Journal of Materials Processing Technology 214 (2014) 544–550

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Analysis and optimization of temperature distribution in carbon fiber reinforced composite materials during microwave curing process

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ARTICLE INFO

Article history:
Received 17 May 2013
Received in revised form 27 September 2013
Accepted 23 October 2013
Available online 31 October 2013

Keywords:
Microwave curing
Composite materials manufacturing
Temperature distribution
Optimization

ABSTRACT

Vacuum assisted microwave curing technologies and modified optical sensing systems have been employed to investigate the influence of ply orientation and thickness on through-thickness temperature distribution of carbon fiber reinforced composite laminates. Two different types of epoxy systems have been studied. The results demonstrated that the ply orientation did not affect the temperature distribution of composite materials. However, the thickness was an important influencing factor. Nearly 10 °C temperature difference was found in 22.5 mm thick laminates. Through analyzing the physical mechanisms during microwave curing, the temperature difference decreased when the heat-loss in surface laminates was reduced and the absorption of microwave energy in the center laminates was improved. The maximum temperature difference of the samples formed using the modified microwave curing technologies in this research could be reduced by 79% to 2.1 °C. Compared with the 5.29 °C temperature difference of laminates using thermal heating process, the maximum temperature difference in laminates using modified microwave curing technologies was reduced by 60%, and the curing time was cut down by 25%.

1. Introduction

Carbon fiber/epoxy composite materials with high mechanical strength, light weight and excellent high-temperature characteristics have gained substantial interest and been widely used in various commercial applications, especially in the aerospace industry. For example, Li et al. (2013) and Shyha et al. (2010) reported that the application of high performance composites increased dramatically in aerospace industry and are expanding.

The huge demand for high performance airplanes have become one of the major forces to drive composite manufacturing technologies. Currently, the conventional thermal heating process of advanced composite laminates with large thickness occurred unacceptable temperature gradients in the thickness direction. Bogetti and Gillespie (1992) reported that the complex gradients of temperature in thickness direction of composite laminates may cause serious process-induced residual stress and deformation.

For the above reason, alternative processing technologies, such as microwave curing technologies have been developed to form composite structures and provide a uniform temperature distribution. Kwak et al. (2011) studied the mechanical properties of carbon fiber reinforced plastics (CFRP) laminates cured by the Vötsch Hephaistos Microwave (VHM) oven, which can provide a homogeneous microwave distribution. The microwave cured samples showed higher mechanical performance than those cured by conventional heating. Liu et al. (2010) reported that microwave curing had no obvious effect on rheological property of polyethylene/carbon black composites. Ku et al. (2001) applied variable frequency microwave facilities to process the polymeric materials, which could offer a rapid and uniform heating over a large volume at a high energy coupling efficiency. Thostenson and Chou (1999) discussed the electromagnetic theory and dielectric response of microwave heating for composite materials, and reported that the application of microwave for processing polymer composite materials have more efficient heat transfer over traditional heat transfer method. Thus, microwave curing technologies have been investigated as an efficient energy delivering and uniform heating method to composite materials.

Industrial microwave processing is usually accomplished at a few fixed frequencies, such as 915 MHz, 2.45 GHz, 5.8 GHz and 24.124 GHz. By using the 2.45 GHz frequency microwave, Yarlagadda and Hsu (2004) implemented the differential scanning calorimeter technique to measure the glass transition temperature on both microwave and conventional heating. Their experiment results showed that the epoxy resins cured by microwave have higher glass transition temperature than the conventional heating. Boey and Yap (2001) reported that microwave curing was more effective than conventional heating in enhancing the

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http://dx.doi.org/10.1016/j.jmatprotec.2013.10.012

reaction rates during cross-linking by testing different curing agents in curing.

As discussed above, the 2.45 GHz frequency microwave curing may have advantages in processing the composite parts. But for carbon fiber reinforced composites, Nightingale and Day (2002) reported that the presence of carbon fibers in the composite may affect the penetrating depth of the microwave energy, because of the electrical conductivity and electromagnetic reflection of carbon fiber bundles. The experiments accomplished by Hunyar et al. (2006) also showed that the anisotropic properties of composite materials may affect the temperature distribution. Lee and Springer (1984) developed a computing model to describe the microwave curing process of continuous fiber reinforced composites and reported the carbon fiber may lead to problems such as arcing in composites. Until now, the temperature gradient in the thickness direction of carbon fiber reinforced composite materials has still not been measured quantitatively. The influencing factors of temperature distribution also need further research.

In order to measure the temperature during microwave curing, Bond et al. (1999) used a miniature gas thermometer with pressure transducer to indicate the temperature of the materials under microwave field. Yarlagadda and Cheok (1999) and Wei et al. (1991) investigated the effect of the microwave curing of epoxies using an Infra-red thermometer, and compared the glass transition temperature of mold materials using microwave heating and conventional oven heating methods. Rao and Rao (2008) used a thermal imaging camera to measure the temperature distribution of a resin samples cured in a microwave oven. However, those approaches can only measure the surface temperature of composite materials. The temperature inside composite materials could not be measured.

