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Microwave processing: fundamentals and applications

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Abstract

In microwave processing, energy is supplied by an electromagnetic field directly to the material. This results in rapid heating throughout the material thickness with reduced thermal gradients. Volumetric heating can also reduce processing times and save energy. The microwave field and the dielectric response of a material govern its ability to heat with microwave energy. A knowledge of electromagnetic theory and dielectric response is essential to optimize the processing of materials through microwave heating. The fundamentals of electromagnetic theory, dielectric response, and applications of microwave heating to materials processing, especially fiber composites, are reviewed in this article. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

In the past 20 years, the microwave oven has become an essential appliance in most kitchens. Faster cooking times and energy savings over conventional cooking methods are the primary benefits. Although the use of microwaves for cooking food is widespread, the application of this technology to the processing of materials is a relatively new development. The use of microwave energy for processing materials has the potential to offer similar advantages in reduced processing times and energy savings.

In conventional thermal processing, energy is transferred to the material through convection, conduction, and radiation of heat from the surfaces of the material. In contrast, microwave energy is delivered directly to materials through molecular interaction with the electromagnetic field. In heat transfer, energy is transferred due to thermal gradients, but microwave heating is the transfer of electromagnetic energy to thermal energy and is energy conversion, rather than heat transfer. This difference in the way energy is delivered can result in many potential advantages to using microwaves for processing of materials. Because microwaves can penetrate materials and deposit energy, heat can be generated throughout the volume of the material. The transfer of energy does not rely on diffusion of heat from the surfaces, and it is possible to achieve rapid and uniform heating of thick materials. In traditional heating, the cycle time is often dominated by slow heating rates that are chosen to minimize steep thermal gradients that result in process-induced stresses. For polymers and ceramics, which are materials with low thermal conductivities, this can result in significantly reduced processing times. Thus, there often is a balance between processing time and product quality in conventional processing. As microwaves can transfer energy throughout the volume of the material, the potential exists to reduce processing time and enhance overall quality.

In addition to volumetric heating, energy transfer at a molecular level can have some additional advantages. Microwaves can be utilized for selective heating of materials. The molecular structure affects the ability of the microwaves to interact with materials and transfer energy. When materials in contact have different dielectric properties, microwaves will selectively couple with the higher loss material. This phenomenon of selective heating can be used for a number of purposes. In conventional joining of ceramics or polymers, considerable time and energy is wasted in heating up the interface by conduction through the substrates. With microwaves, the joint interface can be heated in-situ by incorporating a higher loss material at the interface [1]. In multiple phase materials, some phases may couple more readily with microwaves. Thus, it may be possible to process materials with new or unique microstructures by selectively heating distinct phases. Microwaves may also be able to initiate chemical reactions not possible in conventional processing through selective heating of reactants. Thus, new materials may be created.

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In recent literature, many researchers report non-thermal phenomena that have been broadly termed ‘‘microwave effects’’. Examples of the microwave effect include enhanced reaction rates of thermosetting resins during microwave curing [2] and faster densification rates in ceramics sintering [3]. Although there is considerable debate over the existence of microwave effects, many papers present unexpected results that do not seem to be a consequence of reduced thermal gradients possible within microwave processed materials. Critics of the microwave effect often claim that differences can be attributed to poor temperature measurement and control of experimental conditions that result in systematic error. The existence (or non-existence) of microwave effects continues to be an area of considerable debate and research. Some current literature on the microwave effect is reviewed in later sections.

Although direct heating by microwaves can offer advantages over conventional heat transfer, the different mechanism of energy transfer in microwave heating has also resulted in several new processing challenges. Because energy is transferred by the electromagnetic field, non-uniformity within the electromagnetic field will result in non-uniform heating. As materials are processed, they often undergo physical and structural transformations that affect the dielectric properties. Thus, the ability of microwaves to generate heat varies during the process. Sharp transformations in the ability of microwaves to generate heat can cause difficulties with process modeling and control. Understanding the generation, propagation, and interaction of microwaves with materials is critical. Because the processing equipment determines the electromagnetic field, the design of microwave equipment is particularly important. The properties of the electromagnetic field, chemical composition of the material being processed, structural changes that occur during processing, size and shape of the object being heated, and the physics of the microwave/materials interactions all complicate microwave processing.

Recent interest in microwave processing of materials is highlighted by the number of recent symposia that have been dedicated to microwave processing of materials. To date, the Materials Research Society (MRS) and the American Ceramic Society have held nine symposia that have focused on microwave processing of materials [4–12]. In addition to expanding the published literature on microwave processing, these symposia have addressed many of the difficulties associated with microwave processing. The recent research in microwave equipment design, microwave/materials interactions, and materials processing continues to expand interest in microwave techniques.

The purpose of this article is to offer an overview of the fundamentals of microwaves, processing equipment, and microwave/materials interactions. Some recent applications of microwave heating to materials processing are also reviewed. It is hoped that this paper will benefit those who are interested in the fundamentals of microwave processing or in the recent advancements in this developing field. The review of literature in this article is not intended to be inclusive, and readers interested in the subject should refer to the bibliography, which gives the key sources of information.

2. Microwaves

Microwaves belong to the portion of the electromagnetic spectrum with wavelengths from 1 mm to 1 m with corresponding frequencies between 300 MHz and 300 GHz. Within this portion of the electromagnetic spectrum there are frequencies that are used for cellular phones, radar, and television satellite communications. For microwave heating, two frequencies, reserved by the Federal Communications Commission (FCC) for industrial, scientific, and medical (ISM) purposes are commonly used for microwave heating. The two most commonly used frequencies are 0.915 and 2.45 GHz. Recently, microwave furnaces that allow processing at variable frequencies from 0.9 to 18 GHz have been developed for material processing [13].

3. Electromagnetic theory

Microwave furnaces consist of three major components: the source, the transmission lines, and the applicator. The microwave source generates the electromagnetic radiation, and the transmission lines deliver the electromagnetic energy from the source to the applicator. In the applicator, the energy is either absorbed or reflected by the material. The theoretical analysis of each of these microwave components is governed by the appropriate boundary conditions and the Maxwell equations:

$$\nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t}, \qquad \nabla \cdot \mathbf{B} = 0, \tag{1}$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{I}, \qquad \nabla \cdot \mathbf{D} = \rho,$$

where $\mathbf{E}$ is the electric field vector, $\mathbf{H}$, the magnetic field vector, $\mathbf{D}$, the electric flux density vector, $\mathbf{B}$, the magnetic flux density vector, $\mathbf{I}$, the current density vector, and ρ, the charge density. The Maxwell equations are the physical laws that describe electromagnetic fields that vary with time. The design of microwave sources, transmission lines, applicators, and the ability to combine these elements into an efficient system to process materials require a knowledge and an understanding of electromagnetic theory.

