952028.

[64] Bansal A, Sharma AK, Das S. Metallurgical and mechanical characterization of mild steel-mild steel joint formed by microwave hybrid heating process. Sadhana - Acad Proc Eng Sci 2013;38(4):679–86. https://doi.org/10.1007/s12046-013-0142-4.

[65] Sgriccia N, Hawley M. Thermal, morphological, and electrical characterization of microwave processed natural fiber composites. Compos Sci Technol 2007;67(9): 1986–91. https://doi.org/10.1016/j.compscitech.2006.07.031.

[66] Naik TP, Rana RS, Singh I, Sharma AK. Microwave processing of polymer matrix composites: Review of the understanding and future opportunities. Recent Adv Mech Eng Lect Notes Mech Eng, Springer, Singapore 2021:517–29. https://doi.org/10.1007/978-981-15-7711-6_52.

[67] Yang Z, Peng H, Wang W, Liu T. Crystallization behavior of poly(ε-caprolactone)/layered double hydroxide nanocomposites. J Appl Polym Sci 2010;116:2658–67. https://doi.org/10.1002/app.

[68] Leonelli C, Mason TJ. Microwave and ultrasonic processing: Now a realistic option for industry. Chem Eng Process Process Intensif 2010;49(9):885–900. https://doi.org/10.1016/j.cep.2010.05.006.

[69] Moulart A, Marrett C, Colton J. Polymeric composites for use in electronic and microwave devices. Polym Eng Sci 2004;44(3):588–97. https://doi.org/10.1002/pen.20053.

[70] Zhou J, Li Y, Zhang M, Xu E, Yang T. Effect of lay-up configuration on the microwave absorption properties of carbon fiber reinforced polymer composite materials. Mater Today Commun 2021;26:101960. https://doi.org/10.1016/j.mtcomm.2020.101960.

[71] Singh MK, Zafar S. Development and mechanical characterization of microwave-cured thermoplastic based natural fibre reinforced composites. J Thermoplast Compos Mater 2019;32(10):1427–42. https://doi.org/10.1177/0892705718799832.

[72] Cabral H, Cisneros M, Kenny JM, Vazquez A, Bernal CR. Structure–properties relationship of short jute fiber-reinforced polypropylene composites. J Compos Mater 2005;39(1):51–65. https://doi.org/10.1177/0021998305046434.

[73] Mijović J, Kenny JoséM, Maffezzoli A, Trivisano A, Bellucci F, Nicolais L. The principles of dielectric measurements for in situ monitoring of composite processing. Compos Sci Technol 1993;49(3):277–90. https://doi.org/10.1016/0266-3538(93)90109-T.

[74] Martinelli M, Rolla PA, Tombari E. A method for dynamic dielectric measurements at microwave frequencies: Applications to polymerization process studies. IEEE Trans Instrum Meas 1985;IM-34(3):417–21. https://doi.org/10.1109/TIM.1985.4315361.

[75] Kranbuehl D, Delos S, Yi E. Dynamic dielectric analysis: Nondestructive material evaluation and cure cycle monitoring. Annu Tech Conf - Soc. Plast Eng 1985: 311–7.

[76] Chen M, Siochi EJ, Ward TC, McGrath JE. Basic ideas of microwave processing of polymers. Polym Eng Sci 1993;33(17):1092–109. https://doi.org/10.1002/pen.760331703.

[77] Chawla KK. Composite materials science & engineering. Springer Science & Business. Media 2012. https://doi.org/10.1007/978-0-387-74365-3.

[78] Jones MR. Mechanics of composite materials. Taylor and Francis: CRC Press; 1998.

[79] Olofinjana A, Yarlagadda PKDV, Oloyede A. Microwave processing of adhesive joints using a temperature controlled feedback system. Int J Mach Tools Manuf 2001;41(2):209–25. https://doi.org/10.1016/S0890-6955(00)00060-2.

[80] Zainol I, Day R, Heatley F. Comparison between the thermal and microwave curing of bismaleimide resin. J Appl Polym Sci 2003;90(10):2764–74. https://doi.org/10.1002/app.12933.

