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ORIGINAL ARTICLE

Curing multidirectional carbon fiber reinforced polymer composites with indirect microwave heating

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Abstract

Microwave curing technologies have many advantages in manufacturing fiber reinforced polymer composite materials used in aerospace products, compared with traditional autoclave curing technologies. However, multidirectional carbon fiber reinforced polymer composites can hardly be penetrated and heated by microwave directly, which has become a major obstacle in industrial application worldwide. In this paper, an indirect microwave curing method was proposed to solve this problem. The microwave absorption performance of the indirect microwave heating medium was systematically optimized by evaluating its dielectric properties and reflection loss according to the transmission line theory. On this basis, the microwave susceptive mold was carefully designed and manufactured. Subsequently, the multidirectional carbon fiber/epoxy composite was successfully cured with indirect microwave heating, which was demonstrated by the observation of the curing process with infrared thermal imager and differential scanning calorimetry analysis of the final products. Compared with the traditional thermal curing method, the curing cycle and energy consumption were reduced by 42.1% and 75.9% respectively. Results of further characterization experiments indicated that the mechanical properties of indirect microwave cured specimens were slightly higher than those of the thermally cured counterparts.

Keywords Carbon fiber · Polymer matrix composites · Cure · Indirect microwave heating · Mechanical properties

1 Introduction

Carbon fiber reinforced polymer composites (CFRPs) with outstanding mechanical performance have been widely used in the aerospace industry [1–3]. So far, more than 98% aeronautical composites are fabricated using autoclave curing technology where the material is compacted in a closed tank and heated by the circulating airflow [4]. This heating mechanism directly leads to a series of problems in autoclave curing technology such as large temperature gradients in the thickness direction of composites, long curing cycle, and high energy consumption [5], which cannot meet the increasing demands of large quantity of high performance composite parts in modern aircrafts [6]. Under such circumstances, microwave curing technology has been considered as a very attractive alternative to autoclave curing technology in these years [7–9], due to its many intrinsic advantages such as fast heating and curing rates, volumetric and selective heating, precise temperature control, and so on [10–19].

Through a large number of experimental researches, the authors just found that multidirectional CFRPs can hardly be penetrated and heated by microwave directly. However, this kind of material, especially with a ply of [0°/+ 45°/− 45°/90°], is the most widely used composite (more than 95%) in aircrafts, according to an investigation in Chinese Aerospace Industry. The results of subsequently extensive literature survey indicated that several other scientists also mentioned this problem. In 1984, Lee and Springer reported that microwave would only be able to process relatively thin unidirectional carbon fiber composites, while multidirectional CFRPs cannot be cured effectively by microwave [20]. In 1996, the OAK Ridge National Laboratory pointed out in a report that the multidirectional CFRPs could not be directly processed by both the fixed (2.45 GHz) and variable (2.5~17.5) frequency microwave [21]. In 1999, Thostenson and Chou reviewed the microwave processing technology and indicated that

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the application of microwave to process multidirectional CFRPs was limited due to the high dielectric loss of carbon fibers [22].

In order to realize an effective microwave curing process for multidirectional CFRPs, the indirect microwave heating was applied in the present work. This idea was derived from the microwave processing of some materials with poor dielectric properties. In 2003, Potente et al. [23] formed plastics using indirect microwave welding. In 2006, Seyrankaya and Ozalp [24] investigated the dehydration of sodium carbonate monohydrate in a microwave field with silicon carbide as an indirect heating medium. In 2007, Grossin et al. [25] and Nanthakumar et al. [26] reported the sintering of compounds and pyrite with indirect microwave heating. In 2012, the indirect microwave heating was optimized to achieve the dehydration of pharmaceutical excipients with Pyrex glass as an indirect heating medium by Cuevas et al. [27]. In 2013, indirect and direct microwave regenerations were assessed as potential techniques for desorbing a CO_2/CH_4 mixture from Na-ETS-10 [28]. Indirect microwave regeneration consists of desorption with water followed by microwave drying, while direct microwave regeneration consists of constant power microwave heating. In the same year, Heuguet et al. [29] also reported the sintering of alumina using indirect microwave heating. In 2015, Nasybullin et al. [30] studied the implementation of non-absorbent polymers thermal destruction initiated by indirect heating in an intense electromagnetic microwave field using carbon thermal conversion elements. In 2016, Rao [31] studied the vacuum-assisted microwave curing process of glass-epoxy composite laminates, and used the silica-based microwave susceptive mold to improve the electromagnetic energy absorption. In the same year, Veronesi et al. [32] also researched the microwave sintering process of high entropy alloys in presence of a SiC auxiliary absorber. As mentioned above, these works laid the foundation of indirect microwave heating, but to the best of the authors' knowledge, no research has been found regarding the use of indirect microwave heating to cure multidirectional CFRPs, and thus no research on the optimization of relevant indirect heating medium and design of associated microwave susceptive mold.

The aim of this paper is to propose an indirect microwave curing method to process the multidirectional CFRPs with high efficiency and energy-saving purpose, and on this basis, to optimize the relevant indirect heating medium and design the associated microwave susceptive mold. Specifically, the indirect heating medium was fabricated by a vacuum-assisted resin infusion (VARI) process using short carbon fiber felt and epoxy resin, since it has a close coefficient of thermal expansion with the multidirectional CFRPs. In order to obtain an optimal performance on microwave absorption and thermal conversion, the length and fiber volume fraction of the short carbon fiber as well as the thickness of the indirect heating medium were systematically optimized according to the transmission line theory. On this basis, the microwave susceptive mold was designed and manufactured. Subsequently, one kind of carbon fiber epoxy composite was successfully cured with indirect microwave heating and its mechanical properties were further investigated according to the ASTM standards.

