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Cost-effective open microwave heating of polymer resin using interdigital electrode array film and dispersed carbon nanotubes

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ABSTRACT

Conventional microwave heating requires an expensive facility and its enclosed-type oven limits the size of curable products. This article proposes an open-type microwave heating of a polymer resin using microwaves produced by an interdigital electrode array film positioned between the composites and the mold. The proposed method has the advantages of reduced facility cost and applicability to large composite structures. The dispersion of carbon nanotubes (CNTs) in the resin also enables the use of a relatively low applied voltage for the heating. This is because the CNT-filled resin has a high dielectric loss tangent. The generated heat was observed to increase with the CNT content and a heating efficiency of 70% was achieved. It was particularly observed that a significant temperature increase occurred at 0.08 wt% CNT content owing to the electric percolation phenomenon. Moreover, selective microwave heating using an electrode array also enabled the achievement of a more inhomogeneous increase in temperature.

1. Introduction

Fiber-reinforced plastics (FRPs) are mainly used in aerospace engineering because of their high specific strength and stiffness. They are generally composed of thermosetting resins such as epoxy and unsaturated polyester, and the manufacturing process requires thermal curing. In conventional thermal curing using an oven or autoclave, thermal energy is transferred to the material through the atmosphere. A long cycle is therefore required for complete curing of the resin. Moreover, the massive thermal energy wastage of the process results in a negative heating efficiency. The speed and energy conservation of microwave heating has led to increased interest in it as an alternate curing method [1,2].

In microwave heating, a polymer resin in an electric field transduces electromagnetic energy into thermal energy through dielectric loss. The phenomenon of internal heating directly raises the overall temperature of the resin [3–7]. Papargyris et al. [5] combined microwave heating with the resin transfer molding technique to achieve 50% reduction in the cure cycle time. Zhou et al. [6] and Tanrattanakul and Jaroendee [7] compared the mechanical properties of epoxy composites cured by thermal heating and microwave heating, and found that the latter were as good as the former, and the curing time was also reduced.

Recent studies have investigated the dispersion of conductive fillers such as carbon nanotubes (CNTs) and carbon black (CB) in liquid resins, with the aim of improving the generated heat and cure cycle of microwave heating [8–10]. CNTs have been of particular interest owing to their high aspect ratio and low specific weight, and it has been shown that their unique structures facilitate enhanced mechanical and electrical properties [11–17]. Higginbotham et al. [8] showed that the microwave heating of CNT mixtures could be used to improve polymer processing through the shortening of the processing time and the consequent reduced production cost. Liu et al. [9] investigated the response of high-density polyethylene (HDPE)/CB composites to microwave heating and observed that the addition of CB particles improved the microwave heat-ability of HDPE, and that the heat-ability of the composites varied with the CB content. However, because conventional ovens and microwave heating equipment need to enclose the composite structures, they must be larger than the structures. High costs are therefore involved in the development of equipment for heating large structures, even though the actual microwave heating saves energy. Moreover, the inhomogeneous dielectric loss tangent of the carbon filler mixture may result in an inhomogeneous temperature increase during microwave heating [18]. Furthermore, the generated heat is difficult to anticipate and must be experimentally evaluated, which reduces production efficiency. These disadvantages pose serious challenges to the commercial development of FRP by microwave heating. There is therefore a compelling need for a new method of efficiently heating resins that does not require an expensive device.

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To meet this need, we propose a cost-effective open microwave heating method that utilizes a thin electrode array film and CNT-filled resin. The film is set only between the composites and the mold, thereby enabling the curing of large structures. Moreover, since the dispersion of CNTs in the resin increases both the dielectric loss tangent and the generated heat, expensive high-voltage equipment are not required. Moreover, selective heating by controlling the electrode array is used to resolve the inhomogeneous temperature increase that results from the dielectric loss tangent of the mixture. An equivalent electric circuit model of the open microwave heating was constructed and used to predict the generated heat. Furthermore, the magnitudes of the generated heat for various CNT contents were experimentally determined and compared.