[81] Mijović J, Corso WV, Nicolais L, d'Ambrosio G. In situ real-time study of crosslinking kinetics in thermal and microwave fields. Polym Adv Technol 1998; 9:231–43. https://doi.org/10.1002/(SICI)1099-1581(199804)9:4<231::AID-PAT747>3.0.CO;2-W.

[82] Mijovic J, Wijaya J. Comparative calorimetric study of epoxy cure by microwave vs thermal energy. Macromolecules 1990;23(15):3671–4. https://doi.org/10.1021/ma00217a021.

[83] Zhou J, Li Y, Li N, Hao X, Liu C. Interfacial shear strength of microwave processed carbon fiber/epoxy composites characterized by an improved fiber-bundle pull-out test. Compos Sci Technol 2016;133:173–83. https://doi.org/10.1016/j.compscitech.2016.07.033.

[84] Drzal L, Hook K, Agrawal R. Enhanced chemical bonding at the fiber-matrix interphase in microwave processed composites. Microw Process Mater II, Mater Res Soc Proceedings, Pittsburgh Mater Res Soc 1991;189:449–54.

[85] Bai SL, Djafari V. Interfacial properties of microwave cured composites. Composites 1995;26(9):645–51. https://doi.org/10.1016/0010-4361(95)98913-6.

[86] Odom MGB, Sweeney CB, Parviz D, Sill LP, Saed MA, Green MJ. Rapid curing and additive manufacturing of thermoset systems using scanning microwave heating of carbon nanotube/epoxy composites. Carbon N Y 2017;120:447–53. https://doi.org/10.1016/j.carbon.2017.05.063.

[87] Higginbotham AL, Moloney PG, Waid MC, Duque JG, Kittrell C, Schmidt HK, et al. Carbon nanotube composite curing through absorption of microwave radiation. Compos Sci Technol 2008;68(15-16):3087–92. https://doi.org/10.1016/j.compscitech.2008.07.004.

[88] Hay JN, O'Gara P. Recent developments in thermoset curing methods. Proc Inst Mech Eng Part G: J Aerosp Eng 2006;220(3):187–95. https://doi.org/10.1243/09544100JAERO35.

[89] Kergomard YD, Abenius E, Tertrais H, Barasinski A, Chinesta F, Dufort L. Simulation chain for composite part curing with an industrial microwave oven. 21st Int. ESAFORM Conf Mater Form 2018:020013. https://doi.org/10.1063/1.5034814.

[90] Pal R, Jha AK, Akhtar MJ, Kar KK, Kumar R, Nayak D. Enhanced microwave processing of epoxy nanocomposites using carbon black powders. Adv Powder Technol 2017;28(4):1281–90. https://doi.org/10.1016/j.apt.2017.02.016.

[91] Lye SW, Boey FYC. PC-based monitoring and control system for microwave curing of polymer composites. Mater Manuf Process 1994;9(5):851–68. https://doi.org/10.1080/10426919408934957.

[92] Xu X, Wang X, Liu W, Zhang X, Li Z, Du S. Microwave curing of carbon fiber/bismaleimide composite laminates: Material characterization and hot pressing pretreatment. Mater Des 2016;97:316–23. https://doi.org/10.1016/j.matdes.2016.02.093.

[93] Day RJ, Samoladas E. Micromechanics of model carbon epoxy composites cured using microwave heating. Sci Eng Compos Mater 1998;7:23–50. https://doi.org/10.1515/SECM.1998.7.1-2.23.

[94] Xu X, Wang X, Wei R, Du S. Effect of microwave curing process on the flexural strength and interlaminar shear strength of carbon fiber/bismaleimide composites. Compos Sci Technol 2016;123:10–6. https://doi.org/10.1016/j.compscitech.2015.11.030.

[95] Zhou J, Li Y, Li N, Hao X. Enhanced interlaminar fracture toughness of carbon fiber/bismaleimide composites via microwave curing. J Compos Mater 2017;51 (18):2585–95. https://doi.org/10.1177/0021998316673892.