3.1. Microwave sources

Generation of electromagnetic radiation results from the acceleration of charge. To achieve the high power and frequencies required for microwave heating, most microwave sources are vacuum tubes. Some vacuum tubes that

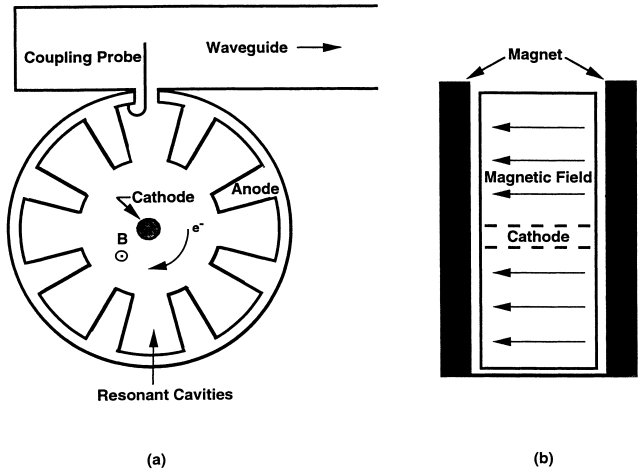

Fig. 1. Schematic diagram of the magnetron microwave tube: (a) top view, (b) side view (after Ref. [42]).

have been used for microwave heating include magnetrons, traveling wave tubes (TWTs), and klystrons. Magnetron tubes, which are used in home microwave ovens, are efficient and reliable [14]. Because magnetrons are mass produced, they are the lowest cost source available. Magnetron tubes use resonant structures to generate the electromagnetic field, and, therefore, are only capable of generating a fixed frequency electromagnetic field. In variable frequency microwave, TWTs are used to generate the electromagnetic field. The design of the TWT allows amplification of a broad band of microwave frequencies in the same tube.

3.1.1. Magnetrons

In vacuum tubes, the anode is at a high potential compared to the cathode. The potential difference produces a strong electric field, and the cathode is heated to remove the loosely bound valence electrons. Once the electrons are removed from the cathode, they are accelerated toward the anode by the electric field. In a magnetron (Fig. 1), an external magnet is used to create a magnetic field orthogonal to the electric field, and the applied magnetic field creates a circumferential force on the electron as it is accelerated to the anode. The force causes the electron to travel in a spiral direction, and this creates a swirling cloud of electrons. As electrons pass the resonant cavities, the cavities set up oscillations in the electron cloud, and the frequency of the oscillations depends on the size of the cavities. Electromagnetic energy is coupled from one of the resonant cavities to the transmission lines through a coaxial line or waveguide launcher.

Two methods are commonly used to control the average power output of magnetron tubes. The output power of the magnetron can be controlled through adjusting the period of operation or adjusting the cathode current or magnetic field strength. In home microwave ovens, the magnetron is operated at full power. During a specified time, the current is turned on and off for segments of the period, and the average power is reduced [15]. This on/off type of control is often referred to as duty cycle control. If continuous microwave power is required, the output power of the magnetron tube can be varied by changing the current amplitude of the cathode or by changing the intensity of the magnetic field. This allows variable control of the microwave power within the range of the source.

3.1.2. Traveling wave tubes

For variable frequency microwaves, high power traveling wave tubes are used as the microwave source. Unlike magnetrons, where the tube is used both to create the frequency of the oscillations and to amplify the signal, the TWT serves only as an amplifier. A voltage-controlled oscillator generates the microwave signal. The input voltage controls the frequency of the oscillator, and the signal is then sent to the TWT for amplification [13]. Because the oscillator determines the microwave frequency, these types of sources are able to rapidly switch the output frequency.

The TWT (Fig. 2) consists of two main components: the electron gun and the helical transmission line. Because there are no resonant structures, it is possible for the TWT to amplify a large variation of frequencies (bandwidth) within the same tube. The heated cathode emits a stream of electrons that is accelerated toward the anode, and the electron stream is focused by an external magnetic field. The purpose of the helix is to slow the phase velocity of the microwave (the velocity in the axial direction of the helix) to a velocity approximately equal to the velocity of the electron beam. The wave propagates along the helix wire, and the pitch of the helix determines the phase velocity of the wave [16].

When the microwave signal propagates along the helix, the axial component of the electromagnetic field interacts with the electron beam (Fig. 3). This results in acceleration and deceleration of electrons within the beam. For amplification of the signal to occur, the velocity of the electron beam should be just faster than the phase velocity of the

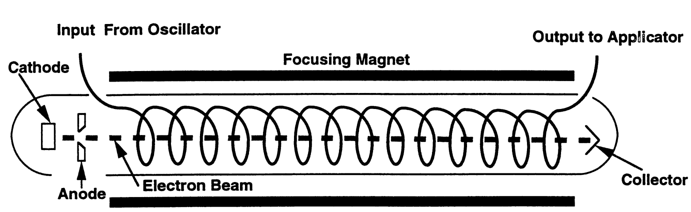

Fig. 2. Schematic diagram of the traveling wave tube (after Ref. [30]).

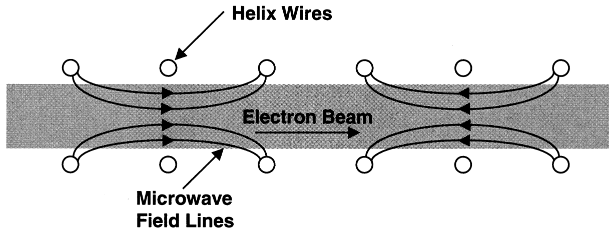

Fig. 3. Interaction of the microwave field with the electron beam in a traveling wave tube (after Ref. [16]).

helix. In this case, more electrons are being decelerated than accelerated, and the signal is amplified because energy is being transferred from the electron beam to the microwave field [17].

3.2. Transmission lines

The transmission lines couple the energy of the microwave source to the applicator. In low power systems, the transmission lines are often coaxial cables, which are similar to cables that are used on televisions. At high frequencies and output power, the losses that occur in coaxial cables are significant, and waveguides are often the transmission line of choice in microwave heating systems. Waveguides are hollow tubes in which the electromagnetic waves propagate. The most commonly used cross-sections are rectangular.

Two modes of microwave propagation are possible in waveguides: transverse electric (TE) and transverse magnetic (TM). For the TE mode, the electric intensity in the direction of propagation is zero. For the TM mode the magnetic intensity in the propagation direction is zero. Every mathematical solution of the electromagnetic wave in a rectangular waveguide can be decomposed into a linear combination of the TE and TM modes. The most common waveguide mode is the TE_{10} mode. The subscripts specify the mode of propagation, and the mode indicates the number of maxima and minima of each field in a waveguide. In addition to waveguides, there are several other transmission line components that are used for equipment protection, sensing purposes, and coupling microwaves with the material in the applicator.

3.2.1. Circulators

When materials are heated that are not good absorbers of electromagnetic energy, a significant amount of power is often reflected back to the microwave source. Excessive reflected power can damage magnetrons. The circulator protects the microwave equipment by acting as the microwave equivalent to a diode in an electrical circuit; microwaves are only allowed to pass through the circulator in one direction. In the three port circulator, one port is connected to the microwave source, another is connected to the applicator, and the third port is connected to a dummy load. The power that is reflected back to the magnetron is diverted, and the dummy load, often water, absorbs the reflected power.

3.2.2. Directional couplers

In microwave heating, the ability of materials to absorb electromagnetic energy depends on the dielectric properties. Thus, the magnitude of the forward and reflected power is of interest to the researcher. Power measurement is accomplished through the directional coupler. Directional couplers are designed so that a small amount of forward and reflected waves are separated and measured by power meters.

3.2.3. Tuners

Tuners are used to maximize the power absorbed by the load through impedance matching. Several tuners, such as irises, three stub tuners, and E-H plane tuners, are used so that differences between the impedance of the microwave source and the load can be adjusted.

3.3. Microwave applicators and processing systems

The design of the applicator is critical to microwave heating because the microwave energy is transferred to materials through the applicator. The temperature fields within the material undergoing microwave heating are inherently linked to the distribution of the electric fields within the applicator. Common microwave applicators include waveguides, traveling wave applicators, single mode cavities, and multi-mode cavities. For processing materials, resonant applicators, such as single mode and multi-mode applicators, are most common because of their high field strengths. The type of applicator used in a microwave processing system often depends on the materials to be processed. Commercially available single mode, multi-mode, and variable frequency multi-mode processing systems are all used for microwave processing research, and each of these systems has advantages and disadvantages.