2 Experiment

2.1 Preparation of indirect heating medium

Short carbon fiber reinforced epoxy composite was used to fabricate the indirect heating medium, due to its good microwave absorption, high fatigue resistance, and similar thermal expansion with the multidirectional CFRPs. The indirect heating medium was made by the VARI process using short carbon fiber felt and epoxy resin. In order to obtain the best efficiency in energy conversion and heat transfer, the length of the short carbon fiber was firstly determined by numerical simulation with HFSS, and then the fiber volume fraction of the short carbon fiber reinforce epoxy composite and the laminate thickness of the indirect heating medium were optimized by experiment. Therefore, two kinds of indirect heating mediums were prepared. One is the medium of different fiber volume fractions (20%, 30%, 40%, 50%, 60% and 70%) with the same thickness of 2 mm. The other is the medium of different laminate thicknesses (2 mm, 3 mm, 4 mm, 6 mm, 8 mm, 10 mm, 12 mm, 14 mm, 16 mm, 18 mm and 24 mm) with optimum fiber volume fraction.

2.2 Microwave absorption optimization of indirect heating medium

The complex permittivity is an important parameter related to the microwave absorption of the short carbon fiber reinforced epoxy composite, which determines the ability of the material to dissipate microwave energy into heat. Hence, the complex permittivity of the prepared short carbon fiber reinforced epoxy composites with different fiber volume fractions were firstly measured by a vector network analyzer (E5071C, Agilent) based on the waveguide transmission line method [14]. In this approach, rectangular samples that fit into the dimensions of the waveguide (109.22 mm in width and 54.61 mm in height) were vertically placed in the center of the test-chamber. The working frequency of the chamber is distributed from 1.72 GHz to 2.61 GHz. By measuring the scattering parameters (S_{11} and S_{12}), the complex permittivity of the composite can be determined accurately. After the permittivity measurement, the composite with the optimal microwave absorption properties was selected as the material to fabricate the indirect heating medium.

When the material is determined, another significant factor that can affect the microwave absorption ability of the indirect heating medium is the laminate thickness. As illustrated in

Fig. 1, the reflection loss (RL), a parameter to reflect the microwave absorption, of indirect heating mediums with different laminate thicknesses was measured on a metal backplane. The value of RL is calculated by Eq. (1) [33].

$$RL(dB) = 20\log|(Z_{in}-1)/(Z_{in}+1)| \tag{1}$$

Here, Z_{in} is the normalized input impedance of the indirect heating medium, and can be expressed as Eq. (2) [33].

$$Z_{in} = \sqrt{\mu_r/\varepsilon_r}\tanh\left[-j(2\pi fd/c)\sqrt{\mu_r/\varepsilon_r}\right] \tag{2}$$

where μ_r and ε_r are the relative complex permeability and permittivity of the indirect heating medium, f is the microwave frequency, d is the thickness of the indirect heating medium, and c is the light velocity in vacuum. For this case, d has different thicknesses (2 mm, 3 mm, 4 mm, 6 mm, 8 mm, 10 mm, 12 mm, 14 mm, 16 mm, 18 mm and 24 mm) and μ_r could be taken as 1 due to the weak magnetic property of short carbon fiber reinforced epoxy composite. After the indirect heating medium was optimized, the structure of the microwave susceptive mold was further designed.

2.3 Fabrication of multidirectional CFRPs

The material used in the present experiment was the USN 05400 carbon fiber reinforced epoxy prepreg (WeiHai GuangWei Composites Co., Ltd.) with a thickness of about 0.125 mm per layer. This kind of material is typically used for the production of some high performance composite parts in the aircraft. The ply of the composite laminate was [0°/+ 45°/ − 45°/90°] which was prepared by a manual lay-up process. The length and width of the composite laminate were about 300 and 200 mm respectively, while the thickness of the laminate was 2 mm for various mechanical tests.

In order to validate the effectiveness of the indirect microwave curing process, two curing procedures were carried out. The first one was the traditional thermal curing which was conducted in a conventional thermal oven (Shanghai Boxun Co., China). The curing schedule was set at 120 °C for 90 min with a heating rate of 1 °C/min and a natural cooling process. The vacuum was kept at −0.098 MPa throughout the curing process. All the process parameters were recommended by the supplier who proclaimed that this curing process can assure the optimal mechanical performance of the material.