2. Materials and methods

2.1. Multifunctional interdigital electrode array

The resin was heated using a multifunctional interdigital electrode array (MIEA) developed by the authors [19,20]. Fig. 1a shows the pattern of the copper electrodes and the wiring of the MIEA, which was fabricated by photolithography. The wiring was attached to the back of the polyimide film, which measured $200 \times 200 \times 0.013\ \text{mm}^3$ and was connected via a through-hole to the interdigital electrodes on the other side. The electrodes were aligned in a grid and the wires were divided into rows and columns. Wires 1, 2, ..., 5 were used to identify the longitudinal connections (the columns), and A, B, ..., E were used to identify the horizontal ones (the rows). Thus, there were 25 interdigital electrodes and 10 wires altogether, and the capacitive interdigital electrodes had input voltages of V+ and Ground. Fig. 1b shows the cross-section of the interdigital electrode and the CNT-filled resin. Because the positive and negative electrodes were arranged alternately, each electrode generated an electric field in the resin in conjunction with its neighbor electrodes.

2.2. Microwave heating of resin

The temperature of a resin can be raised by microwave heating using a MIEA. When a dielectric material such as a polyester resin is placed in the electric field, the dipoles of the resin align with the electric field, resulting in polarization. When the frequency of the electric field is much higher than the rotation of the dipole, movement is hindered, which results in frictional heating. The microwave heating value P of the resin is given by [19]

$$P = VI \cos\left(\frac{\pi}{2} - \delta\right) \tag{1}$$

where V is the voltage applied to the dielectric resin, I is the current flowing through the resin, and δ is the loss angle of the resin.

For the dielectric material, $\delta \ll 1$, hence,

$$P = VI \sin\delta \approx VI \tan\delta \tag{2}$$

where $\tan\delta$ is the dielectric loss tangent, which was approximately 0.01 at about 10 kHz for the unsaturated polyester resin [21].

The equivalent circuit of the MIEA was modeled by a resistor and capacitor in parallel. The electric current I that flows through the capacitor is

$$I = 2\pi fCV \tag{3}$$

where f is the frequency of the alternating voltage and C is the capacitance of the capacitor. By substituting Eq. (3) in Eq. (2), the heating value P can be rewritten using the applied voltage and the dielectric loss tangent of the resin as

$$P = 2\pi fCV^2 \tan\delta \tag{4}$$

It can be seen from the preceding equation that a higher voltage and dielectric loss tangent are required for a higher heating value at a given frequency. Pure polyester resin with a low $\tan\delta$ value of 0.01 requires a high voltage for sufficient heating value, which is the reason why conventional microwave heating requires

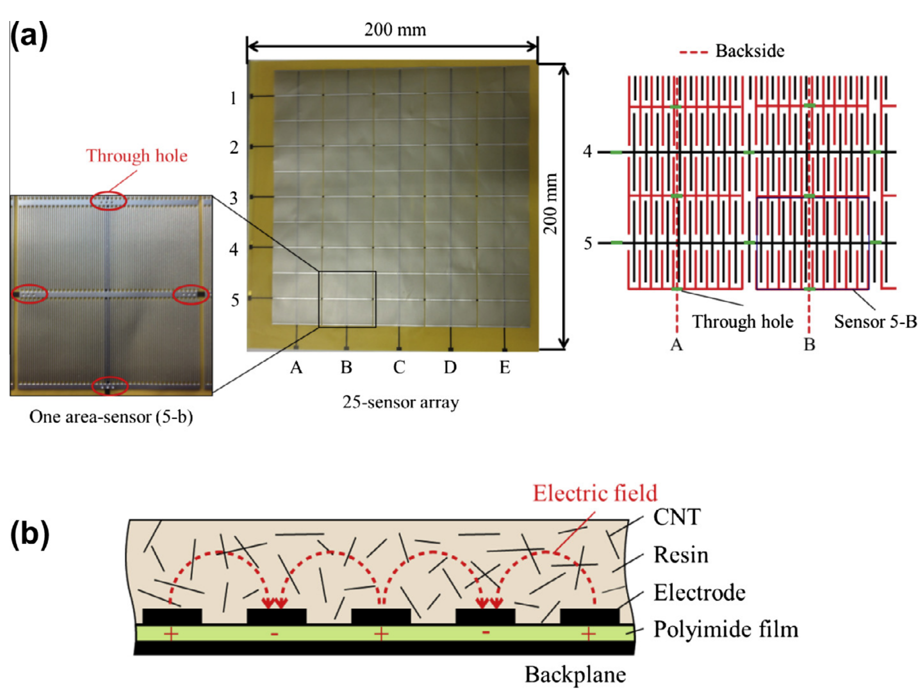

Fig. 1. Multifunctional interdigital electrode array (MIEA) film for resin heating: (a) Schematic and (b) cross-sectional view of interdigital electrode with CNT-filled resin.