[96] Xu X, Wang X, Cai Q, Wang Xu, Wei R, Du S. Improvement of the compressive strength of carbon fiber/epoxy composites via microwave curing. J Mater Sci Technol 2016;32(3):226–32. https://doi.org/10.1016/j.jmst.2015.10.006.

[97] Shimamoto D, Tominaga Y, Hotta Y. Effect of microwave irradiation on carbon fiber/epoxy resin composite fabricated by vacuum assisted resin transfer molding. Adv Compos Mater 2016;25(sup1):71–9. https://doi.org/10.1080/09243046.2016.1178998.

[98] Fang X, Scola DA. Investigation of microwave energy to cure carbon fiber reinforced phenylethynyl-terminated polyimide composites, PETI-5/IM7. J Polym Sci Part A Polym Chem 1999;37:4616–28. https://doi.org/10.1002/(SICI)1099-0518(19991215)37:24<4616::AID-POLA20>3.0.CO;2-W.

[99] Papargyris DA, Day RJ, Nesbitt A, Bakavos D. Comparison of the mechanical and physical properties of a carbon fibre epoxy composite manufactured by resin transfer moulding using conventional and microwave heating. Compos Sci Technol 2008;68(7-8):1854–61. https://doi.org/10.1016/j.compscitech.2008.01.010.

[100] Li N, Li Y, Zhou J, He Y, Hao X. Drilling delamination and thermal damage of carbon nanotube/carbon fiber reinforced epoxy composites processed by microwave curing. Int J Mach Tools Manuf 2015;97:11–7. https://doi.org/10.1016/j.ijmachtools.2015.06.005.

[101] Zhou J, Li Y, Zhu Z, Xu E, Li S, Sui S. Microwave heating and curing of metal-like CFRP laminates through ultrathin and flexible resonance structures. Compos Sci Technol 2022;218:109200. https://doi.org/10.1016/j.compscitech.2021.109200.

[102] Li Y, Li N, Zhou J, Cheng Q. Microwave curing of multidirectional carbon fiber reinforced polymer composites. Compos Struct 2019;212:83–93. https://doi.org/10.1016/j.compstruct.2019.01.027.

[103] Zhou J, Li Y, Liu S, Zhang Y, Wang P, Sui S. Zone-regulated microwave heating of CFRP laminates via ultrathin and flexible resonance structures with different working frequencies. Compos Commun 2022;29:101016. https://doi.org/10.1016/j.coco.2021.101016.

[104] Li S, Li Y, Zhou J, Wen Y. Improvement of heating uniformity by limiting the absorption of hot areas in microwave processing of CFRP composites. Materials (Basel) 2021;14:7769. https://doi.org/10.3390/ma14247769.

[105] Joshi SC, Bhudolia SK. Microwave–thermal technique for energy and time efficient curing of carbon fiber reinforced polymer prepreg composites. J Compos Mater 2014;48(24):3035–48. https://doi.org/10.1177/0021998313504606.

[106] Chopra K, Sharma P, Jatav AS. Experimental analysis over natural fibre (sisal) reinforced composite, with microwave and compression moulding. Imp J Interdiscip Res 2016;2:1493–9.

[107] Mitra A, Sharma P, Jatav AS. Comparison on mechanical properties of microwave cured polypropylene composites reinforced with hemp with compression moulding technique. Imp J Interdiscip Res 2016;2:1139–46.

[108] Singh MK, Zafar S. Influence of microwave power on mechanical properties of microwave-cured polyethylene / coir composites. J Nat Fibers 2020;17(6): 845–60. https://doi.org/10.1080/15440478.2018.1534192.

[109] Arora G, Pathak H, Zafar S. Fabrication and characterization of microwave cured high-density polyethylene/carbon nanotube and polypropylene/carbon nanotube composites. J Compos Mater 2019;53(15):2091–104. https://doi.org/10.1177/0021998318822705.

[110] Pundhir N, Pathak H, Zafar S. Crashworthiness of automobile made of HDPE/kenaf and HDPE/MWCNT polymer composites. J Phys Conf Ser 2019;1240(1): 012098. https://doi.org/10.1088/1742-6596/1240/1/012098.