For the indirect microwave curing, a vacuum bagging system was used to prepare the multidirectional CFRPs. As shown in Fig. 2, the composite laminate was sandwiched between two identical indirect heating mediums, which were used to convert microwave energy into heat. Aluminum foils were sealed along the edges of the laminate to curb the potential arcing problem of the carbon fibers under the strong microwave irradiation. Nonporous isolation films placed between the CFRP laminate and indirect heating medium were used to avoid resin adhesion, while the upper porous isolation film was to let the excess resin be absorbed by the bleeder cloth. The glass fiber cloth on the outside of the indirect heating medium was used to reduce unnecessary heat loss to the surrounding environment, and the breather was adopted to ensure a uniform vacuum pressure. The vacuum bag was applied to enclose the whole setup with a sealing tape around the edges and a hose connected to a vacuum pump. The polytetrafluoroethylene (PTFE) plate was used to support the whole system. Actually, for some real composite parts with large size, it may be much more convenient by just using one indirect heating medium as the mold surface directly. Further in-depth research is to be conducted on the author’s on-going research work. After the composite was well packaged, it was placed in a microwave oven for curing. Compared with the heat conduction by hot airflow in the thermal curing process, the heat transfer efficiency between the indirect heating medium and the CFRP laminate was improved significantly, since microwave travels at the speed of light and heats the susceptive molds instantaneously, and the indirect heating medium also has a much higher thermal conductivity than air. For the purpose of making full use of these advantages in time and energy consumption, the same temperature dwells of 90 min at 120 °C with a higher ramp-up rate of 5 °C/min was adopted, followed by a natural cooling process. The equipment used in this process is a high performance octahedron microwave oven, which was designed and manufactured by the authors’ research team [17]. It has 16 independent microwave sources operating at 2.45 GHz ± 50 MHz distributing uniformly around the cavity. This construction can guarantee a more even power distribution than a regular oven by multiple reflections and splitting. Both an infrared thermal imager and three fiber optic fluorescence sensors, two for indirect heating medium and one for composite laminate, were employed to

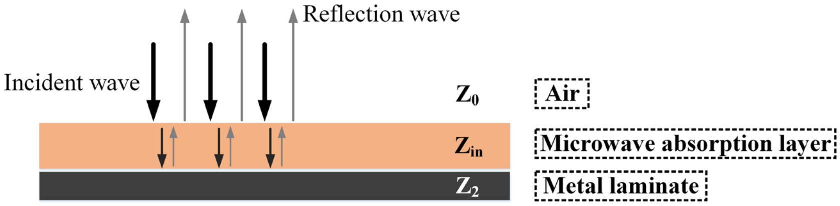
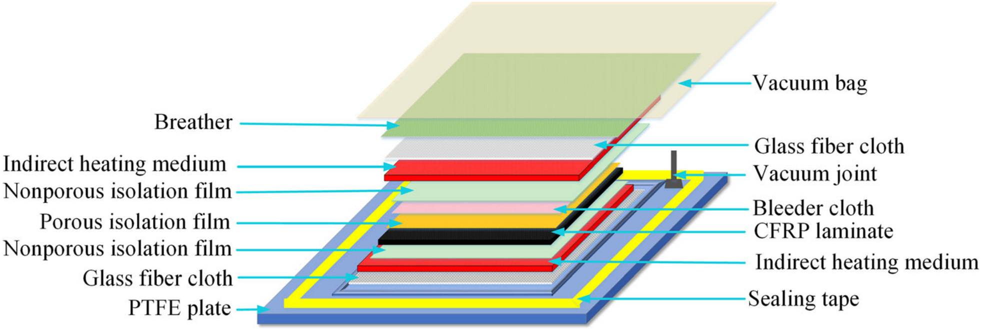


Fig. 1 Schematic model of absorber on the metal backplane

Fig. 2 Vacuum bagging system used in indirect microwave curing process



monitor the temperature of the indirect heating medium and composite laminate. The difference between the monitoring temperature and setting temperature of the composite was used to control the microwave power in real time.

2.4 Differential scanning calorimetry

Differential scanning calorimetry (DSC) analysis was carried out using NETZSCH 204F1 to determine whether the multidirectional CFRPs had been completely cured. During the test, the sample with the weight in the range of 10~20 mg were sealed into aluminum hermetic DSC pans. Both the sample and reference compound were heated from 25 °C to 210 °C at a ramp rate of 5 °C/min under a nitrogen gas atmosphere at a constant flow of 70 mL/min. In order to improve the reliability of the test results, three samples from different portions of multidirectional carbon fiber/epoxy composite were selected and measured.

2.5 Mechanical tests

In order to investigate the effect of indirect microwave curing on the mechanical properties of multidirectional CFRPs, compressive strength and interlaminar shear strength (ILSS) of both thermally cured and indirect microwave cured specimens were tested on an MTS CMT7000 microcomputer-controlled electronic materials testing machine, in accordance with the ASTM standard D6641/D6641M [34] and D2344/D2344M [35] at room temperature. Five samples were tested for each process to improve the reliability of the experimental result.

3 Results and discussion

3.1 Design and optimization of microwave susceptive mold

The designed microwave susceptive mold was mainly composed by supporting structure, insulation layer, and indirect heating medium (see Fig. 2). Among them, the supporting structure was made by PTFE, considering its excellent microwave transparent property and good stiffness under a relatively high temperature. The insulation layer is mainly used to reduce the heat transfer between the indirect heating medium and its surrounding environment for energy saving. Based on this consideration, glass fiber cloth was selected to act as this role because of its good insulation property and high-temperature resistance. As for the indirect heating medium, its configuration directly relates to the efficiency of the indirect microwave curing process, so it has been systematically designed to obtain a good microwave absorption performance from the following three aspects, i.e., the length and volume fraction of short carbon fiber, as well as the thickness of the indirect heating medium.

3.1.1 Determination of carbon fiber length for indirect heating medium

Since the electromagnetic characteristics of the carbon fiber have important influence on the microwave conversion, they were firstly investigated by the simulation in HFSS. The electromagnetic waves arriving at the carbon fiber can be equivalent to a uniform plane wave, so the linear polarization plane wave excitation was employed in the simulation. The direction of the electromagnetic wave was perpendicular to the fiber axis, and the direction of the electric field was parallel to the fiber axis. Since the carbon fiber is a kind of nonmagnetic material, only the electric characteristics were analyzed. Figure 3 is the simulation results of the carbon fiber with a length of 0.5 mm, 1 mm, 2 mm, 5 mm, 10 mm and 20 mm. The diameter of the carbon fiber was 0.7 μm. It can be observed that the strong electric field mainly concentrates on two ends of the fiber, like a dumbbell. The ratio between the length covered by electric field and the total length of carbon fiber is defined as the coverage of the electric field. As shown, the coverage of the electric field decreases from 87% to 38% when the carbon fiber length increases from 0.5 mm to 20 mm, while the average strength of the electric field increases from 8.32×10^3v/m to 1.13×10^5v/m at the same time. During the microwave curing process, the coverage of the electric field is related to the uniformity of the temperature distribution, and the strength of the electric field is related to the heating rate of the material.

