Composite Structures xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Composite Structures

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

Characteristics of silicon carbide fiber-reinforced composite for microwave absorbing structures

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ARTICLE INFO

Keywords:
Microwave-absorbing structure
Semi-conductive fiber
Silicon carbide fiber
Composite material
Complex permittivity

ABSTRACT

A microwave-absorbing structure is a multifunctional composite composed of lossy materials, to obtain optimal electromagnetic properties combined with structural load-bearing capability. Microwave energy-loss properties can be obtained by modifying the matrix with a lossy filler, or by using a reinforcing fiber with lossy characteristics. The silicon carbide fiber is a conventional semi-conductive fiber that can cause microwave-energy loss, and can comprise a composite material by using a general resin system without lossy additives. This study investigated the mechanical and electromagnetic properties of SiC/epoxy composites, and the performance of microwave-absorbing structures composed of the SiC/epoxy. The fiber volume fraction and tensile properties of a SiC/epoxy composite cured at 6.0 bar were measured. Electromagnetic properties of SiC/epoxy composites cured at different pressures from 7.0 bar to 3.5 bar were measured in addition. Single-slab and multi-slab absorbers were fabricated, and their performance was evaluated. The −10-dB bandwidth and the minimum return loss of the four-slab absorber were 3.4 GHz and −31.0 dB, respectively.

An analysis of the SiC/epoxy-composite characteristics indicated that it had excellent workability and mechanical-property advantages, although the performance of the SiC/epoxy microwave absorber was ordinary.

1. Introduction

With the dissemination of radio technologies, the necessity for microwave absorbers has been on the rise as a countermeasure and a medium for a safe radio environment. Many studies have been conducted on efficient microwave absorbers in the fields of electromagnetic interference and stealth technologies, because it is possible to absorb scattered electromagnetic waves to improve the performance of an electronic device, or conceal an object from a radar system.

Microwave absorbers can be classified according to various design principles. Vinoy and Jha classified microwave absorbers as either graded-interface or resonant types, depending on the method of energy absorption [1]. The graded-interface type absorber, represented by a pyramid, attenuates electromagnetic-wave energy gradually. It is typically made from foam, including lossy materials such as carbon black and ferrites with a specific shape, to generate tapered loading that effectively attenuates microwaves. Therefore, the graded-interface type absorber requires a large volume, and is a non-structural absorber. The resonant-type absorber, however, resonates with the microwaves at a specific frequency to cause loss of microwave energy. Because it is designed as a thin plate, it can be applied to the surface of a structure. At the same time, there is a strict limit on the absorption bandwidth, because it is constrained by the permeability and thickness of the microwave absorber [2].

A microwave-absorbing material with lossy properties, represented by complex permittivity and permeability, is typically a composite material encompassing at least one kind of lossy inclusion. Depending on the organization of the lossy material, it can be classified as either matrix-control type or fiber-control type. The matrix-control type includes a lossy material in the matrix. The conventional method for fabricating such a material is to mix a lossy filler and matrix resin with a dispersion method, such as a stirrer or three-roll-mill, and cure the filler-mixed resin [3–7,13–16]. This method is advantageous for studying the change in electromagnetic properties as a function of the filler amount. Through such a study, it is possible to choose a composite material that has the most appropriate electromagnetic properties to design a microwave absorber [3]. However, quality control is an important issue for nanocomposites, since fabrication variables such as dispersion condition and curing pressure can lead to property instability [4]. Moreover, the resin experiences a drastic increase in viscosity during filler addition that adversely affects its workability, especially in the presence of reinforcing fibers [6]. This leads to relatively low fiber

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https://doi.org/10.1016/j.compstruct.2018.01.081
Received 3 January 2018; Accepted 22 January 2018

volume fraction in the case of fiber-reinforced composite fabrication with filler-added resin [7].

Shin and Song conducted studies on the characteristics of glass/CNT added epoxy for mass production. A prepreg with a resin content of 41.5% was prepared by the hot-melt method, and the composite was cured in an autoclave at 7.0 bar [7]. The fiber volume fraction of the glass/CNT added epoxy composite was 51%, while that of the pristine glass/epoxy was 63%. This implies that the high viscosity of the CNT-added resin interrupted the removal of surplus resin from the prepreg [7]. When the curing pressure was decreased to 3.5 bar, the composite showed a substantial change in electromagnetic properties, with a 9.5% decrease in the real part of the permittivity, and a 39.4% decrease in the imaginary part [5]. This is because the epoxy and CNT were removed in different proportions, leaving some part of the CNT during the surplus resin removal at the high autoclave-curing pressure. The increased CNT content results in percolation, which is the cause of a sharp increase in the electrical conductivity [5]. Due to the high sensitivity of electromagnetic properties to the manufacturing conditions, a small error in quality control can lead to a lack of uniformity in mass production.

There is limited research on the fiber-control type lossy materials, and previous studies on non-dielectric fiber have mainly focused on high electrical conductivity electromagnetic-interference shielding [8–10]. However, a few of studies on semi-conductive fibers have shown the possibility of designing a microwave absorber without extra filler [11,12]. When using a regular resin system as the fiber-control type for the microwave absorber, there are considerable advantages in composite fabrication if the fiber has coequal mechanical properties with the existing fibers.

