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Microwave curing of carbon fiber/bismaleimide composite laminates: Material characterization and hot pressing pretreatment

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ABSTRACT

Microwave curing is proposed as an alternative cost-effective process to thermal curing for composite materials. Carbon fiber/bismaleimide composite laminates were fabricated by vacuum assisted microwave processing without arcing. The physical and mechanical properties of cured composites were compared to those produced using autoclave and conventional oven curing. To compensate for the lower vacuum pressure and further improve part quality, hot pressing pretreatment and subsequent microwave radiation were studied. The results indicated that microwave cured samples with 37% of the thermal manufacturing cycle time, obtained basically identical molecular structure and exhibited full curing. Uniformity and consistency of microwave curing was verified by assessing the mechanical strength at different positions in a laminate. The microwave processed panel properties showed a noticeable enhancement as compared with those cured in a traditional oven. A slightly superior performance to autoclave laminates was observed for the composites manufactured with the hot-pressing pretreatment followed by microwave processing.

1. Introduction

In the aerospace industry, carbon fiber reinforced bismaleimide (BMI) composites are increasingly used as high-temperature structural materials because of their light weight, high specific mechanical strength, superior thermal stability and fatigue resistance at high humidity [1,2]. The manufacturing process of BMI based composite structure generally requires curing. In conventional thermal curing using an oven or autoclave, the entire cavity atmosphere needs to be heated up at relatively slow ramp rates and thermal energy is transferred to the material through convection and conduction. Thus, a long cycle time is required for complete curing of the resin [3]. Moreover, autoclave processing has intrinsically high capital investment and operational costs, which have restricted the wider industrial application of advanced polymer composites. Therefore, there is an enormous interest in developing alternative processing routes for curing high performance composites at higher rates and lower cost [4].

Due to the rapid heat transfer and volumetric heating, microwave curing technology has attracted growing attention and been shown to be a promising cost-effective process for producing carbon fiber reinforced polymer (CFRP) composites in recent years. Compared with the traditional thermal curing methods, microwave processing with the specific heating mechanism presents several practical advantages and tangible benefits, including high heating efficiency, energy saving, reduced manufacturing costs, shorter processing time, improved material properties and better process controllability [5–8]. The microwave absorption capacity of CFRP composite systems is thought to be dominated by the conductivity of carbon fibers and therefore the selective heating of the fibers transfers heat by conduction to the polymer matrix, providing better bonding at the fiber/matrix interface [9,10]. Nevertheless, there are numerous challenges that need to be overcome in order to successfully implement the microwave processing for CFRP composites. One major challenge relates to electric field breakdown, or arcing of carbon fiber bundles, which can result in very high localized temperatures and damage to the materials and fabrication assemblies [11].

Since microwave processing holds great potential for improving current composite production techniques, a considerable amount of research has been carried out regarding microwave curing of CFRP composites [12–30]. The preceding work has primarily concentrated on epoxy matrix composites and revealed that microwave radiation can realize uniform curing, reduce processing time and improve mechanical properties. For microwave cured carbon fiber/epoxy composites, the flexural properties [16,18,21], interlaminar shear strength (ILSS) [16,18], tensile properties [19–21,24,27], in-plane shear strength (IPSS) [24,27] and compressive properties [24,28] have been investigated and compared to thermally cured ones. Likewise, numerical simulations of microwave heating [17] and temperature distribution during microwave curing [22,30] have been studied. But there are relatively few publications with respect to the microwave curing of carbon fiber/

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bismaleimide composites. Li et al. [23] demonstrated that cure-induced strains were drastically reduced in microwave processed carbon fiber/BMI composites. The effect of microwave curing on the flexural strength and ILSS of carbon fiber/BMI composites was reported earlier by our research team [29]. However, the physical and mechanical properties of microwave cured carbon fiber/BMI composite laminates have not been widely investigated. Furthermore, the compensation process for the absence of high pressure in microwave curing has not yet been fully exploited.

In the present work, vacuum bagged carbon fiber reinforced bismaleimide composite laminates were cured with the optimum microwave cure process established in our previous study [29]. The uniformity of microwave curing was evaluated based on the flexural strength and ILSS of samples at different positions in a laminate. The molecular structure, physical (degree of cure, void content and fiber volume fraction) and mechanical (flexural, ILSS and compressive) properties of microwave cured panels were compared with those of autoclave cured and conventional oven cured laminates. To remedy the lack of high pressure and consolidate the plies further, the hot pressing pretreatment was designed and followed by vacuum assisted microwave processing. Its effect on the flexural properties and ILSS of the composites was investigated.