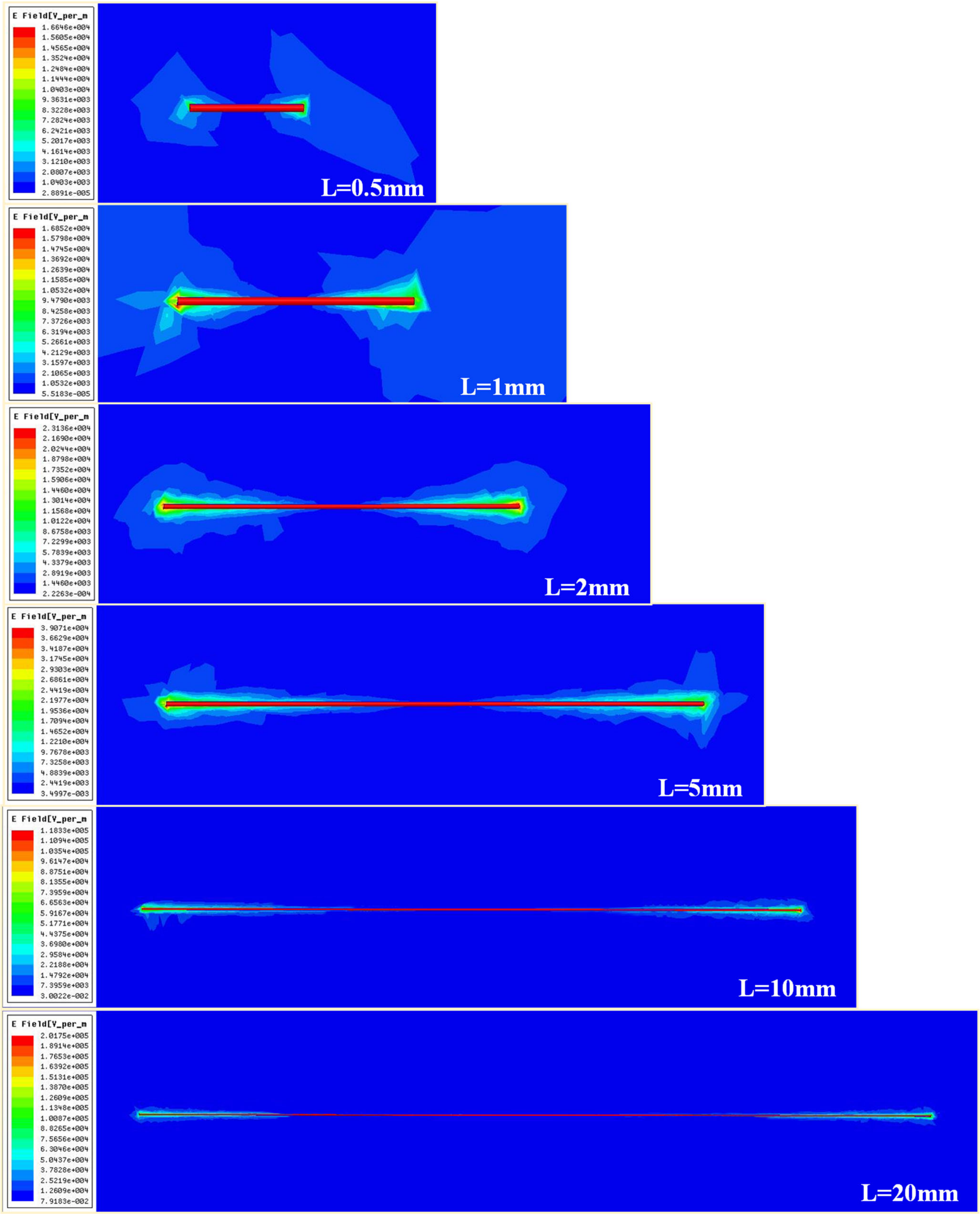


Fig. 3 Simulation results of the electric field distribution on the carbon fiber with various lengths

Therefore, both of the two parameters should be taken into account simultaneously to determine the length of the carbon fiber. As a consequence, the short carbon fiber with the length of 5 mm was finally used to fabricate the indirect heating medium.

3.1.2 Design of carbon fiber volume fraction for indirect heating medium

In the case of non-magnetic materials, the complex permittivity is an important parameter which describes the level of heat generation inside a microwave absorbent material. Hence, it has to be carefully designed. The complex permittivity of materials can be considered and defined by Eq. (3) [36].

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{3}$$

where the real part ε' (also known as dielectric constant) represents the ability of the material to store electrical energy in the material, and the imaginary part ε'' (also known as dielectric loss) is related to the amount of energy that can be dissipated into heat. The dielectric loss tangent tanδ is the ratio of the imaginary part ε'' to the real part ε', as described in Eq. (4) [36]. It is usually used to evaluate the wave absorbing properties of materials comprehensively.