Silicon carbide, a ceramic material, has been widely used for research on microwave absorbers, due to its semiconductive characteristics. SiC has been added to composites as a filler or a continuous fiber to absorb microwave energy [12–19]. Since the SiC fiber has excellent mechanical and electromagnetic properties, it is suitable for microwave-absorbing structures. Due to the oxidation resistance of the SiC-matrix, SiC_f/SiC composites are well suited for high-temperature applications [9,20–23]. Polymer-matrix composites reinforced with SiC fibers have also shown excellent performance in common structural applications.

This paper deals with characteristics of a silicon-carbide fiber-reinforced composite as a microwave absorber. The composite was fabricated by a hand lay-up process and an autoclave system. The fiber volume fraction and tensile properties, and the sensitivity of the SiC/epoxy-composite electromagnetic properties to the curing pressure, were evaluated. In addition, several microwave-absorbing structures were fabricated using two kinds of SiC fibers. The results showed that the semi-conductive fiber has excellent workability, and can serve as a replacement for the matrix-control type composite material.

2. Experimental

2.1. Specimen preparation

In this study, two kinds of dry-woven SiC fabrics, arbitrarily named A-SiC and B-SiC, and an epoxy-resin system, were employed for composite fabrication. The SiC fabrics (Ube Industries, Ltd., Japan) provide a wide range of electrical conductivity. Two such products, with semiconducting properties, were arbitrarily selected. YD-128 epoxy resin and TH-431 hardener (Kukdo Chemical, Korea) were used due to their suitable properties. The resin and hardener were mixed at a ratio of 10:6, and the mixture was exposed to vacuum for 1 h while being heated to 40 °C to suppress void generation. The fabrics were wetted with the mixed resin and stacked as laminated-composite designs. The composite was cured in an autoclave, with the layup sequence for a bagging operation depicted in Fig. 1, to remove the surplus resin. The autoclave-curing cycle was as shown in Fig. 2, while the curing pressure was deliberately varied from 3.5 bar to 7.0 bar.

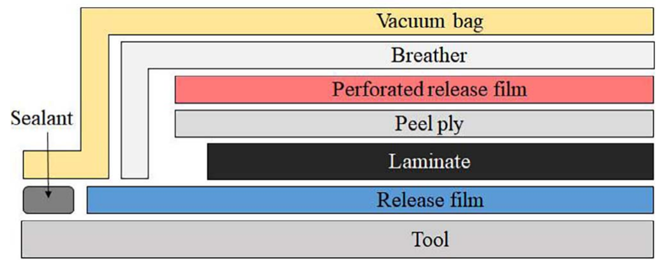

Fig. 1. Bagging layup sequence for autoclave curing.

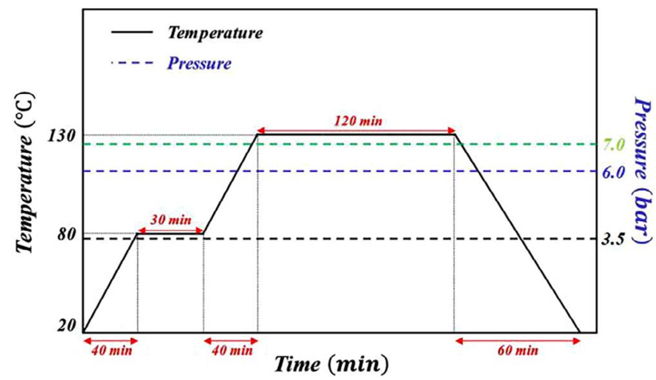

Fig. 2. Autoclave curing cycle.

The cured composite was cut to each specimen size: 10 mm × 10 mm and 2-mm-thick for fiber volume-fraction measurements, and 200 mm × 25 mm and 2-mm-thick for tensile testing. The specimen for measuring the electromagnetic properties was 180 mm × 200 mm and approximately 1.2 mm thick, although there were minor differences depending on the curing pressure.

2.2. Characterization methods

Characterization of the SiC/epoxy composite included fiber volume-fraction measurement, tensile testing, and electromagnetic-property evaluation. The fiber volume-fraction measurement was based on the muffle-furnace matrix burn-off method described in ASTM D3171. The epoxy matrix of the composite was burned off at 600 °C for 6 h, and the fiber volume fraction was calculated using the weight difference between the composite and the remaining balance. Tensile testing on the SiC/epoxy composite was conducted in accordance with ASTM D3039, with an Instron 4482 universal testing machine (Instron, USA). The tensile modulus was calculated using the test data between 1000$\mu\varepsilon$ and 3000$\mu\varepsilon$, and the tensile strength was calculated at the fracture point.

The electromagnetic properties of the composite were evaluated by an MMS free-space microwave measurement system (Sharp Hue, Inc., USA). The S-parameters measured by two port antennas were converted to the complex permittivity, while the permeability was assumed to be 1-j0, since SiC/epoxy is a nonmagnetic material. During evaluation of the microwave-absorber performance, only one of the two antennas was used, since the microwave absorber includes a reflector that prevents microwave transmission.

2.3. Microwave absorber design

A microwave-absorbing structure, composed of an absorber and a microwave reflector, can be depicted as a transmission line by the equivalent circuit model. The input impedance of the structure can be calculated using the transmission-line model, of which the details are described in a related study [7]. Since the absorption performance is maximized when the input impedance is equal to the intrinsic