[111] Pundhir N, Zafar S, Pathak H. Performance evaluation of HDPE/MWCNT and HDPE/kenaf composites. J Thermoplast Compos Mater 2021;34(10):1315–33. https://doi.org/10.1177/0892705719868278.

[112] Madhu P, Sanjay MR, Jawaid M, Siengchin S, Khan A, Pruncu CI. A new study on effect of various chemical treatments on agave americana fiber for composite reinforcement: Physico-chemical, thermal, mechanical and morphological properties. Polym Test 2020;85:106437. https://doi.org/10.1016/j.polymertesting.2020.106437.

[113] Vijay R, Lenin Singaravelu D, Vinod A, Sanjay MR, Siengchin S, Jawaid M, et al. Characterization of raw and alkali treated new natural cellulosic fibers from tridax procumbens. Int J Biol Macromol 2019;125:99–108. https://doi.org/10.1016/j.ijbiomac.2018.12.056.

[114] Romero-Zúñiga GY, González-Morones P, Sánchez-Valdés S, Yáñez-Macías R, Sifuentes-Nieves I, García-Hernández Z, et al. Microwave radiation as alternative to modify natural fibers: Recent trends and opportunities – A review. J Nat Fibers 2021:1–17. https://doi.org/10.1080/15440478.2021.1952140.

[115] Bright BM, Joseph SB, Abu HS, Mustapha JM, Siengchin S, Mavinkere RS, et al. Characterization of chemically treated new natural cellulosic fibers from peduncle of cocos nucifera L. Var typica Polym Compos 2021;42:6403–16. https://doi.org/10.1002/pc.26307.

[116] Hassan ML, Hassan EA, Oksman KN. Effect of pretreatment of bagasse fibers on the properties of chitosan/microfibrillated cellulose nanocomposites. J Mater Sci 2011;46(6):1732–40. https://doi.org/10.1007/s10853-010-4992-4.

[117] Bengtsson M, Baillif ML, Oksman K. Extrusion and mechanical properties of highly filled cellulose fibre–polypropylene composites. Compos Part A Appl Sci Manuf 2007;38(8):1922–31.

[118] Fenske K, Misra D. Dielectric materials at microwave frequencies. Appl Microw Wirel 2000;12:92–100.

[119] Kumar D, Sharma RC. Advances in conductive polymers. Eur Polym J 1998;34(8):1053–60. https://doi.org/10.1016/S0014-3057(97)00204-8.

[120] Yarlagadda PKDV, Chai TC. An investigation into welding of engineering thermoplastics using focused microwave energy. J Mater Process Technol 1998;74(1-3):199–212. https://doi.org/10.1016/S0924-0136(97)00269-0.

[121] Ku HS, Siores E, Ball JA, Chan P. Processing of polymer matrix composites using variable frequency microwave (VFM). In13th International Conference on Composite Materials (ICCM-13): Proceedings 2001 (pp. 212-212). Scientific and Technical Documents Publishing House.

[122] Boey FYC, Lee WL. Microwave radiation curing of a thermosetting composite. J Mater Sci Lett 1990;9(10):1172–3. https://doi.org/10.1007/BF00721880.

[123] Bai SL, Djafari V, Andréani M, François D. A comparative study of the mechanical behaviour of an epoxy resin cured by microwaves with one cured thermally. Eur Polym J 1995;31(9):875–84. https://doi.org/10.1016/0014-3057(95)00042-9.

[124] Yue CY, Looi HC. Influence of thermal and microwave processing on the mechanical and interfacial properties of a glass/epoxy composite. Composites 1995;26(11):767–73.

[125] Boey FYC, Yap BH, Chia L. Microwave curing of epoxy-amine system - Effect of curing agent on the rate enhancement. Polym Test 1999;18(2):93–109. https://doi.org/10.1016/S0142-9418(98)00014-2.

[126] Boey FYC, Yap BH. Microwave curing of an epoxy-amine system: Effect of curing agent on the glass-transition temperature. Polym Test 2001;20(8):837–45. https://doi.org/10.1016/S0142-9418(00)00070-2.