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

During microwave heating process, the microwave power absorption density per unit volume of materials can be calculated as follows [36].

$$p = 2\pi f E^2 \varepsilon' \tan\delta \left(W/m^3\right) \tag{5}$$

where E is the strength the electric field.

The complex permittivity of a number of indirect heating mediums with different fiber volume fractions is presented in Fig. 4. As shown in Fig. 4a, the dielectric constant ε' of these mediums exhibits a complicated changing tendency when the frequency increases from 1.72 GHz to 2.61 GHz. At the fixed frequency of 2.45 GHz, the ε' values gradually increases from 122.87 to 268.23 when the fiber volume fraction of the indirect heating medium increases from 20% to 70%. This indicated that the carbon fiber, as a good conductor, has a strong ability in electric energy storage under the microwave irradiation. As the content of the carbon fiber increases, the storage capacity of the indirect heating medium improved rapidly due to its increased conductivity. Whereas, the reflection of the microwave also increased at the same time, and thus a lot of electromagnetic wave was reflected back, leading to a low microwave absorption of the material. The ε'' value represents the energy loss caused by the electric dipole moment rearrangement under electric field. As shown in Fig. 4b, the dielectric loss ε'' of these mediums also shows different changing tendencies in the frequency range of 1.72 GHz to 2.61 GHz. At the fixed frequency of 2.45 GHz, the ε'' values firstly increase from 46.55 to 350.38 when the fiber volume fraction increases from 20% to 50%, then decreases to 121.31 as the fiber volume fraction continues to increase. Therefore, it is concluded that the indirect heating medium obtained the excellent energy conversion ability with the fiber volume fraction of 50%.

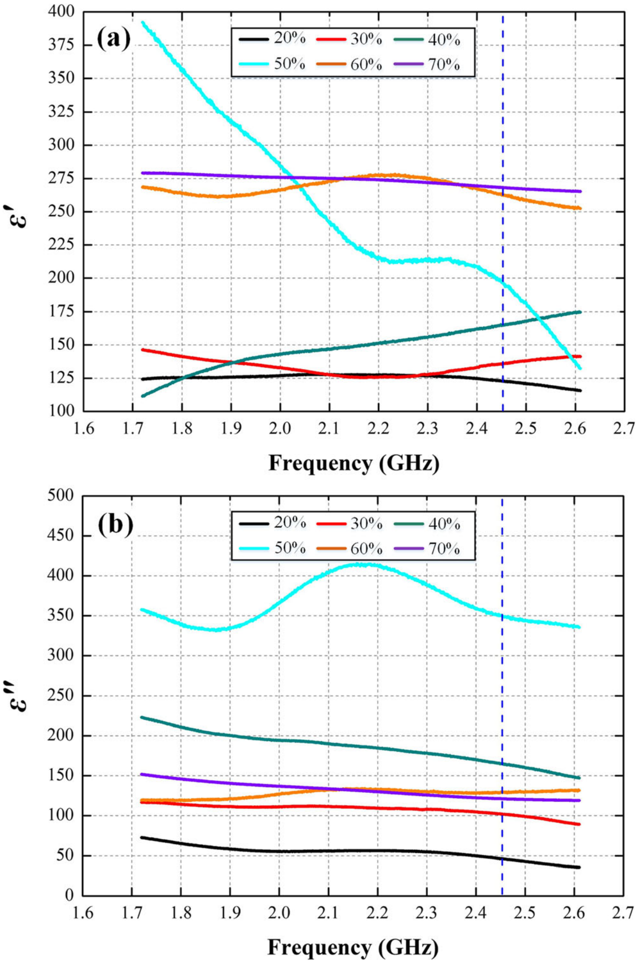


Fig. 4 Dielectric constant (**a**) and dielectric loss (**b**) of various indirect heating mediums with different fiber volume fraction

The dielectric loss tangent tanδ is another critical factor to evaluate the microwave absorption performance of an absorber. The higher the tangent value, the more electromagnetic wave energy can be converted to the other form of energy, mainly thermal energy. The tanδ values of these samples with different fiber contents are shown in Fig. 5, which presents a similar changing tendency with the dielectric loss ε'' at the fixed frequency 2.45 GHz. It can be seen that the dielectric loss tangent tanδ also obtains the maximum value of 1.78 when the fiber volume fraction is 50%. As mentioned above, it can be concluded that the fiber volume fraction does have a great impact on the microwave absorption performance of the indirect heating medium. A too high or too low value may

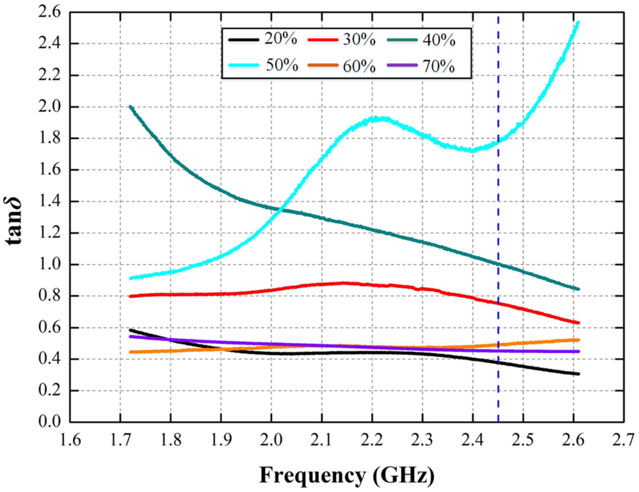


Fig. 5 Dielectric loss tangent of various indirect heating mediums with different fiber volume fraction

