Composite Structures 200 (2018) 371–379

Contents lists available at ScienceDirect

Composite Structures

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

Characterization and analysis of the thermal damages of aramid/epoxy composite laminates induced by the dielectric heating effect of microwaves

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ARTICLE INFO

Keywords:
Aramid fiber
Anisotropy
Thermal damage
Electrical properties

ABSTRACT

Aramid/epoxy composite is one of the most promising materials for fabricating wave-transmitting structural components due to its excellent dielectric and mechanical properties. The temperature field of a composite can be greatly influenced by the dielectric heating effect when exposed to electromagnetic environments. In this investigation, the composites were subjected to microwave radiation of different power densities. The equilibrium temperature, power thresholds and damage morphologies of quasi-isotropic laminates were compared with that of unidirectional composites. Following this, the mechanism of different responses to microwave radiations were analyzed. The obtained results indicate that for the same thickness the quasi-isotropic laminates have better resistance to microwave radiation as compared to unidirectional composites. Besides, the unidirectional composites tend to form oval-shaped damaged regions while the quasi-isotropic laminates form almost circular regions. Furthermore, at about 200 °C, the composites had a sudden increase in temperature that lead to thermal damage.

1. Introduction

In recent years, the research investigations focusing towards the fiber reinforced composite for fabricating wave-transmitting structural components such as radomes and vertical tails are increasing, owing to the advantages of lightweight, broadband, and low-cost processing [1,2]. Particularly, aramid/epoxy composites have been found to be the best candidates for wave-transmitting materials because of their low density, high-temperature resistance, excellent dielectric and better mechanical properties [3–8].

Generally, for the resin matrix composites, the energy loss of the microwaves is mainly caused by the dipole relaxation. The dipoles of the composite were polarized when exposed to high frequency alternating electric fields, and the polarisation degree changes with the applied electric fields [9,10]. Meanwhile, the dipoles rub against each other during the iterative polarization processes, and a part of the energy of microwaves transformed into heat through the interactions between the dipoles. The heat generated by the composite in the above process can be calculated by using the following Eq. (1):

$$P = 2\pi f E^2 \varepsilon_0 \varepsilon'' \quad (1)$$

where f is the frequency of the microwave source, E is the electric field strength, ε_0 is the permittivity of vacuum and ε'' is the imaginary part of the complex permittivity of the composite. The thermal interactions of microwave radiation have been well applied to a range of fields in the material science such as chemical reactions and the curing process of resin [11–13]. However, both the dielectric loss and the thermal conductivity of the composite could be influenced by the temperature remarkably [14,15]. The above changes will in turn increase the rate of heat generation and hinder the heat transfer of the composite and consequently accelerate the damage process of the composite.

Meanwhile, the electronic warfare involving advanced technologies is developing as a mainstream in the modern military, and electronic countermeasure which is predominantly driven by the performance of radar in it [16–19]. In such situations, radomes always work under high power microwave radiations since the power intensities of a single radar demonstrated significantly upwards, where the radiation power of the whole array antenna could achieve several kilowatts [20,21]. Therefore, the thermal damages and degradation in the performance of wave-transmitting composites have already turn out to be the critical factors in the engineering applications when exposed to electromagnetic environments. Unfortunately, only a limited number of studies have reported on the influence of variations in the temperature fields and thermal damages of the cured composites induced by

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https://doi.org/10.1016/j.compstruct.2018.05.092
Received 26 February 2018; Received in revised form 11 May 2018; Accepted 18 May 2018
0263-8223/

Table 1
The microwave radiation testing specimen.

Category	Quantity	Thickness	Thickness tolerance	Lay-up
I	5	1 mm	± 0.10 mm	$[0]_8$
II	5	1 mm	± 0.10 mm	$[45/0/-45/90]_s$
III	5	2 mm	± 0.12 mm	$[0]_{16}$
IV	5	2 mm	± 0.12 mm	$[45/0/-45/90]_{2s}$
V	5	3 mm	± 0.15 mm	$[0]_{24}$
VI	5	3 mm	± 0.15 mm	$[45/0/-45/90]_{3s}$

microwave radiations during their life-cycle. Thus, the focus of this investigation is on the thermal behavior and to determine the damage tolerance of aramid/epoxy composites induced by the heating effect of microwaves.

In this study, the complex permittivity and thermal diffusivity of aramid/epoxy laminates were measured from 30 °C to 250 °C. A microwave radiation system with an adjustable power output has been established, besides verifying the stability and repeatability of the system. The aramid/epoxy composites were radiated at different power densities and the determined equilibrium temperature, surface morphologies and power thresholds of unidirectional laminates were compared with quasi-isotropic laminates. The mechanism regarding different responses between the two laminates to microwave radiations has been analyzed. The differences in the damage of the composite specimens in the thickness direction were observed. In addition, the temperature history of the composites during the damage processes were continuously monitored using thermocouple wires.