3.3.1. Single mode

In the microwave applicator, or cavity, theoretical analysis can be performed to describe the response of microwaves. Given the geometry of the applicator, it is often possible to solve the Maxwell equations analytically or numerically with the appropriate boundary conditions. The design of single mode applicators is based on solution of the Maxwell equations to support one resonant mode. Consequently, the size of single mode applicators is of the order of approximately one wavelength, and to maintain the resonant mode, these cavities require a microwave source that has little variation in the frequency output. Because the electromagnetic field can be determined using analytical or numerical techniques, the areas of high and low electromagnetic field are known, and single mode applicators have non-uniform, but predictable, electromagnetic field distributions. In general, single mode cavities have one ‘‘hot spot’’ where the microwave field strength is high.

This ability to design an applicator where the locations of high and low field strengths are known can offer some distinct advantages. Through proper design, single mode applicators can be used to focus the microwave field at a given location. This technique has been exploited for joining of ceramics [18,19]. In this application, it is desired to concentrate the microwave energy at the joint interface without heating the bulk of the ceramic. By placing the ceramic joint in the area of high electric field, localized heating of the ceramic joint will be achieved. Clearly, the size limitations of a single mode applicator limit this technique to relatively small joints that will fit within the area of high field strength in a single mode applicator. More recently, Tinga et al. [20] have developed an open-ended single mode applicator for continuous joining of ceramic sheets that can overcome some of these practical limitations.

In addition, a knowledge of the electromagnetic field distribution can allow materials to be placed in the area of highest field strength for optimum coupling. Therefore, these cavities have been used for laboratory-scale studies of interactions between microwaves and materials. For example, single mode cavities are often used for studying the effect of microwaves on the curing kinetics of thermosetting resins [2,21,22]. For cure kinetic studies, the single mode cavity offers a very controlled environment where the small samples can be placed for optimum coupling. In larger microwave cavities, small samples used for the kinetic studies do not represent a significant coupling load, and the process is more difficult to control for small coupling loads. An additional advantage of single mode cavities is the ability to monitor the dielectric properties during processing [23].

Although the heating patterns of single mode cavities are non-uniform, in some single mode applicators it is possible to switch resonant modes. Sometimes the different resonant modes that are possible within the applicator have complementary heating patterns. Mode switching in single mode applicators is accomplished through altering the geometry of the applicator or by adjusting the frequency of the microwave source. In the cylindrical single mode applicator developed at Michigan State University and commercialized by Wavemat Inc., the height of the applicator can be adjusted. By adjusting the height, the applicator can be ‘‘tuned’’ to a different resonant mode. From a knowledge of these heating patterns in single mode cavities, the resonant mode can be changed during use to achieve a uniform in-plane temperature within the material [24]. Because time is required to change the dimensions of the cavity, variable frequency TWT microwave sources have been investigated for mode switching [25]. In TWTs, the frequency can be changed so the cavity can accommodate a different resonant mode, and the use of these sources overcomes the time-delay associated with mechanically changing the dimensions of the cavity. Although these types of applicators may be able to accept multiple resonant modes, only one mode can be chosen at a given time.

Other applications for single mode applicators include use as preheaters for the pultrusion process [26] and applicators designed for processing of ceramic filaments [27,28]. Although single mode applicators have potential for some applications and laboratory-scale investigations of microwave/materials interactions, single mode cavities are difficult to scale-up to many industrial applications due to the geometric limitations and non-uniformity of the fields. Therefore, single mode cavities are generally designed for specific purposes. Larger microwave applicators with more uniform fields are required to process large, complicated shaped components.

3.3.2. Multi-mode applicators

Applicators that are capable of sustaining a number of high order modes at the same time are known as multi-mode cavities. This type of applicator is used in home microwave ovens. Unlike the design of single mode applicators, which are designed based on solutions of the electromagnetic field equations for a given applicator geometry, the design of multi-mode applicators are often based on trial and error, experience, and intuition [29]. As the size of the microwave cavity increases, the number of possible resonant modes also increase. Consequently, multi-mode applicators are usually much larger than one wavelength. For a rectangular cavity, the mode equation for the resonant frequencies is [30]:

$$f_{nml} = c\left[\left(\frac{l}{2d}\right)^2+\left(\frac{m}{2b}\right)^2+\left(\frac{n}{2a}\right)^2\right]^{1/2}, \qquad (2)$$

where f_{nml} is the TE_{nml} or TM_{nml} mode's resonant frequency; c is the speed of light; n, m, l, are the number of half-sinusoid variations in the standing wave pattern along the x, y, and z-axes; a, b, and d are the dimensions of the cavity in the x, y, and z directions.

The presence of different modes results in multiple hot spots within the microwave cavity. Like single mode cavities, local fluctuations in the electromagnetic field result in localized overheating. To reduce the effect of hot spots, several techniques are used to improve the field uniformity. The uniformity of the microwave field can be improved by increasing the size of the cavity. Because the number of modes within a multi-mode applicator increases rapidly as the dimensions of the cavity increase (Eq. (2)), the heating patterns associated with the different resonance modes begin to overlap. The rule of thumb to achieve uniformity within an applicator is to have the longest dimension be 100 times greater than the wavelength of the operating frequency [31]. Unfortunately, at the common microwave frequency of 2.45 GHz, the largest dimension would exceed 40 ft. It is possible to achieve a greater field uniformity by operating at a higher frequency. At higher frequencies, the wavelength is shorter, and the applicator required to achieve uniformity can be reduced to a practical size.

Although higher frequency processing may seem to be

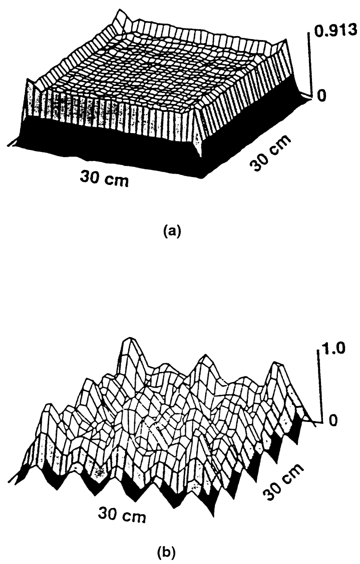

Fig. 4. Power distributions in: (a) a variable frequency microwave (2 GHz bandwidth) and (b) a microwave operating at 2.45 GHz (after Ref. [13]).

the solution to creating greater uniformity, 2.45 GHz is able to penetrate deeper to create volumetric heating. Consequently, many attempts have been made to achieve more uniform heating within smaller multi-mode ovens at 2.45 GHz [32]. A familiar example can be found in the home microwave oven. These ovens are often equipped with turntables that rotate during operation. The purpose of the turntable is to reduce the effect of multiple hot spots by passing the food through areas of high and low power and, therefore, achieve time-averaged uniformity. Another technique for improving the field uniformity is through mode stirring. Mode stirrers are reflectors, which resemble fans, that rotate within the cavity near the waveguide input. The mode stirrers ''mix up'' the modes by reflecting waves off the irregularly shaped blades and continuously redistribute the electromagnetic field. Like turntables, mode stirring creates time-averaged uniformity. In addition, adding multiple microwave inputs within a multi-mode cavity can further enhance the uniformity [33].

Most techniques for creating uniformity depend on modifying the electromagnetic field within the microwave cavity. Another method developed to achieve more uniform heating is hybrid heating. Hybrid heating can be achieved through combining microwave heating with conventional heat transfer through radiation, convection, or conduction. Variations of this method have been used successfully by researchers at the Oak Ridge National Laboratory [34] and the University of Florida [35] to heat ceramics in a multi-mode furnace uniformly.