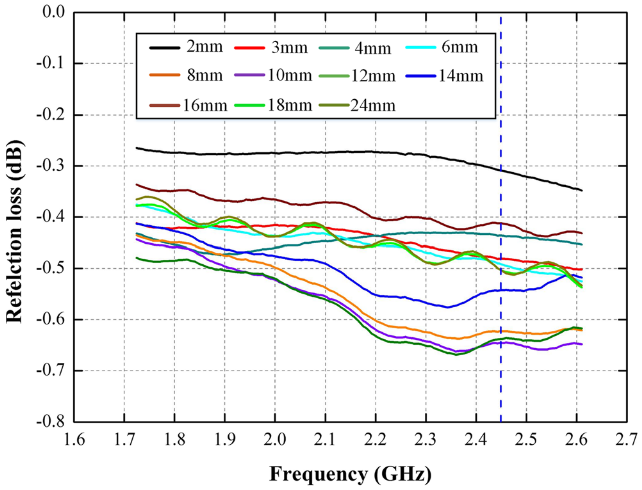


Fig. 6 Reflection loss of various indirect heating mediums with different thicknesses

bring adverse influence on the absorption of electromagnetic wave. As a result, the carbon fiber content of the indirect heating medium was determined as 50% to obtain an excellent microwave absorption.

3.1.3 Design of thickness for indirect heating medium

After the material of the indirect heating medium was determined, the only parameter that would influence the microwave absorption property is the thickness. The thickness of the indirect heating medium is directly related to the impedance matching condition of the microwave absorption. As known, the electromagnetic wave can be reflected from the material surface, absorbed by the material and/or transmitted through the material when it irradiates on the surface of an object. Among them, the reflection is related to the impedance mismatch between air and the object, the absorption is the energy dissipated by the object, while the transmission is the remaining part of the electromagnetic energy after reflection and absorption. In the current work, only the reflection part and absorption part were taken into account since the reflection loss of the indirect medium was measured on a metal backplane.

The value of the reflection loss in decibel directly represents the energy consumption in the medium, and was used to describe the microwave absorption of different indirect heating mediums. The reflection loss of various indirect heating mediums with different thicknesses at the frequency range of 1.72 GHz to 2.61 GHz are given in Fig. 6. Generally, the reflection loss of these indirect heating mediums increases with the microwave frequency. At the fixed frequency of 2.45 GHz, the reflection loss value firstly increases from − 0.31 dB to − 0.64 dB when the thickness increases from 2 mm to 10 mm, and then decreases to − 0.50 dB when the thickness further increases to 24 mm. This indicated that at the thickness range of 2~10 mm, the increase in medium thickness facilitated the microwave penetrating into the indirect heating medium, while a negative effect would be generated with the further increase in the thickness of the indirect heating medium. Thus, the indirect heating medium with a thickness of 10 mm was used to fabricate the microwave susceptive mold.

As mentioned above, the optimum indirect heating medium with the carbon fiber length of 5 mm, fiber volume fraction of 50%, and medium thickness of 10 mm was designed and manufactured. Subsequently, multidirectional CFRPs were cured by the designed microwave susceptive molds.

3.2 Effectiveness of indirect microwave curing method

The multidirectional CFRP laminate was cured using the designed microwave susceptive mold in the microwave cavity. The temperature distribution of the indirect heating medium was captured using an infrared thermal imager and controlled by a multi-pattern compensation method [37]. Figure 7 is the captured infrared thermal images at different curing stage, i.e., the temperature arrives at 50 °C, 80 °C, 100 °C, and 120 °C for 0 min, 120 °C for 30 min, and 120 °C for 60 min. As shown, the temperature distribution was slightly uneven at the initial curing stage, but it was significantly improved after dwelling at 120 °C for some time. This clearly indicated that the multidirectional CFRP laminate was effectively heated using the designed microwave susceptive mold.

After the curing process was completed, DSC analysis was performed on both of the thermally cured and indirect microwave cured multidirectional CFRP laminate. Corresponding results are shown in Fig. 8. As shown, no apparent exothermal peak can be observed in the diagram, which implies that both

Fig. 7 Infrared thermal images at different indirect microwave curing stages

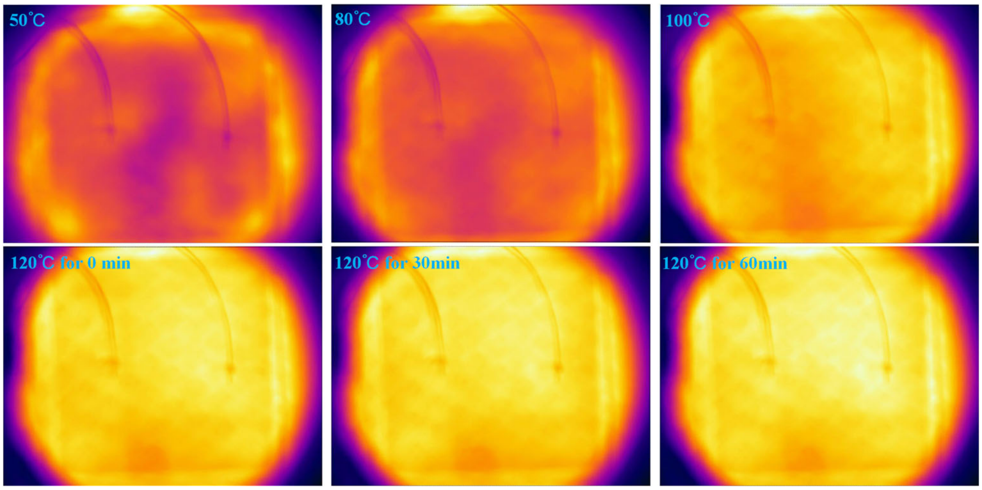


Fig. 8 DSC profiles of the thermally cured and indirect microwave cured multidirectional carbon fiber/epoxy composite samples