[127] Nightingale C, Day RJ. Flexural and interlaminar shear strength properties of carbon fibre/epoxy composites cured thermally and with microwave radiation. Compos Part A Appl Sci Manuf 2002;33(7):1021–30. https://doi.org/10.1016/S1359-835X(02)00031-3.

[128] Mooteri PS, Sridhara BK, Rao S, Prakash MR, Rao RMVGK. Studies on mechanical behavior of microwave and thermally cured glass fiber reinforced polymer composites. J Reinf Plast Compos 2006;25(5):503–12. https://doi.org/10.1177/0731684406058290.

[129] Cardona F, Ku H, Pattarachaiyakoop N, Rogers D, Trada M. Fracture toughness of phenol formaldehyde composites post-cured in microwaves. J Electromagn Waves Appl 2007;21(14):2137–46. https://doi.org/10.1163/156939307783152867.

[130] Ku H, Chan WL, Trada M, Baddeley D. An evaluation of fracture toughness of vinyl ester composites cured under microwave conditions. J Mater Eng Perform 2007;16(6):741–5. https://doi.org/10.1007/s11665-007-9104-5.

[131] Ku H, Trada M, Puttgunta VC. Mechanical properties of vinyl ester composites cured by microwave irradiation: Pilot study. Key Eng Mater 2007;334–335:537–40. https://doi.org/10.4028/www.scientific.net/kem.334-335.537.

[132] Adeodu AO, Anyaeche CO, Oluwole OO. Modeling of microwave curing of unsaturated polyester based composite materials as production process guide. J Adv Eng Technol 2014;13(1(1)):1–6. https://doi.org/10.15297/JAET.V1I1.05.

[133] De Vergara UL, Sarrionandia M, Gondra K, Aurrekoetxea J. Impact behaviour of basalt fibre reinforced furan composites cured under microwave and thermal conditions. Compos Part B Eng 2014;66:156–61. https://doi.org/10.1016/j.compositesb.2014.05.009.

[134] Sato K, Hotta Y. Carbon fiber/epoxy composite materials cured thermally and with microwave irradiation. Compos Interfaces 2015;22(1):67–74. https://doi.org/10.1080/15685543.2015.988581.

[135] Hang X, Li Y, Hao X, Li N, Wen Y. Effects of temperature profiles of microwave curing processes on mechanical properties of carbon fibre-reinforced composites. Proc Inst Mech Eng Part B J Eng Manuf 2017;231(8):1332–40. https://doi.org/10.1177/0954405415596142.

[136] Pal R, Akhtar MJ, Kar KK. Microwave-assisted curing of silicon carbide-reinforced epoxy composites: Role of dielectric properties. Jom 2018;70(7):1295–301. https://doi.org/10.1007/s11837-018-2855-7.

[137] Ehi PI, Tonye DI, Victor PA, Elvis OA. Effect of high-frequency microwave radiation on the mechanical properties of plantain (Musa paradisiaca) fibre/epoxy biocomposite. J Phys Sci 2018;29(3):23–35.

[138] Pattanaik A, Mukherjee M, Mishra SB. Influence of curing condition on thermo-mechanical properties of fly ash reinforced epoxy composite. Compos Part B Eng 2019;176:107301. https://doi.org/10.1016/j.compositesb.2019.107301.

[139] Chaitanya S, Cheedarala RK, Song JI. Microwave-synthesized Mg+2 doped jute fibers and their application as a reinforcement in biocomposites. Compos Part B Eng 2020;197:108154. https://doi.org/10.1016/j.compositesb.2020.108154.

[140] Akinyemi AB, Omoniyi ET, Onuzulike G. Effect of microwave assisted alkali pretreatment and other pretreatment methods on some properties of bamboo fibre reinforced cement composites. Constr Build Mater 2020;245:118405. https://doi.org/10.1016/j.conbuildmat.2020.118405.

[141] Zhang J, Duan Y, Wang B, Zhang X. Interfacial enhancement for carbon fibre reinforced electron beam cured polymer composite by microwave irradiation. Polymer 2020;192:122327. https://doi.org/10.1016/j.polymer.2020.122327.