Multi-mode applicators are typically more versatile than single mode applicators for batch operations and processing of large, complicated shaped objects. Thus, multi-mode systems are by far the most common processing systems used in industrial applications. Microwave processing research at the University of Delaware and University of Florida has focused on the use of multi-mode systems for processing of polymer composites and ceramics. The processing system at the University of Delaware (Model 101 Microwave Materials Technologies, Inc.) is a 6 kW, 500 l multi-mode microwave system. The large cavity is equipped with multiple waveguide inputs and mode stirrers to enhance uniformity of the microwave field. In addition, the cavity can be evacuated and backfilled with a cover gas for processing of ceramics in a controlled environment. For polymer composites research, the vacuum system has been modified to apply pressure to composite laminates using a vacuum bag.

Recently, variable frequency multi-mode processing systems have been developed for materials research. The variable frequency microwave furnace (VFMF), developed by researchers at the Oak Ridge National Laboratory and Lambda Technologies, Inc., has been able to overcome the problems of power non-uniformity within multi-mode cavities. The system makes use of the TWT source to sweep the frequency of the microwave field. The cavity used in this type of system is a multi-mode cavity. The result is time-averaged power uniformity within the microwave cavity. The ability to excite many different resonant modes by sweeping the frequency allows for uniform heating in a small cavity. It has been demonstrated that large composite laminates can be cured and post-cured [36] and large volumes of resin can be uniformly cured in a variable frequency microwave [37]. Similar to the fixed frequency multi-mode processing systems, uniformity will be further enhanced in a large applicator due to the greater number of resonant modes possible.

Qualitative models for power distribution in the VFMF were developed to illustrate the ability to create uniformity in a small cavity by sweeping frequencies through a bandwidth [13,38]. The model uses Eq. (2) to calculate the mode resonant frequencies within the bandwidth. The power for each resonant frequency was calculated and added together to get the normalized power density (Fig. 4). As expected from the increase in possible resonant modes, the uniformity of the microwave energy when the frequency is swept is improved. Although the variable frequency microwave approach is a very elegant means to create uniformity in a small cavity, TWT sources are extremely expensive relative to the amount of power generated. It is the authors' belief that fixed frequency processing has the greatest potential for industrial applications due to the robustness of the technology and the much lower relative cost of equipment.

4. Microwave/materials interaction

Energy is transferred to materials by interaction of the electromagnetic fields at the molecular level, and the dielectric properties ultimately determine the effect of the electromagnetic field on the material. Thus, the physics of the microwave/materials interaction is of primary importance

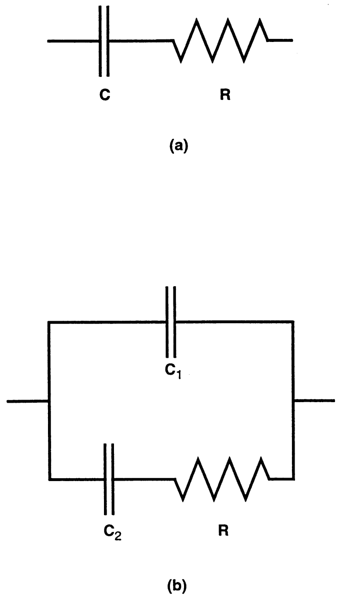

Fig. 5. Electrical circuits used to model dielectric materials (after Ref. [41]).

in microwave processing. The interaction of microwaves with molecular dipoles results in rotation of the dipoles, and energy is dissipated as heat from internal resistance to the rotation. In the following section, the principles behind

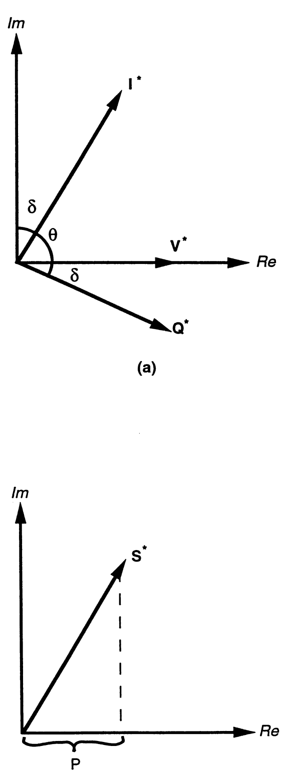

Fig. 6. Phazor diagrams for: (a) current, voltage and charge (b) power in an electrical circuit (after Ref. [41]).

microwave/materials interactions, power absorption, and measurement of dielectric properties are presented. Whenever possible, simplified models and analogies for microwave/materials interactions are presented to assist in understanding the physics behind the material response. Readers who are interested in more detailed models should consult the references.

4.1. Dielectric properties

For heat to be generated within the material, the microwaves must be able to enter the material and transmit energy. The dielectric constant (ε') and the dielectric loss factor (ε'') quantify the capacitive and conductive components of the dielectric response. These components are often expressed in terms of the complex dielectric constant (ε^*)

$$\varepsilon^* = \varepsilon' - \mathrm{i}\varepsilon''. \tag{3}$$

Another commonly used term for expressing the dielectric response is the loss tangent.

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'}. \tag{4}$$

There exist a number of properties that contribute to the dielectric response of materials. These properties include electronic polarization, atomic polarization, ionic conduction, dipole (orientation) polarization, and Maxwell–Wagner polarization mechanisms. At microwave frequencies, dipole polarization is thought to be the most important mechanism for energy transfer at the molecular level [39,40]. In addition, in composite materials, Maxwell–Wagner polarization, which results from the accumulation of charge at the material interface, is also an important heating mechanism [39].

In dielectric materials, the local charge moves in response to an applied electric field. Within materials, there exists bound charge and free charge, and motion of the bound charge results in polarization. Polarization of electric charge where the translational motion is restricted or polarization of molecules where the rotational motion is restricted results in a lag between the electric field and the polarization. This time lag, known as the relaxation time, is due to dissipation of energy as heat within the material. Microwave heating is a result of this dielectric relaxation.

4.2. Dielectric relaxation

Relaxation phenomena are often encountered in a variety of chemical, mechanical or electrical systems. Relaxation times are generally defined by differential equations of the following form where h and k are variables:

$$\tau\frac{\partial k}{\partial t} + k = h. \tag{5}$$

The relaxation phenomenon in dielectric materials is analogous to relaxation in electrical circuits. Models that describe the relaxation of dielectric materials are often based on

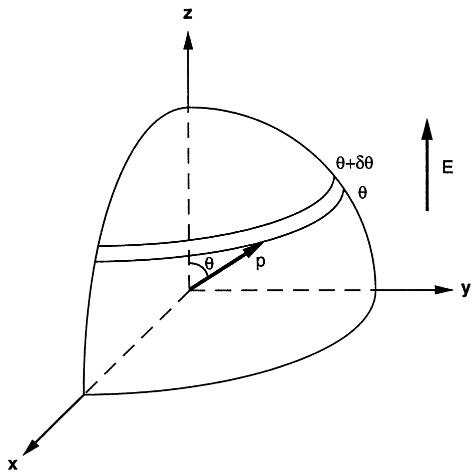

Fig. 7. Model of a dipole used in the Debye description of an ideal liquid (after Ref. [42]).

electrical circuits that are composed of resistors and capacitors in series or parallel.

