Journal of Materials Science & Technology 32 (2016) 226–232

Contents lists available at ScienceDirect

Journal of Materials Science & Technology

journal homepage: www.jmst.org

Improvement of the Compressive Strength of Carbon Fiber/Epoxy Composites via Microwave Curing

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ARTICLE INFO

Article history:
Received 8 April 2015
Received in revised form
23 June 2015
Accepted 26 June 2015
Available online 8 October 2015

Key words:
Carbon fiber
Epoxy
Microwave curing
Compressive properties

Microwave processing was used to cure the carbon fiber/epoxy composites and designed for improving the compressive strength of the materials. By controlling the power of microwave heating, vacuum bagged laminates were fabricated under one atmosphere pressure without arcing. The physical and mechanical properties of composites produced through vacuum bagging using microwave and thermal curing were compared and the multistep (2-step or 3-step) microwave curing process for improved compressive properties was established. The results indicated that microwave cured samples had somewhat differentiated molecular structure and showed slightly higher glass transition temperature. The 2-step process was found to be more conducive to the enhancement of the compressive strength than the 3-step process. A 39% cure cycle time reduction and a 22% compressive strength increment were achieved for the composites manufactured with microwave radiation. The improvement in specific compressive strength was attributed to better interfacial bonding between resin matrix and the fibers, which was also demonstrated via scanning electron microscopy analysis.

1. Introduction

Carbon fiber reinforced polymer (CFRP) composite materials with high strength to weight ratio, excellent high-temperature characteristics and resistance to fatigue have gained substantial interest over last decades and been widely used in the weight-critical aerospace industry[1]. Recently, the most advanced commercial aircrafts, such as Airbus A380 and Boeing 787 dream-liner, utilize composites for up to 50 wt% of their construction[2]. The high cost has still been the primary bottleneck for wider industrial use of fiber-reinforced polymer composites. In terms of cost reduction for composites, microwave processing is thought to be the economically feasible and promising solution[3]. On account of the special heating mechanism, microwave curing offers many remarkable advantages over regular thermal curing, including energy saving, lower operating costs, higher heating efficiency, increased throughput, curtailed processing time and improved processing control[4–7].

To date, a considerable amount of research has already been conducted on microwave processing of different composite systems[8–24]. There has been some work devoted to the study of microwave curing for the CFRP composites, which has revealed that microwave curing can reduce processing time and improve mechanical properties[21–24]. However, with respect to microwaves being adopted in the composite processing industry, currently there exist two main obstacles: local hot spots resulting from uneven microwave distribution and arcing induced by the interaction between carbon fiber and microwave energy[24].

The compressive strength of carbon fiber composites is significantly less than their tensile strength[25], which implies that the compression load carrying capacity may be relatively limited. Therefore, much attention has been paid to the improvement of the compressive strength of CFRP laminates primarily subjected to compression loading. Since microwaves have an exceptional impact on the interfacial bond behavior between carbon fiber and resin matrix, microwave processing method has great potential to become one effective route for improving the compressive strength of CFRP composites. The improvement in the flexural properties, interlaminar shear strength properties[21,22] and tensile properties[23,24] of microwave cured carbon fiber composites has been observed, whereas the research on microwave curing to improve their compressive properties has rarely been reported.

The presence of voids in the fiber-reinforced composites will have a detrimental impact on their mechanical properties, including the compressive strength which is known to be sensitive to the void content. Thus, the removal of voids is quite critical in many advanced composite aerospace structures[26,27]. The number of voids

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http://dx.doi.org/10.1016/j.jmst.2015.10.006

can be reduced by physically transporting them out of the resin/fiber network through the use of vacuum bagging[28]. But the vacuum bag may be punctured and the material may be burnt due to arcing in the CFRP microwave curing. While several researchers, for this reason, abandoned vacuum bagging method in microwave curing process[21,23], some others identified the ways of avoiding arcing: using aluminum tape or epoxy resin to shield the tips of carbon fibers[24], and employing the sealant taps to adhere the vacuum bag along the edge of composites[29]. However, these approaches appear to have poor universality and flexibility in industrial application for vacuum assisted microwave curing technology, suggesting that one more general approach needs to be exploited.

The aim of the present work is to incorporate microwave processing into the vacuum bag molding for CFRP production and improve the compressive strength of composite laminates by means of microwave curing technique. Through controlling the power of microwave radiation, vacuum techniques were productively performed to assist the microwave curing for carbon fiber/epoxy composite laminates without arcing. The molecular structure, the degree of cure, the glass transition temperature (T_g) and the compressive properties of microwave cured samples were investigated and compared with those manufactured using conventional vacuum bagging method.