[142] Jelmy EJ, Lakshmanan M, Kothurkar NK. Microwave absorbing behavior of glass fiber reinforced MWCNT-PANi/epoxy composite laminates. Mater Today Proc 2020;26:36–43. https://doi.org/10.1016/j.matpr.2019.04.203.

[143] Ali S, Bajpai PK, Singh I, Sharma AK. Curing of natural fibre-reinforced thermoplastic composites using microwave energy. J Reinf Plast Compos 2014;33(11):993–9. https://doi.org/10.1177/0731684414523326.

[144] George TJ, Jacob N, Francis FK, Joseph M. Investigation on mechanical properties of various microwave cured natural fibre reinforced polymer composites. interface. 2013;5:8.

[145] Mohammed AA, Bachtiar D, Rejab MRM, Siregar JP. Effect of microwave treatment on tensile properties of sugar palm fibre reinforced thermoplastic polyurethane composites. Def Technol 2018;14(4):287–90. https://doi.org/10.1016/j.dt.2018.05.008.

[146] Singh MK, Zafar S, Talha M. Development and characterisation of poly-L-lactide-based foams fabricated through microwave-assisted compression moulding. J Cell Plast 2019;55(5):523–41. https://doi.org/10.1177/0021955X19850728.

[147] Akinyemi BA, Bamidele A, Joel E. Response of coir fibre reinforced cement composites to water repellent chemical additive and microwave accelerated curing. Cellulose 2019;26(8):4987–99. https://doi.org/10.1007/s10570-019-02414-z.

[148] Singh S, Sharma J, Ujjwaldeep KG, Saha M. Development and optimization of process parameters of microwaved cured polymer based natural fibre coir reinforced composite. Int J Trend Sci Res Dev 2019;3:93–7.

[149] Verma N, Zafar S. Investigations on mechanical performance of multi-layered microwave processed HDPE/Sisal composites for automobile applications. Appl Mech Mater 2019;895:64–9. https://doi.org/10.4028/www.scientific.net/amm.895.64.

[150] Verma N, Zafar S, Pathak H. Microwave-assisted composite fabrication of nano-hydroxyapatite reinforced ultra-high molecular weight polyethylene composite. Mater Res Express 2019;6(11):115333. https://doi.org/10.1088/2053-1591/ab4b28.

[151] Singh MK, Verma N, Zafar S. Optimization of process parameters of microwave processed PLLA/coir composites for enhanced mechanical behavior. J Phys Conf Ser 2019;1240(1):012038. https://doi.org/10.1088/1742-6596/1240/1/012038.

[152] Singh MK, Zafar S. Abrasive wear mechanism of microwave-assisted compression molded Kenaf/HDPE composite. J Tribol 2020;142:1–11. https://doi.org/10.1115/1.4046858.

[153] Singh MK, Zafar S. Effect of layering sequence on mechanical properties of woven kenaf/jute fabric hybrid laminated microwave-processed composites. J Ind Text 2020;152808372091121. https://doi.org/10.1177/1528083720911219.

[154] Verma N, Zafar S, Talha M. Application of microwave energy for rapid fabrication of nano- hydroxyapatite reinforced polycaprolactone composite foam. Manuf Lett 2020;23:9–13. https://doi.org/10.1016/j.mfglet.2019.11.006.

[155] Tewari R, Singh MK, Zafar S, Powar S. Parametric optimization of laser drilling of microwave-processed Kenaf/HDPE composite. Polym Polym Compos 2021;29(3):176–87. https://doi.org/10.1177/0967391120905705.

[156] Guleria T, Verma N, Zafar S, Jain V. Fabrication of Kevlar®-reinforced ultra-high molecular weight polyethylene composite through microwave-assisted compression molding for body armor applications. J Reinf Plast Compos 2020;40(7–8):307–20. https://doi.org/10.1177/0731684420959449.

[157] Tewari R, Singh MK, Zafar S. Utilization of forest and plastic wastes for composite manufacturing using microwave-assisted compression molding for low load applications. J Polym Res 2021;28:409. https://doi.org/10.1007/s10965-021-02778-6.