2. Experiments

2.1. Preparation of the composite specimen

The unidirectional and quasi-isotropic laminates were fabricated by the autoclave vacuum bag molding process using the unidirectional aramid/epoxy prepreg (Aviation Industry Corporation of China, Beijing, China). The thickness of the prepreg is 0.125 mm and the fiber volume fraction is 62.8%. The composites were cured at 130 °C for 1 h prior to a post-curing process which was carried out at 180 °C for 3 h. Meanwhile, a vacuum and a pressure of 0.7 MPa were applied to the vacuum bag. Before curing the metal molds were placed on the top of the prepregs to obtain smooth flat surfaces. The type and the quantity of specimens employed for the microwave radiation experiments are listed in Table 1. In addition, before the curing process, the thermocouple wires were laid at the center of the composite in the thickness direction.

2.2. Dielectric property test

The composite laminates were machined to the size of 22.86 mm × 10.16 mm using a waterjet cutting. The dielectric property tests were carried out on a vector network analyzer (CETC AV3672B) using the rectangular waveguide method. In order to measure the dielectric properties of the composites at different temperatures, the rectangular waveguide fixture was equipped with an inner heater and temperature control units. The composite specimens were measured from 30 °C to 250 °C at 10 °C/min and 20 min was required to reach the thermal equilibrium at each of the measurement temperature. Considering that the angle between the fiber direction and the electric vectors can strongly affect the dielectric properties of the unidirectional composites, the relative complex permittivity of the unidirectional composites was measured by considering the fiber to electric vector in

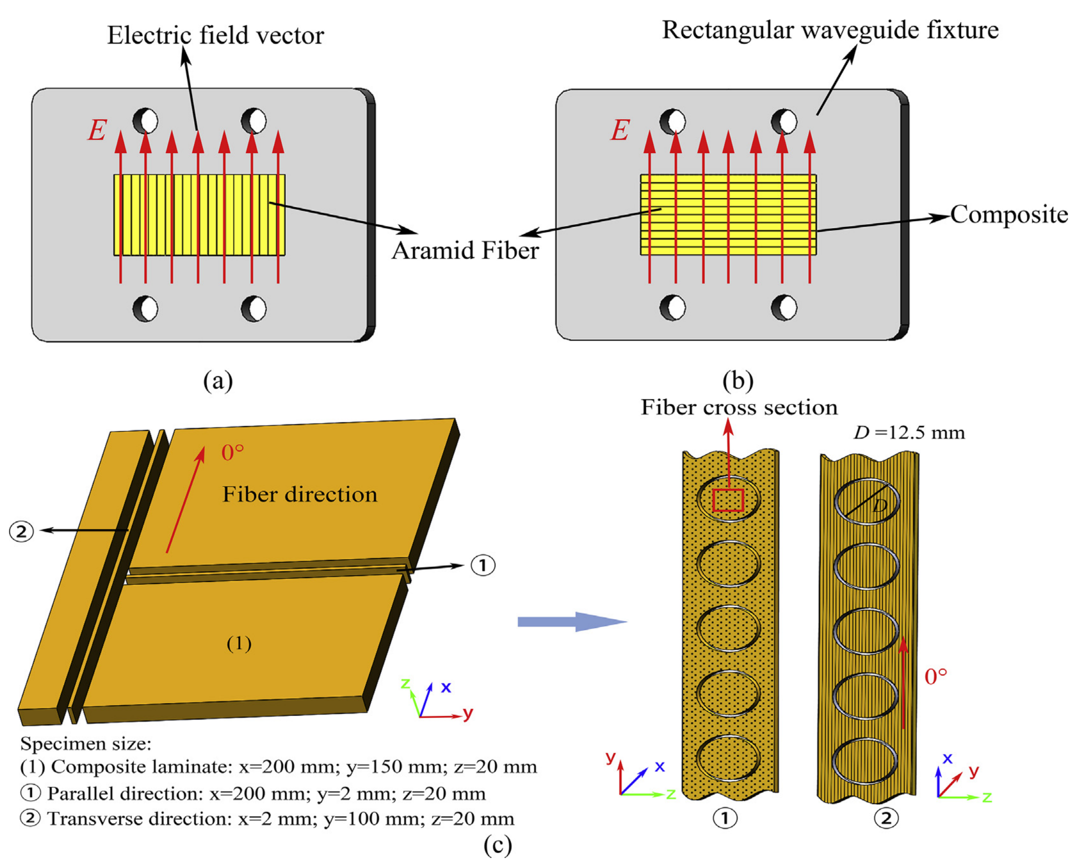

Fig. 1. The sketch of the unidirectional specimens: (a) parallel distribution in the dielectric measurement; (b) perpendicular distribution in the dielectric measurement and (c) the thermal test specimens.