2. Experimental

2.1. Material

The composite system employed in this research was a unidirectional prepreg (supplied by Shanghai Aircraft Manufacturing Co., Ltd.), comprising the epoxy system available to provide a balance of toughness and mechanical properties with T800 grade carbon fiber reinforcement. The initial fiber volume fraction is 57.56%. This prepreg material is optimized for wing structure ensuring maximum performance at minimum weight in commercial aircrafts.

2.2. Vacuum bagging

Composite laminates, consisting of 14 plies measuring 175 mm × 90 mm with the carbon fibers in the 0° direction parallel to the 175 mm side, were prepared for the thermal curing and microwave curing. All cured composites were fabricated using the vacuum bag lay-up, as illustrated schematically in Fig. 1. Prior to curing the prepreg, the laminates were de-bulked for 60 min to remove bulk trapped air from lay-up and consolidate laminates further. The consolidation pressure inside the vacuum bag was approximately 0.1 MPa (an atmospheric pressure).

The consumables used inside the microwave field should be wave-transparent materials. Metal materials are known to reflect microwave energy and cannot be used as the tooling for microwave curing. Hence, the microwave-transparent materials such as quartz glass and polytetrafluoroethylene (PTFE) plate were employed to manufacture the tooling for microwave processing, as shown in Fig. 1. Besides, the heat resisting polyimide film was selected as release film and vacuum bag material.

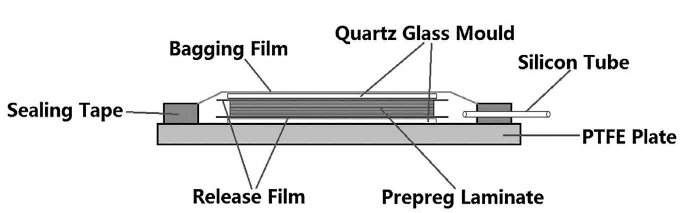

Fig. 1. Vacuum bagging arrangement used in this work.

2.3. Curing procedures

2.3.1. Thermal curing

The cure schedule suggested by the prepreg supplier is 180 ± 6 °C for 120 min and the supplier proclaims that the thermal curing conditions can assure the optimal mechanical performance. The sample laminates vacuum bagged were placed in a conventional thermal oven. In accordance with the recommended cure cycle, the oven temperature was increased to 180 °C at a ramp rate of 2.5 °C/min and held for 120 min. Finally it was cooled to room temperature. Full vacuum was applied and the pressure was kept at 0.1 MPa throughout the cure process.

2.3.2. Microwave curing

The equipment utilized for microwave curing in this work was a WZD1S-03 industrial microwave oven manufactured by Nanjing Sanle Microwave Technology Development Co., Ltd. (Nanjing, China). The electromagnetic microwave generator has a continuous variable power output of 0–1000 W at a fixed frequency of 2.45 GHz and the power of magnetrons can be manually adjusted. The temperature of the sample was monitored using an infrared thermometer in the microwave oven. Additionally, the manufacturer claims that the microwave chamber and waveguide can offer an even microwave field distribution.

For carbon fiber reinforced epoxy resin matrix composites, a particular aspect of the microwave curing technology is the arcing of the carbon fiber bundles, which would damage the vacuum bag and materials[29]. In consideration of the strong absorption of carbon fibers on microwave energy[20], many tentative efforts toward avoiding arcing were made to weaken the coupling effect through the microwave power regulation. It was identified that the microwave power less than 180 W could enable composite laminates to cure without arcing and fabricate under the vacuum pressure of 0.1 MPa throughout the entire cycle. Especially, an enough lower power should be utilized initially to prevent spark formation, which would puncture the vacuum bag resulting in the loss of vacuum and pressure on the laminates.

During microwave heating, the material will not only absorb heat but also dissipate heat to the cold surrounding. In the prophase, the material absorbs more heat energy than that it dissipates, so the temperature increases with increasing heating time. When heat absorption equals to heat dissipation, a thermal equilibrium will be created in the material, so the temperature gradually tends to stabilize and levels off to a constant value. The temperature profiles for laminates at different power levels, plotted versus microwave heating time, are shown in Fig. 2. At the initial stage of microwave processing, the microwave heating rates at 100, 133 and 167 W are found to be approximately 30, 35 and 40 °C/min, respectively, remarkably greater than the rate of 2.5 °C/min in thermal curing. The equilibrium temperature at 100, 133 and 167 W reaches about 170 °C, 182 °C and 188 °C, respectively. Thus, the heating rate and the ultimate temperature obtained by microwave heating increase with enhancing the microwave power. It is noteworthy that the equilibrium temperature at 100, 133 or 167 W relatively approaches the thermal curing temperature 180 °C.

The microwave process conditions involving processing time and power level used for each laminate are listed in Table 1, which also shows the values of panel thickness for laminates fabricated via microwaves under the full vacuum pressure. For composites C5–10 using the multistep (2-step or 3-step) heating process, the microwave power of 100 W in the beginning was employed to guarantee the cure process without arcing and preheat the laminates,