The simplest circuit that exhibits a relaxation time is a resistor and capacitor in series (Fig. 5(a)). By summing up the voltage, V, across both the resistor and the capacitor, the following differential equation for charge, Q, in the circuit can be obtained:

$$R\frac{\partial Q}{\partial t} + \frac{Q}{C} = V, \tag{6}$$

where R and C stand for the resistance and capacitance, respectively, and t is the time. Eq. (6) can be rearranged in the form of Eq. (5)

$$\tau\frac{\partial Q}{\partial t} + Q = CV, \tag{7}$$

where

$$\tau = RC \tag{8}$$

is the relaxation time. The solution to this differential equation, where the applied voltage is sinusoidal and assumed to be $V_0 e^{i\omega t}$ in complex, polar coordinates is [41]

$$Q^*(\omega, t) = \frac{V_0}{\omega Z(\omega)} e^{i(\omega t - \delta)}, \tag{9}$$

where δ is the angle between the charge vector, Q^*, and the voltage vector, V^* in a phazor representation in the complex plane (Fig. 6(a)). The lag between the charge and the voltage is directly proportional to δ when the power dissipation is small. Also, in Eq. (9) ω is the angular frequency and $Z(\omega)$ is the impedance.

An important circuit used as a model for dielectric materials is a series resistor and capacitor in parallel with a capacitor (Fig. 5(b)). From elementary circuit analysis, the impedance of this circuit can be determined:

$$Z = \left(\frac{i\omega C_1}{Ri\omega C_1 + 1} + i\omega C_2\right)^{-1}, \tag{10}$$

where C_1 and C_2 are the capacitances defined in Fig. 5(b). The relationship between the charge and the voltage is defined as the following [41]:

$$Q^*(\omega, t) = C^*(\omega)V^*(\omega, t), \tag{11}$$

where C^* is the complex capacitance. Therefore, the relation between impedance and capacitance can be determined for a sinusiodal varying current as:

$$Z(\omega) = \frac{1}{1 + i\omega C^*(\omega)}. \tag{12}$$

From Eqs. (10) and (12) the complex capacitance can be determined.

$$C^* = C_1 + \frac{C_2}{1 + \omega^2 C_2^2 R^2} - \frac{i\omega R C_2^2}{1 + \omega^2 C_2^2 R^2}. \tag{13}$$

This form of the complex capacitance is identical to the form of the classical Debye solution for an ideal dielectric liquid. There are several ways to derive the Debye equations based on the microscopic interaction of the dipoles with applied electromagnetic fields [41,42]. The classical Debye description of an ideal dielectric liquid is useful to understand the physics behind the interaction of microwaves with materials at the molecular level. In the Debye description, a single molecule with a small electric dipole is assumed to be at the center of a spherical volume. When there is no electromagnetic field present, the dipoles are randomly oriented throughout the material. When the electromagnetic field is applied, the dipoles tend to orient in the direction of the electric field (Fig. 7). A force balance on the dipole yields the following equation:

$$I\frac{\partial^2 \theta}{\partial t^2} + C\frac{\partial \theta}{\partial t} - pE\sin\theta = 0, \tag{14}$$

where E is the magnitude of the electric field, θ, the angle between the dipole and the microwave field, I, the dipole moment of inertia, C, the internal viscous damping within the material, and p, the dipole moment.

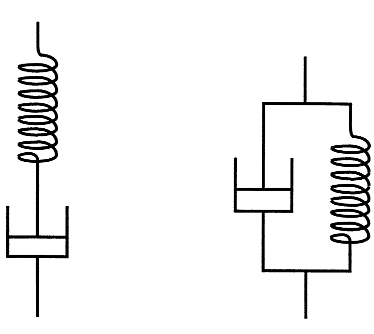

Fig. 8. The (a) Maxwell and (b) Voigt models for viscoelasticity (after Ref. [43]).

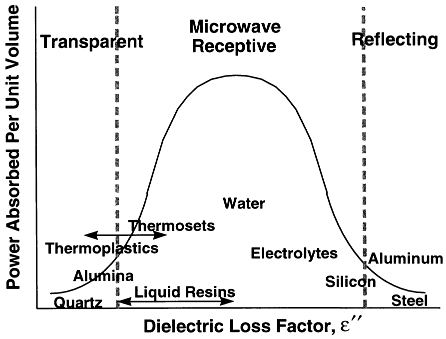

Fig. 9. Relationship between the dielectric loss factor and ability to absorb microwave power for some common materials.

From the foregoing equation of motion, a statistical analysis of the dipole orientations could be considered, and the following relation for the complex dielectric constant can be obtained [42],

$$\varepsilon^* = \varepsilon_\infty + \frac{\varepsilon_0 - \varepsilon_\infty}{1 + (\omega\tau)^2} - \frac{\mathrm{i}(\varepsilon_0 - \varepsilon_\infty)\omega\tau}{1 + (\omega\tau)^2}, \tag{15}$$

where ε_0 is the dielectric constant where the frequency is zero and ε_∞ is the dielectric constant where the frequency is infinite. This is identical to the form of Eq. (13) where the capacitance has been replaced by the dielectric constants.

The Debye solution for an ideal liquid is quite simplified and is often not applicable to many materials. The Debye model results in only one relaxation time, and often materials exhibit more than one relaxation time. As a result, more complicated models have been developed to describe the dielectric behavior of different types of materials [40]. The Debye model for dielectric properties is analogous to the Voigt and Maxwell models consisting of springs and dashpots that are used in polymer viscoelasticity (Fig. 8). Although these models are often not applicable to many materials, they form the foundation from which more complicated models are formed. The phenomenon of relaxation in dielectric materials is analogous to viscoelasticity because the governing equations are of the same form [43]. Although the Debye model is simplified, it shows that the relaxation time is affected by the structure of the material. The ability of materials to heat is related to the ability of the dipoles to orient in the electromagnetic field, and this ability to orient defines the dielectric properties.

4.3. Energy conversion

The dielectric properties of materials in combination with the applied electromagnetic fields result in the conversion of electromagnetic energy to heat. The power that is transmitted to an object can be determined by the use of the Poynting Vector Theorem [30], which can be derived from the Maxwell equations. The power that is transmitted across the surface, *S*, of a volume, *V*, is given by the real portion of the following equation:

$$\frac{1}{2}\oint_s \mathbf{E} \times \mathbf{H}^* \cdot \mathrm{d}\mathbf{S}, \tag{16}$$

where $\mathbf{E} \times \mathbf{H}^*$ is the Poynting vector and the *, in this case, denotes complex conjugate. Using the divergence theorem, the Maxwell equations, and by assuming materials properties for the volume the following equation can be obtained for the real portion of the Poynting power theorem:

$$\frac{1}{2}\int_v (\omega\mu\mathbf{H}\cdot\mathbf{H}^* + \omega\varepsilon''\mathbf{E}\cdot\mathbf{E}^* + \sigma\mathbf{E}\cdot\mathbf{E}^*)\mathrm{d}V, \tag{17}$$

where μ'' represents the imaginary component of the magnetic permeability and σ is the conductance. In dielectric materials, the magnetic permeability is usually small and the first term can be neglected. In addition, $\omega\varepsilon''$ can be considered as an equivalent conductance [30]. If the electric field is assumed to be uniform throughout the volume, the following simplified equation for power, *P*, absorbed per unit volume can be obtained from Eq. (17):

$$P = 2\pi f\varepsilon'' E^2. \tag{18}$$

As energy is absorbed within the material, the electric field decreases as a function of the distance from the surface of the material. Therefore, Eq. (18) is valid for only very thin materials. The penetration depth is defined as the distance from the sample surface where the absorbed power is 1/*e* of the absorbed power at the surface. Beyond this depth, volumetric heating due to microwave energy is negligible. Assuming the dielectric constant of free space is ε_0, the penetration depth is given by the following equation [39]:

$$d = \frac{c\varepsilon^0}{2\pi f\varepsilon''}. \tag{19}$$

The penetration depth and knowledge of how the electric field decreases from the surface are particularly important in processing thick materials. If the penetration depth of the microwave is much less than the thickness of the material only the surface is heated. The rest of the sample is heated through conduction. Eq. (19) shows the dependence of the penetration depth on the frequency of operation. As mentioned earlier, greater uniformity achieved in multi-mode applicators by operating at higher frequencies is at the expense of penetration depth.