[158] Verma N, Singh MK, Zafar S, Pathak H. Comparative study of in-situ temperature measurement during microwave-assisted compression-molding and conventionally compression-molding process. CIRP J Manuf Sci Technol 2021;35:336–45. https://doi.org/10.1016/j.cirpj.2021.07.005.

[159] Saukta R, Rana RS, Naik TP, Melese KG, Mishra RR. Design of a customized fixture for joining jute fiber-based composites using microwave energy. Adv Eng Des Lect Notes Mech Eng, Springer, Singapore 2021:31–9. https://doi.org/10.1007/978-981-33-4018-3_4.

[160] Mondal A, Upadhyaya A, Agrawal D. Microwave and conventional sintering of 90W–7Ni–3Cu alloys with premixed and prealloyed binder phase. Mater Sci Eng A 2010;527(26):6870–8. https://doi.org/10.1016/j.msea.2010.07.074.

[161] Mondal A, Upadhyaya A, Agrawal D. Effect of heating mode and sintering temperature on the consolidation of 90W–7Ni–3Fe alloys. J Alloys Compd 2011;509(2):301–10. https://doi.org/10.1016/j.jallcom.2010.09.008.

[162] Upadhyaya A, Tiwari SK, Mishra P. Microwave sintering of W-Ni–Fe alloy. Scr Mater 2007;56(1):5–8. https://doi.org/10.1016/j.scriptamat.2006.09.010.
[163] Panda SS, Singh V, Upadhyaya A, Agrawal D. Sintering response of austenitic (316L) and ferritic (434L) stainless steel consolidated in conventional and microwave furnaces. Scr Mater 2006;54(12):2179–83. https://doi.org/10.1016/j.scriptamat.2006.02.034.
[164] Fang Y, Agrawal DK, Roy DM, Roy R. Fabrication of transparent hydroxyapatite ceramics by ambient-pressure sintering. Mater Lett 1995;23(1-3):147–51. https://doi.org/10.1016/0167-577X(95)00016-X.
[165] Lingappa SM, Srinath MS, Amarendra HJ. Melting of bulk non-ferrous metallic materials by microwave hybrid heating (MHH) and conventional heating: A comparative study on energy consumption. J Brazilian Soc Mech Sci Eng 2018;40:1. https://doi.org/10.1007/s40430-017-0921-7.
[166] Gouthama TR, Harisha G, Manjunatha YR, Kumara SMM, Srinath MS, Lingappa MS. Melting of tin using muffle furnace and microwave energy and its characterization. IOP Conf Ser Mater Sci Eng 2016;149:012100. https://doi.org/10.1088/1757-899X/149/1/012100.
[167] Chandrasekaran S, Basak T, Ramanathan S. Experimental and theoretical investigation on microwave melting of metals. J Mater Process Technol 2011;211(3):482–7. https://doi.org/10.1016/j.jmatprotec.2010.11.001.
[168] Sloan J. Microwave: An alternative to the autoclave? CompositesWorld 2011. https://www.compositesworld.com/articles/microwave-an-alternative-to-the-autoclave (accessed December 11, 2021).
[169] Jerby E, Meir Y, Salzberg A, Aharoni E, Levy A, Torralba JP, et al. Incremental metal-powder solidification by localized microwave-heating and its potential for additive manufacturing. Addit Manuf 2015;6:53–66. https://doi.org/10.1016/j.addma.2015.03.002.
[170] Sweeney CB, Lackey BA, Pospisil MJ, Achee TC, Hicks VK, Moran AG, et al. Welding of 3D-printed carbon nanotube–polymer composites by locally induced microwave heating. Sci Adv 2017;3(6). https://doi.org/10.1126/sciadv.1700262.
[171] Rani M, Choudhary P, Krishnan V, Zafar S. Development of sustainable microwave-based approach to recover glass fibers for wind turbine blades composite waste. Resour Conserv Recycl 2022;179:106107. https://doi.org/10.1016/j.resconrec.2021.106107.