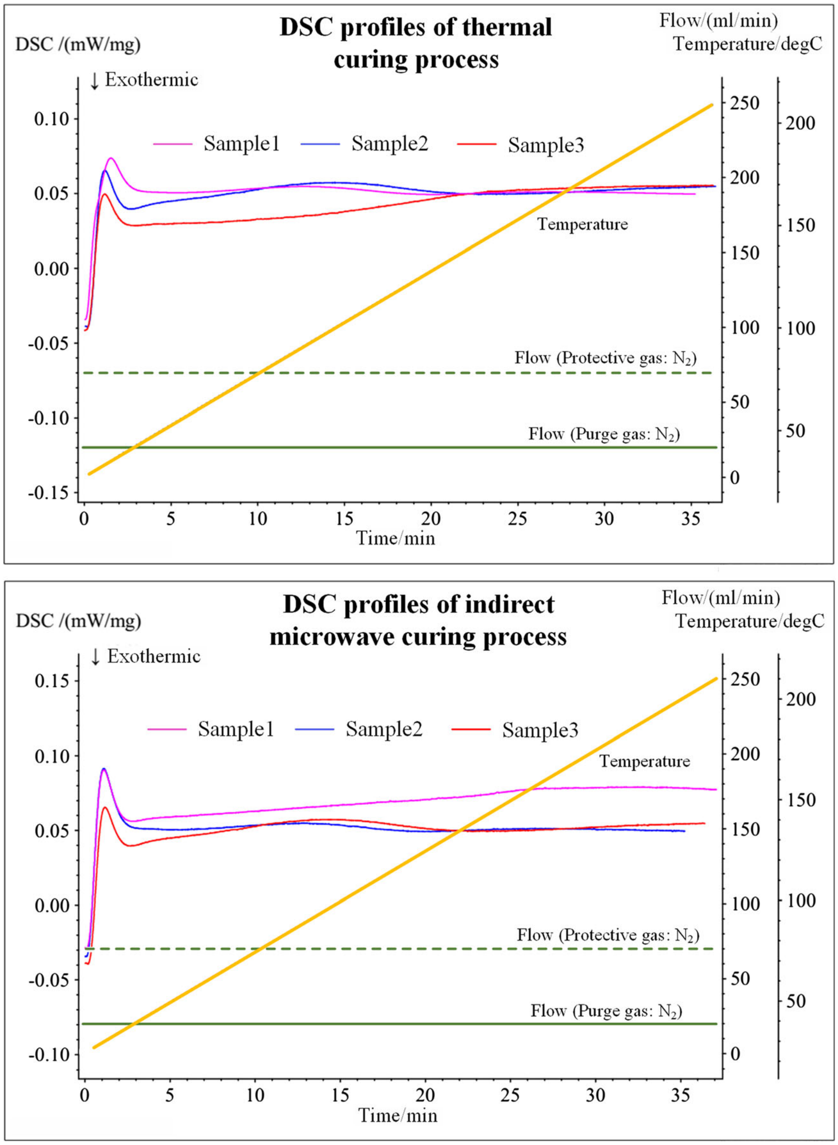


Table 1 Comparisons of curing cycle and energy consumption between the thermal curing process and indirect microwave curing process

Process	Thermal curing	Indirect microwave curing
Curing cycle	190 min	110 min
Energy consumption	9.06 kw·h	2.18 kw·h

the thermally cured and indirect microwave cured multidirectional CFRP laminate were fully cured and acceptable for subsequent experiments.

The curing cycle and energy consumption of the thermal curing process and indirect microwave curing process are summarized in Table 1. It can be seen that curing cycle and energy consumption of the indirect microwave curing process reduced by 42.1% and 75.9% respectively, compared with the thermal curing process. This is because a much higher heating rate can be adopted during the indirect microwave curing process due to a smaller thermal inertia and lower operating power, as the heat does not need to travel a long distance from the heater to composite parts.

3.3 Mechanical properties of indirect microwave cured multidirectional CFRPs

After multidirectional CFRPs were completely cured, their mechanical properties including compressive strength and ILSS were investigated according to the ASTM standard. Photographs of the test configuration and corresponding results are shown in Fig. 9. It can be observed that in both two tests, the load tends to increase linearly with the displacement in the first stage, then the ramp rate decreases gradually when it approaches the yield point, and finally a sharp drop appears because of complete damage. Because there is some difference in sample size, the peak force of several samples in the same group varies slightly within a certain range. Based on these load-displacement curves, the compressive strength and ILSS of the thermally cured and indirect microwave cured