Eqs. (18) and (19) give an insight as to which dielectric materials are suitable for microwave processing. Materials with a high conductance and low capacitance (such as metals) have high dielectric loss factors. As the dielectric loss factor gets very large, the penetration depth approaches zero. Materials with this dielectric behavior are considered reflectors. Materials with low dielectric loss factors have a very large penetration depth. As a result, very little of the energy is absorbed in the material, and the material is transparent to microwave energy. Because of this behavior,

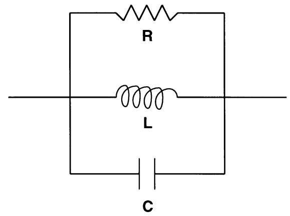

Fig. 10. Parallel RLC circuit.

microwaves transfer energy most effectively to materials that have dielectric loss factors in the middle of the conductivity range (see Fig. 9). In contrast, conventional heating transfers heat most efficiently to materials with high conductivity.

Although Eqs. (18) and (19) are useful for assessing the effect of electrical properties on microwave power absorption, material processing is much more complex. The dielectric properties are dependent on the mobility of the dipoles within the structure, and therefore the dielectric properties are functions of temperature, frequency, and, for reacting systems, degree of reaction. Therefore, the ability of the material to absorb energy changes during processing. For example, at room temperature silicon carbide (SiC) has a loss factor of 1.71 at 2.45 GHz. The loss factor at 695°C for the same frequency is 27.99 [44].

The phase shift of current in electrical circuits is analogous to how energy is dissipated in dielectric materials. As mentioned before, dipole polarization lags behind the electric field due to internal forces in the material. The phase shift, δ, between the dipole displacement and the electric field result in dielectric losses. The in-phase component of the dipole displacement with the electric field is power absorbed by the dielectric material as heat. In alternating current electrical circuits, the current is out of phase with the voltage. The complex power is the product of the complex current and voltage [45].

$$S = \mathbf{V}^* \mathbf{I}^*, \tag{20}$$

where S is the complex power. If the preceding equation is rewritten in terms of the complex capacitance, as defined earlier, the following equation results:

$$S = i\omega C^* \mathbf{V}\mathbf{V}^*, \tag{21}$$

where the real portion is the power dissipated in the electrical circuit (Fig. 6(b)). This is analogous to the Poynting power theorem in dielectrics.

4.4. Measurement of dielectric properties

Because the dielectric properties govern the ability of materials to heat in microwave fields, the measurement of these properties as a function of temperature, frequency, or other relevant parameters is important. Many authors [46–48] have reviewed different techniques for dielectric property measurements at microwave frequencies.

The two most common techniques are the resonant cavity, or cavity perturbation method, and the transmission and reflection method. In the resonant cavity method, the ratio of energy stored in the cavity to the energy lost (often referred to as the quality or Q-factor) is measured in an empty cavity and a cavity with a small sample in it. Because microwave systems are often designed by replacing system components with equivalent electrical circuits [16], the Q-factor is based on the parallel RLC (resistance–inductance–capacitance) resonant circuit theory (Fig. 10). The Q-factor for a parallel RLC circuit is [45]:

$$Q = R\sqrt{\frac{L}{C}} \tag{22}$$

the addition of the sample in the cavity perturbs the electromagnetic field, and it changes R, L, C, and, hence, the impedance of the equivalent circuit. The changes in the Q-factor and resonant frequency of the cavity can be related to the dielectric constant the loss tangent of the sample. In the transmission and reflection method, a sample is placed in a waveguide and the phase and amplitude of the transmitted and reflected waves are examined. The differences in these waves give information on the dielectric properties. For high-temperature dielectric property measurements on ceramics, factors, such as accurate temperature measurement, complicate the measurement of dielectric properties using these techniques [47].

5. Ceramics and ceramic matrix composites

An area of microwave processing that has received a lot of attention is ceramic processing. Because ceramics have low thermal conductivities and are processed at high temperatures, many researchers have attempted to take advantage of volumetric heating for sintering, chemical vapor infiltration (CVI), and pyrolysis of polymeric precursors. Other applications include joining [18,19,49] fiber processing [27,28], and plasma pyrolysis [50].

5.1. Material behavior

Many ceramics, such as silicon carbide (SiC) and magnesium oxide (MgO), have dielectric properties that are suitable for microwave processing. Other materials, such as silicon nitride (Si_3N_4) and alumina (Al_2O_3), are poor absorbers of microwaves up to a critical temperature. Above this temperature, the dielectric loss factor begins to increase, and the material begins to couple with microwaves [51]. Ceramics that must reach a critical temperature before they couple with microwaves present some processing difficulties. Before reaching the critical temperature, these materials have very low loss factors, and, therefore, they get heated very slowly in the microwave field. When ceramics are processed in non-uniform electromagnetic fields, the local temperature can vary within the material. If a local volume reaches the critical temperature before the rest of

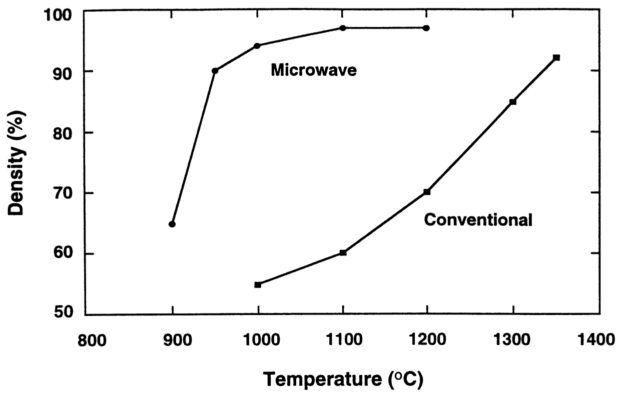

Fig. 11. Density versus sintering temperature for alumina sintered in a microwave and a conventional furnace (after Ref. [3]).

the material, that area begins to heat more rapidly, and the temperature begins to increase even more. This can result in localized thermal runaway that can cause stresses that are high enough to fracture the material [52]. Hybrid heating can be used to help process materials that exhibit this behavior. Before the critical temperature is reached, the ceramic is heated through traditional heat transfer. As the material begins to get heated, and its loss factor increases, it begins to couple more effectively with microwaves.

5.2. Processing

Much of the research in microwave processing of ceramics has been performed on sintering. In conventional ceramics processing, ceramic power is compacted under high pressure into the desired shape. High temperature sintering follows the compaction. During sintering, the ceramic particles join and the porosity, caused by compacting the particles, is gradually reduced. In thermal processing, the ceramics are sintered in a high temperature furnace. Because the material is heated from the surface, steep thermal gradients can result. In microwave processing, where the material is directly heated, the thermal gradients are reduced. In fact, microwave processed ceramics often have reverse thermal gradients due to convective and radiative heat loss from the surface of the ceramic to the unheated cavity. To avoid steep reverse thermal gradients, the surface of the ceramic is often insulated from the unheated microwave cavity. Ceramics are particularly susceptible to thermal gradients because thermal stresses can be high enough to initiate fracture in brittle ceramics.