2. Experimental

2.1. Materials and sample preparation

The material used in this work was 5428/T700 unidirectional prepreg (purchased from AVIC Composite Corporation Ltd.), which is combined with a toughened BMI resin and T700 carbon fiber. The resin content is 35 ± 3% and the fiber areal density is 130 ± 5 g/m^2. This prepreg is primarily employed for manufacturing the load-bearing composite structural components with long-term service temperature of 170 °C in the advanced aircraft.

Twenty-two prepreg plies 170 mm in length × 90 mm in width with the fibers aligned along the length axis, were laminated to produce the unidirectional carbon fiber/BMI composite samples for autoclave, oven and microwave curing. All cured composites were fabricated by the vacuum bag lay-up, as illustrated schematically in Fig. 1. Glass fiber fabric coated with Teflon was used as peel ply. The heat-resisting polyimide film was selected as release film and bagging film. Microwave-transparent quartz glass moulds with dimensions of 200 mm × 120 mm × 4 mm, were manufactured for vacuum assisted microwave processing. Prior to the curing, the laminates were debulked using vacuum bagging for 30 min at 0.1 MPa to remove the trapped air from hand lay-up.

2.2. Autoclave curing

According to curing process of 5428 BMI resin, the manufacturer recommended cure cycle as described below was employed for autoclave processing of the prepreg panels, which can allow the composites to achieve exceptional performance with low porosity and high fiber volume fraction. A consolidation pressure of 0.6 MPa was applied when temperature reached 100 °C and then maintained throughout the autoclave curing cycle with full vacuum.

The curing process:

a. Heat from room temperature to 150 °C at 2 °C/min, and then dwell at 150 °C for 90 min.
b. Heat from 150 °C to 180 °C at 2 °C/min, and then dwell at 180 °C for 120 min.
c. Heat from 180 °C to 210 °C at 2 °C/min, and then dwell at 210 °C for 300 min.
d. Cool from 210 °C to below 60 °C at 2.5 °C/min.

2.3. Microwave curing

The WZD1S-03 industrial microwave equipment was used for the microwave curing of CFRP composites, which was consistent with the one employed previously [28,29]. The magnetron had a continuous variable power output of 0–1000 W at a frequency of 2.45 GHz and the waveguide was designed to produce a homogeneous distribution of microwave field. The corresponding real-time temperature was monitored by a digital noncontact infrared thermometer fixed in the top of microwave oven. The composite plies in vacuum bags were placed inside the microwave cavity and linked to an internal Teflon port, which was connected to a vacuum pump, as shown in Fig. 2. A PTFE plate was added to the bottom of the vacuum bagging arrangement in order to reduce heat loss to the cold oven surfaces.

Over a large number of trials, the interaction between carbon fiber and microwave energy could be notably alleviated by limiting the microwave power. It was identified that the microwave power below 200 W could effectively avoid the occurrence of arcing. The optimum microwave cure cycle established in our earlier work [29] was chosen to implement the microwave processing of composite laminates without arcing at a curing pressure of 0.1 MPa throughout the entire cycle. The laminate sample alone was put into the microwave oven and the actual panel temperature profile measured during microwave curing is plotted in Fig. 3. The microwave curing technique was found to be capable of readily achieving ramp rates of 20–40 °C/min [28,29], which was even faster than the ramp rate of up to 15 °C/min for the Quickstep process (a novel and rapid out-of-autoclave curing process) [31,32]. As compared to 2–3 °C/min usually employed for autoclave or other traditional thermal processing techniques, such high heating rate would transform the rheological behavior and reaction progress of resin system, and further affect the physical and mechanical properties of carbon fiber/BMI composites.

During the processing of thermoset composites, external pressure drove the excess resin, air bubbles and volatiles out of the laminates [4]. The high-consolidation pressure in autoclave curing, usually assisted by compressed nitrogen, facilitated the dissolution and removal of voids while ensuring full compaction [21,31]. Nevertheless, no

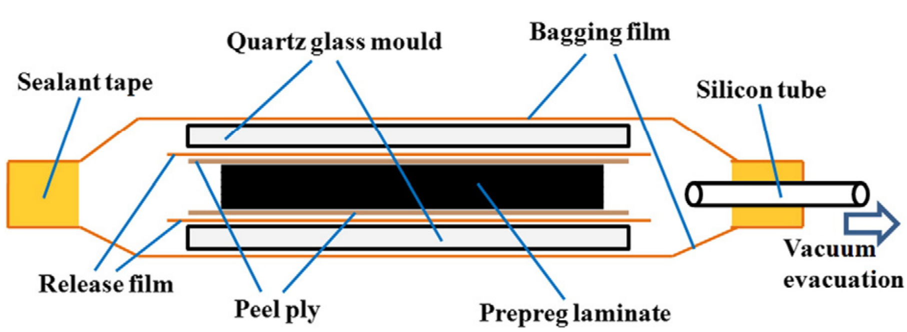

Fig. 1. Schematic representation of vacuum bagging assembly.