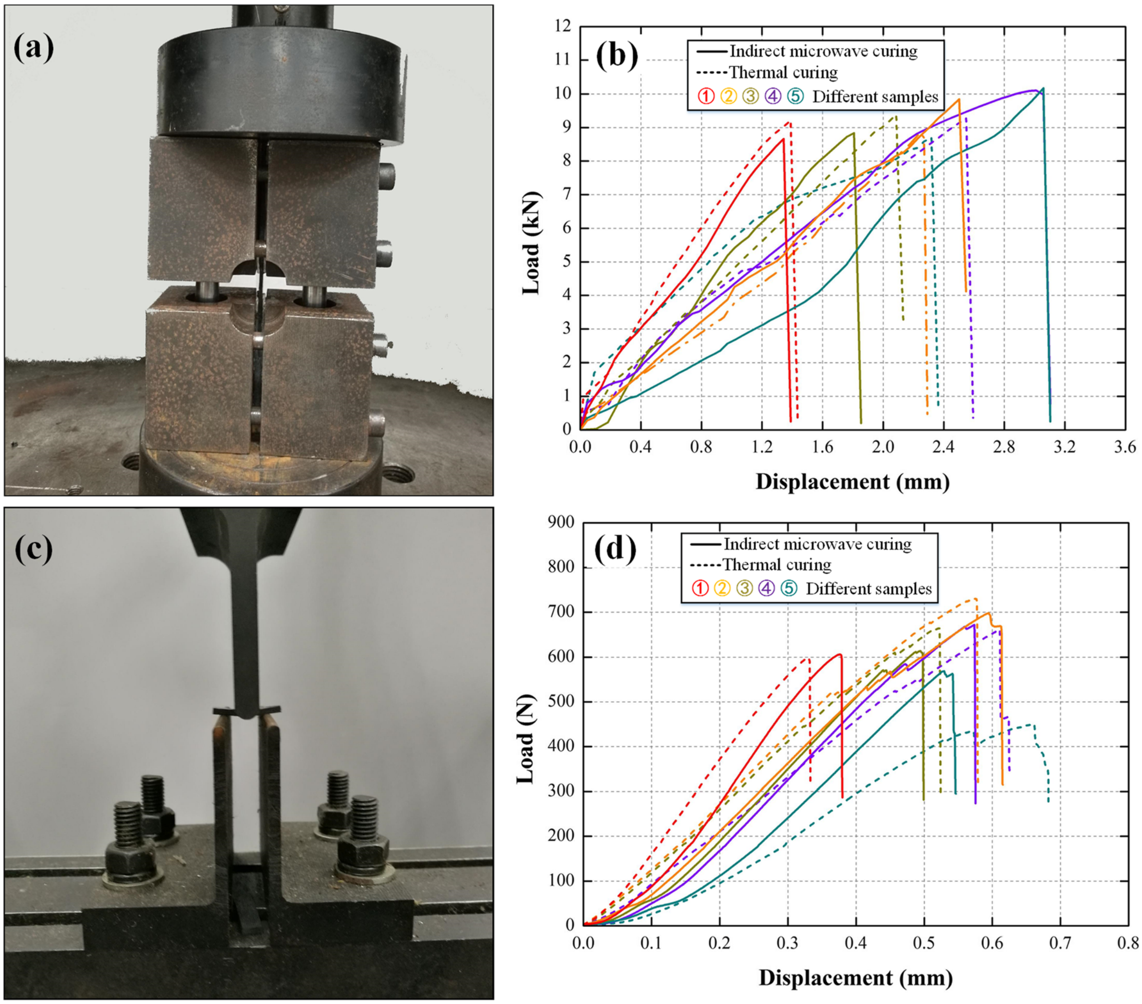


Fig. 9 Photograph (**a**) and test results (**b**) of the compressive test of the multidirectional carbon fiber/epoxy composite. Photograph (**c**) and test results (**d**) of the ILSS test of the multidirectional carbon fiber/epoxy composite

Table 2 Mechanical properties of the thermally cured and indirect microwave cured multidirectional carbon fiber/epoxy composite

Mechanical properties	Process	Strength (MPa)						
		1	2	3	4	5	Average	SD
Compressive	TC	396.07	398.86	410.97	414.39	392.75	402.61	8.52
	IMC	431.60	383.03	437.10	401.74	456.35	421.96	26.19
ILSS	TC	32.47	49.63	52.68	53.79	44.96	46.71	7.75
	IMC	48.64	52.61	45.30	56.61	47.31	50.09	4.04

TC, thermal curing; *IMC*, indirect microwave curing; *SD*, standard deviation

specimens were calculated and summarized in Table 2. As shown, both of the compressive strength and ILSS of the indirect microwave cured specimens are little higher than those of the thermally cured ones, which brings an improvement of about 4.8% and 7.2% respectively. This may be ascribed to a better compaction effect caused by the hard indirect heating medium at the upper surface of the composite, just like a pressure equalizing plate. As mentioned above, the feasibility of the indirect microwave curing method for multidirectional CFRPs has been demonstrated.

4 Conclusions

In this paper, an indirect microwave curing method was proposed to cure the multidirectional CFRPs. The microwave susceptive mold was carefully designed to have supporting structure, insulation layer, and indirect heating medium. Among them, the indirect heating medium is the most important part regarding to the curing efficiency, so it has been systematically optimized to obtain the best microwave absorption performance with a reflection loss value of − 0.64 dB. The optimum indirect microwave heating medium has the carbon fiber length of 5 mm, fiber volume fraction of 50%, and medium thickness of 10 mm. On this basis, one kind of multidirectional carbon fiber/epoxy composite was successfully cured by this method. The cure cycle and energy consumption of the indirect microwave curing process were only 57.9% and 24.1% of the traditional thermal curing method. Experimental results of mechanical tests indicated that both the compressive strength and ILSS of indirect microwave cured specimens were 4.8% and 7.2% higher than those of the thermally cured ones, which may be ascribed to a better compaction effect caused by the hard indirect heating medium at the upper surface of the composite, just like a pressure equalizing plate.

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