Many researchers have reported significant reductions in processing times of microwave over conventional sintering [3,52–55]. Janney and Kimrey [3] conducted research on the microwave sintering of alumina. In Fig. 11 the percentage theoretical density of alumina processed for the same time in microwave and thermal environments (50°C/min, held for 1 h) is shown as a function of sintering temperature. Fig. 11 clearly demonstrates that there is an acceleration of material densification in microwave processing. The density of microwave sintered alumina rapidly increases with temperature compared with the thermally processed alumina. Additional experiments studying the kinetics of the thermally activated mass-transfer process in sintering determined that the activation energy for alumina observed in microwave processing was over 70% lower than the activation energy for conventional processing. This enhancement in the sintering is an often reported ‘‘microwave effect’’.

More recently, a number of researchers have attempted to develop models that can account for these non-thermal microwave effects. In order to explain enhanced sintering, Willert-Porada [56] developed a model based on the thermodynamic stability of pores surrounded by grains in an external electric field. The dielectric inhomogeneity of the ceramic results in enhancement of the electric field at convex surfaces within the pores. The local enhancement of the electric field improves material flux at the convex surfaces and affects the local driving force for densification. Calame et al. [57] performed calculations of electric field enhancement in spherical neck ceramic microstructures and reported that the peak intensities of the electric field in the microstructure can be much higher than the applied field.

In addition to increased sintering rates, microwave sintering often results in enhanced mechanical properties. Due to the reduced thermal gradients in microwave sintering, there is lower process-induced stress. In addition, the uniformity of the ceramic microstructure can be improved with microwave heating. Because of the shorter sintering cycles and reduced thermal gradients, finer grain sizes can be obtained and there is more uniformity in the grain size and shape factor [55]. The greater uniformity in the microstructure results in reduced scatter in the mechanical properties.

In most traditional techniques for processing ceramic matrix composites, a fibrous preform is infiltrated with a ceramic powder or slurry. The composite is then pressed or cast to form the desired shape followed by densification. These processes can damage the preform and, thus, lower the quality of the final product. Chemical vapor infiltration (CVI) is an attractive process for manufacturing ceramic matrix and carbon/carbon composites because a reactant gas infiltrates the preform and the vapors deposit solid phases on the fibers to form the ceramic matrix. Because the decomposition reaction of the vapor occurs more rapidly at higher temperatures, the solid phase deposits preferentially in hotter areas when thermal gradients are present. This can result in non-uniform density, high porosity, and long processing times when materials have traditional thermal gradients. As mentioned before, reverse thermal gradients are often present in microwave processing due to heat transfer from the surface. In microwave assisted CVI, this reverse thermal gradient can be exploited to promote vapor infiltration into the preform. This results in densification of the composite beginning from the interior of the preform.

Numerical simulations of the CVI process also have demonstrated that the ability to create reverse thermal gradients can result in more efficient matrix deposition [58]. Morell et al. [59] have investigated the use of microwaves for the processing of carbon/carbon composites through pulsing the microwave power. Because the volume heating is instantaneous when the microwave field is turned on, the preform can be rapidly heated up to the reaction temperature. When the microwave power is removed, the preform temperature is reduced and more reactant gas is allowed to diffuse into the porous preform. Additionally, Ting et al. [60] have demonstrated the ability of microwaves to enhance the infiltration into carbon preforms to depths greater than 2.5 mm. Currier and Devlin [61] have reviewed the key processing aspects of microwave-assisted CVI as compared with traditional techniques. In addition, they have compared numerical and experimental studies of the CVI process.

Other novel techniques for manufacturing ceramic matrix composites show promise for future research in microwave processing. Pyrolysis of polymeric precursors has been used for many years to produce carbon–carbon composites and recently, attention has been given to pyrolysis of pre-ceramic polymers for the processing of ceramic matrix composites. The application of microwave heating for producing carbon/carbon composites has shown that high-quality samples can be produced with a significant reduction in the processing time [62]. In preliminary studies of ceramic matrix composites, microwave power has been utilized to pyrolize polycarbosilane to produce silicon carbide [63] and to pyrolize perhydropolysilizane to produce silicon nitride [64]. Similar to the results for sintering, processing times were shortened. The use of microwave heating was found to enhance the crystallinity at lower temperatures compared with conventional pyrolysis.

6. Polymers and polymer matrix composites

Because polymers and their composites also have low thermal conductivity, many of the technical challenges associated with conventional processing of ceramics also exist for polymers. Consequently, there has been much research in the area of microwave processing for polymers and composites. A major barrier in the use of thermosetting composites in many applications is the long cure and post-cure processing times required to achieve the required mechanical properties. As in the case of ceramics, research has revealed that microwave processing can reduce processing times and improve mechanical properties.

6.1. Material behavior

The chemical structure, and hence, the dielectric behavior of thermosetting and thermoplastic polymers is quite different. Therefore, the processing requirements are also different for the two classes of polymers. In fiber reinforced composites, the non-homogeneous microstructure also affects the interaction of microwaves with these materials.

The dielectric properties of thermosetting resins undergoing cure has been investigated at microwave frequencies [65] and at lower frequencies [66,67]. As thermosets undergo crosslinking, the dielectric properties change as a result of changes in the network structure. These changes in the dielectric properties correspond directly with changes in the resin viscosity. Initially, the liquid resin couples well with microwaves. As crosslinking proceeds and viscosity increases, the dielectric loss decreases because changes in the resin viscosity affect the ability of dipoles to orient in the electric field. These changes in dielectric properties are of particular interest for in-situ monitoring of the cure process, and a knowledge of these changes can be used to optimize the cure cycle in microwave processing [67,68].

The dielectric behavior of thermoplastics, however, is similar to the dielectric behavior of many ceramics. Thermoplastics are difficult to heat until they reach a critical temperature [40]. In addition, the crystallinity affects the dielectric properties. Polymers with a degree of crystallinity above 45% are essentially transparent to microwaves due to the restriction of dipoles. As the degree of crystallinity increases, the loss factor decreases [40]. Although thermoplastic polymers generally have low loss factors at room temperature, the addition of conductive fillers or fibers can strongly influence the overall dielectric loss.

The ability to process polymeric materials with microwaves depends on the dipole structure, frequency of processing, temperature, and additives or fillers that have been included with the polymer. In microwave heating of polymer composites, microwaves selectively couple with the constituent material of higher dielectric loss. For composites with low conductivity fibers, such as glass or aramid fibers, the dielectric loss of the composite is dominated by the dielectric properties of the polymer matrix. In contrast, the dielectric loss of carbon fiber composites is dominated by the fiber. As a further complication, the dielectric properties are anisotropic, and, therefore, the composite microstructure significantly affects the penetration of microwaves.

The interaction of microwave power with fiber reinforced composite materials was first investigated by Lee and Springer [69,70]. Through their research, they developed a model, using knowledge of the electromagnetic field properties, dielectric properties of the constituent materials, and the geometry of the ply lay-up to determine the reflectance, transmission, and absorbed power in the composite. Because the dielectric properties of a single composite lamina are anisotropic, interfaces within the composite laminate where adjacent plies are aligned in different orientations result in a discontinuity of the dielectric properties. The creation of this discontinuity results in internal reflection within the composite, and this internal reflection can result in a complicated distribution of electromagnetic fields within these materials. Later, Wei et al. [71] developed a similar model that describes the microwave heating of composites in single mode cavities. To incorporate the different resonant modes possible in single mode applicators, a five parameter model that describes the mode shape and the input power of the microwaves was developed.

6.2. Polymer processing

Early literature on the microwave processing of polymers and composites reported a drastic reduction in the required cure time [72]. Since the early experimental investigations of microwave curing of composites, there have been many attempts to understand the effect of microwaves, if any, on the chemical kinetics and physical properties of microwave-cured polymers.