This paper reports on-going work carried out by the authors in the investigation of the through-thickness temperature distribution of carbon fiber reinforced composite laminates influenced by ply orientation and thickness. A multiple mode applicator was used for microwave curing, and vacuum techniques were performed to assist the microwave curing. Fiber Bragg Grating (FBG) sensors were applied in the modified optical sensing system to measure both the surface and center temperature of composite parts during the forming process. Two different types of epoxy systems were studied. The physical mechanisms during microwave curing were analyzed and the microwave curing technologies were modified to provide a uniform temperature distribution.

2. The experiment

2.1. Materials used

The laminates used in this experiment are T300/6509 and T300/10128 carbon fiber/epoxy unidirectional prepreg. The resin content of both prepreg is 33%. The two materials are typically used for the production of high performance composite structures, such as composite fairing, panels and wind ribs of aircrafts. They respectively represent the average toughness with low glass transition temperature epoxy resins, and high toughness with high glass transition temperature epoxy resins. Other supporting materials are supplied by Airtech Company, such as vacuum bag L500Y, release film Peelplysc01, breather B150 and perforated release film RP3. The thermo-mechanical properties of the epoxy and fiber are given in Table 1, where "E" means tensile modulus, "G" means shear modulus, "μ" represents Poisson's ratio and "α" represents the coefficient of thermal expansion.

2.2. Sample preparation

The sample composite laminate, with dimensions of 100 mm × 100 mm, was produced by hand cutting and lay-up of two types of prepreg. Metal materials are known to reflect microwave energy, thus a tooling suitable for use inside the microwave field is wave-transparent material, such as glass and ceramic tooling. A ceramic tooling for use inside the microwave field was manufactured, with low coefficient of thermal expansion and excellent thermal stability.

Table 1
Thermo-mechanical properties of polymer systems.

Material	E (GPa)	G (GPa)	μ	α ($\times 10^{-6}$/°C)
10128 epoxy	5.12	1.87	0.37	42.51
6509 epoxy	4.35	1.59	0.37	43.92

A particular aspect of the microwave curing technology is the arcing of the carbon fiber bundles. Composite materials may be damaged during arcing. Thus sealant tapes were used to seal the vacuum bag to suppress the arcing between the carbon fibers. It was adhered along the edge of composite materials and compacted using vacuum pressure, as shown in Fig. 1. This setup allowed the microwave processing of composites without arcing and had a better performance. The temperature at the top surface, center and bottom surface of the composite laminates were measured by embedded FBG sensors in the materials. Four FBG sensors were numbered and packaged in a glass capillary to monitor the cure cycle (see Fig. 1).

In order to investigate the through-thickness temperature distribution of the composite laminates influenced by ply orientation and thickness, the single factor experiment approaches were taken. Table 2 shows the experimental parameters of ply orientation and thickness. The T300/6509 and T300/10128 composites were both studied in each experiment. For the ply orientation experiment, the samples had the same thickness (7.5 mm), but with different ply orientations. The composite samples prepared for ply thickness experiment had different thickness, but with the same [0/90] ply orientation.

2.3. The curing procedure and devices used

A high performance industrial microwave oven (NJL2-1) was custom-modified to accommodate the vacuum pipe and FBG sensors. Two electromagnetic microwave generators have a variable power output of 0–800 W at a frequency of 2.45 GHz and are installed at the bottom of the multiple mode applicator. The power of magnetrons can be continuously adjusted. The waveguides of two generators are designed to produce a multiple mode field, which can guarantee a uniform electromagnetic wave distribution. The temperature was measured by an SM125 optical sensing

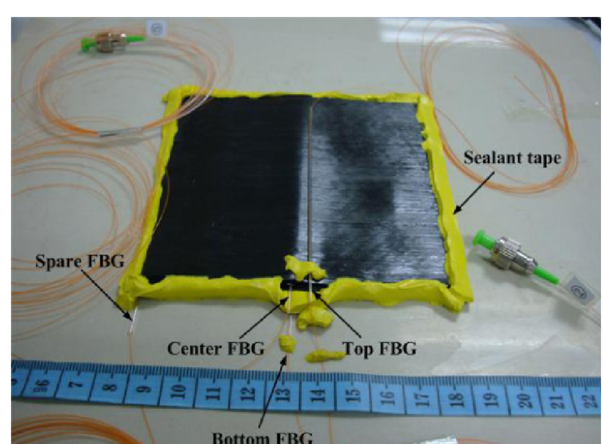

Fig. 1. Sample preparation for the composite curing process.