One of the most commonly reported ''microwave effects'' is the acceleration of the cure kinetics of thermosetting resins. The existence of the microwave effect in thermosetting resins is quite controversial, and there have been conflicting results on this topic. Marand et al. [2], Wei et al. [21], and Jordan et al. [73] have studied the cure kinetics of epoxy resin systems. In all of these investigations, the reaction rates were enhanced and times to gelation and vitrification were reduced due to microwave heating. Marand et al. showed that the molecular structure and curing agent affect the magnitude of the acceleration in microwave heating. Research by Wei and co-workers was conducted to determine the effects of microwaves on the molecular structure, and it was shown that the molecular structure of some polymers is different when cured using microwaves as compared with conventional curing [21]. These results are in contrast to the work of Mijovic and co-workers who have noticed either no change in the cure kinetics [74] or a retardation of the cure kinetics [75] when cured by microwaves. In their recent work, an in-situ method was used to investigate the crosslinking of several different materials and they assert that the claims of accelerated cure kinetics are unfounded [74]. The conflicting results by different laboratories indicate the need for additional work in this area.

If the application of microwaves can affect the molecular structure of the polymer, then the resulting mechanical properties may be affected. Some researchers have focused their research on using microwaves to excite chemical reactions that are not possible with traditional processing by incorporating microwave absorbing functional groups in the polymer chain [22]. This can enhance the heating rate and can result in a significant in a significant increase in the reaction rate. Other research has focused on controlling the morphological features of the polymer structure by using microwaves to control the amount of phase separation in polymer blends to design the physical properties of the polymers [76].

In a comparison of microwave and thermal cure on the mechanical properties of epoxy resin by Singer et al. [77], it was found that the tensile strength of the microwave specimens below 80% degree of cure was significantly lower than thermally cured specimens. As the extent of cure increased, the tensile strength of the microwave specimens improved, and at 100% degree of cure the mechanical strength of the microwave cured specimens surpassed the thermally cured ones. In addition, the modulus of elasticity was slightly higher in the microwave-cured specimens. Singer and co-workers suggested that reduced strength at lower degrees of cure is a result of less molecular entanglement of the polymer network due to alignment in the electric field. The higher reported modulus could also be due to molecular arrangement in the electric field because alignment may produce higher molecular packing with lower free volume resulting in a higher modulus. The results of this investigation are consistent with the results of Bai et al. [78]. Bai demonstrated both increased tensile strength and modulus for microwave cured specimens. Whereas Jordan et al. [73] reported no significant changes in the elastic properties of epoxy resins cured under microwaves.

6.3. Polymer composites

Much of the motivation behind the study of microwave curing of polymers is in the potential application to processing of polymeric composites. The difficulties associated with processing thermoset composite laminates are well known, and for thick composite laminates, the processing difficulties are often magnified. In traditional thermal processing, materials must be heated at a slow rate to allow heat to be conducted throughout the thickness. In addition, the exothermic chemical reactions generate internal heat that is slow to dissipate through conduction. The result is a complex temperature distribution within the laminate, which can give rise to non-uniform cure, uncontrolled spatial solidification, thermal degradation, and process-induced stresses. The application of volumetric heating due to microwaves can potentially reduce some of these difficulties.

Lee and Springer [70] were among the first to undertake a fundamental investigation of microwave curing. Although microwaves were able to couple well with glass fiber composites, they reported that microwaves would only be able to process relatively thin unidirectional carbon fiber composites. This limitation was due to the high dielectric loss of the carbon fiber. In angle ply laminates, the reflectance of the first few layers was too high to achieve efficient heating of thick laminates. In addition, the incorporation of high conductivity fibers may result in the formation of local hot spots and electrical arcing. Roussy and Pierce [42] suggest that because the conductivity of the fiber is high, heating of carbon fiber composites will be better suited to lower radio-frequency fields. Recently, however, researchers have shown the ability to cure thick cross-ply carbon fiber/epoxy composites with single mode microwave cavities [79]. In numerical simulations of the curing process, Wei et al. [80] have shown the ability to minimize the exothermic temperature excursion in carbon fiber/epoxy laminates of up to 2 in. in thickness. There also have been several attempts at intelligent processing of these composites through knowledge-based systems [81,82]. In addition, it has been shown that carbon fiber composites are applicable to microwave-assisted pultrusion [83]. Although the penetration depth of the microwaves is somewhat limited in carbon fiber/epoxy composites, Lind et al. [84] have attempted to take advantage of these loss properties by designing an open-ended single mode cavity for the thermoplastic fiber placement process. In this process, a thermoplastic prepreg is consolidated in-situ as the composite is formed. Because the penetration depth is small, the microwaves are able to selectively heat and consolidate the top layer of the composite.

In carbon fiber composites, selective heating by microwaves can be seen. As carbon fibers selectively couple with microwaves, the fibers heat the resin in contact with the fibers through conduction. The result is increased mechanical properties of the material due to stronger bonding at the fiber/matrix interface [85]. Other researchers have also reported stronger bonding at the fiber/matrix interface for glass fiber composites [86].

Although the application of microwave heating to carbon–fiber composites may be limited in certain applications, the technological importance of microwave heating to the processing of glass or organic fiber composites should not be overlooked. An interesting industrial application of microwave heating is seen in the manufacture of engineered wood products. In a similar process to microwave-assisted pultrusion [26], strips of wood combined with a phenolic thermoset resin are pulled through a die and cured using microwaves. This process is used to produce thick beams for structural applications. It was shown that the thickness of Parallam™ beams, from MacMillan Blodel Research, is limited to 2 in. (5 cm) when formed with traditional processing techniques [87]. The microwave system, however, is able to uniformly heat and cure beams that are 12 in. thick (30 cm).

In microwave processing, thermal gradients and processing times can be reduced through the volumetric deposition of energy. Because heat generation due to microwaves is instantaneous, controlling the microwave field allowing heat from the exothermic reaction to dissipate to the unheated cavity can minimize the internal temperature overshoot. In addition, the thermal lag during the ramp segment of the cure cycle can be eliminated by volumetric heating. Jow et al. [88] and Thostenson and Chou [89] have demonstrated the ability to minimize the temperature overshoot due to the exothermic heat generation through computer controlled feedback. The elimination of the thermal lag results in better control over the spatial solidification within the composite laminate [90,91].

As a result of the significant potential of microwave heating to the processing of polymeric composites, researchers have utilized different microwave cavities for producing composites and applied microwaves to a variety of composites manufacturing processes. Wei et al. [71] have investigated the microwave heating of thick-section composites in single mode cavities and Thostenson [89] has experimentally investigated microwave curing of thick-section composites in a large multi-mode cavity. In addition, Boey et al. [92–94] have designed a traveling wave applicator to fit inside a traditional autoclave so they can experimentally investigate and control high pressure microwave curing. In addition to autoclave processing, microwave-assisted manufacturing of composites has been applied to resin transfer molding [89], pultrusion [29,83], and fiber placement [84].

7. Conclusions

Microwave processing is a relatively new development in materials processing. The ability of microwaves to couple energy directly to the material is the primary advantage of microwave processing as compared to conventional techniques. The volumetric heating ability of microwaves allows for more rapid, uniform heating, decreased processing time, and often enhanced material properties. The application of microwave heating to the manufacturing of ceramic and polymeric materials has the potential to improve the quality and reduce manufacturing costs.

Understanding the electromagnetic fields, microwave/material interaction, material transformations, and heat transfer is essential for optimizing the process. There have been many reported microwave effects related to both processing of ceramic and polymeric composites, and there continues to be debate as to the existence of these ‘‘effects’’. Clearly, the application of microwave and radio frequencies for processing of materials can have advantages over traditional heat transfer. In the past decade there has been significant advancement in the understanding of microwaves for the processing of materials, but more research must be conducted to have a full understanding of the process.

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