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Effect of microwave curing process on the flexural strength and interlaminar shear strength of carbon fiber/bismaleimide composites

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ABSTRACT

Microwave heating has been conceived as a rapid and cost-effective method for curing carbon fiber composites. In this paper, microwave radiation was used to cure carbon fiber/bismaleimide composites aiming at shortening the production cycle time. Through controlling the microwave power, vacuum bagged laminates were fabricated under one atmosphere pressure without arcing. Degree of cure, void content and fiber volume fraction were measured to evaluate part quality. Three-point flexure and short beam shear testing were employed for mechanical assessment. Variation in the microwave cure cycle had a significant effect on the material properties. The optimum processing parameters for microwave curing were established based on analysis of the mechanical performance. A cycle time reduction of nearly 63% was obtained compared to thermal processing. The physical and mechanical properties of microwave cured samples were found to be superior to those cured in a conventional oven. The composite panels manufactured by the optimized microwave cure process exhibited a slight decrease in flexural strength but equivalent interlaminar shear strength in comparison with those produced by autoclave curing.

1. Introduction

Carbon fiber reinforced polymer (CFRP) composites have been increasingly used as structural materials in the aerospace industry over the last decades owing to their light weight, high specific mechanical strength and corrosion resistance [1,2]. Compared with epoxy resins, bismaleimide (BMI) resins are high-temperature resistant thermosetting polymers and contain superior thermal stability as well as fatigue resistance at high humidity [3,4]. Thus, carbon fiber reinforced BMI resin composites are attractive for aerospace structural applications where elevated temperature is required. Currently, high performance composite parts are predominantly fabricated by the consolidation at high temperature of laminates made up of prepreg plies in an autoclave because the elevated pressure guarantees full lay-up compaction, leading to the maximum fiber volume fraction and negligible porosity [5]. However, autoclave techniques not only require intrinsically high capital investment and operating costs, but also consume a large amount of time and energy in the manufacturing process. Additionally, it is difficult for traditional autoclave methods to achieve the demands for shortening the cycle time and increasing the production rate of aerospace composites [6]. Therefore, enormous effort has been made to develop alternative curing technologies aimed at producing materials of similar part quality to aerospace grade composites, but with shorter production time and lower processing cost.

Microwave processing can be considered as an alternative cost-effective route for curing CFRP composite materials due to its rapid and volumetric heating capabilities. Because of the specific heating mechanism, microwave curing offers many remarkable advantages over traditional thermal curing, including energy saving, lower operating costs, higher heating efficiency, increased throughput, curtailed processing time and improved processing control [7–9]. Nevertheless, before microwave heating/curing can be considered for (structural) industrial applications, there are some major challenges needing to be addressed, such as even energy distribution and consistency, arcing of carbon fiber bundles, absence of high pressure, tooling design and part quality [10–12].

To date, a great number of papers have been published on microwave processing of CFRP composite systems [10–22]. Previous research work has revealed that microwave processing can realize uniform curing, reduce processing cycle time and improve

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mechanical properties. Improvements in the flexural properties [15,18], interlaminar shear strength (ILSS) [15,16], tensile properties [10,11,17,18] and compressive properties [11,19] have been observed for microwave cured carbon fiber/epoxy composites as compared to thermally cured ones. Hunyar et al. [20] developed autoclave-free systems for microwave processing of carbon fiber reinforced epoxy composites and presented experimental verification along with results of numerical simulations. Li et al. [21] reported the maximum temperature difference in carbon fiber/epoxy laminates using microwave curing technology was reduced by 60% in comparison with thermal heating process. Li et al. [22] demonstrated that the cure-induced strains were drastically reduced in carbon fiber/BMI composites using microwave processing. Mijovic et al. [23] and Zainol et al. [24] studied the microwave curing of BMI resin systems and indicated that there was no difference in the chemical reactions taking place during microwave cure and thermal cure. As mentioned above, the preceding work on microwave curing for CFRP has primarily concentrated on epoxy matrix composites, whereas there are very few publications with respect to the microwave curing of carbon fiber reinforced bismaleimide composites. In addition, the influence of microwave curing on the mechanical properties of carbon fiber/BMI composites has rarely been reported in literature.

This investigation employed microwave radiation for curing carbon fiber reinforced BMI composites with vacuum bagging. Arcing was avoided by limiting the microwave power. Based on the temperature profiles during microwave heating and the thermal cure cycle, various microwave cure cycles were designed. Then the optimum processing parameters were established for microwave curing of vacuum bagged carbon fiber/BMI laminates. Part quality was assessed through physical (degree of cure, void content and fiber volume fraction) and mechanical (flexural strength and ILSS) testing. The microwave cured panels were compared with autoclave cured and conventional oven cured laminates.

2. Experimental

2.1. Materials and equipment

The composite system employed in this research was 5428/T700 unidirectional prepreg (supplied by AVIC Composite Corporation Ltd.), which is comprised of a toughened BMI resin matrix and T700 carbon fiber reinforcement. This prepreg material is mainly used for primary and secondary composite structures in the aerospace industry.

The equipment used for microwave processing in this experiment was a WZD1S-03 industrial microwave oven manufactured by Nanjing Sanle Microwave Technology Development Co., Ltd. (Nanjing, China). The dimensions of the microwave cavity were 350 mm in length, 340 mm in width and 230 mm in height. A magnetron with a continuously variable power output of 0–1000 W at a fixed frequency of 2.45 GHz, was installed on the top of the multi-mode applicator. The waveguide of the microwave generator was designed to produce a uniform microwave field distribution. There was a Teflon tube with a diameter of 10 mm and a length of 40 mm in the side of the cavity, where the vacuum hose was connected. The real-time temperature of the sample was monitored by an infrared thermometer fixed at the top of microwave oven.

2.2. Vacuum bagging

Carbon fiber/BMI resin composites comprising 22 plies measuring 170 mm × 90 mm with the fibers in the 0° direction aligned along the 170 mm side were prepared for autoclave, oven and microwave curing experiments. All cured panels were fabricated using the vacuum bag lay-up as illustrated in Fig. 1. Microwave-transparent quartz glass moulds were manufactured for vacuum assisted microwave processing. Prior to curing the prepreg, the laminates were de-bulked for 30 min at 0.1 MPa to remove the entrapped air in the laminate using vacuum bagging. Vacuum pressure was continuously applied during the curing process.

2.3. Curing methodologies

2.3.1. Autoclave curing

The manufacturer recommended cure cycle for autoclave processing of the prepreg laminates is depicted in Fig. 2, which can allow the product to achieve its maximum performance with low porosity and high fiber volume fraction. At a constant pressure of 0.7 MPa, a heating rate of 2 °C/min and a cooling rate of 2.5 °C/min were used for the autoclave curing process.

2.3.2. Conventional oven curing

A conventional thermal oven was utilized to produce the composite panels with the purpose of simulating the thermal cure cycle using vacuum bag only without any additional consolidation pressure. The cure cycle was identical as the one employed for the autoclave curing trials (Fig. 2). Vacuum pressure was kept at 0.1 MPa throughout the oven cure process.

2.3.3. Microwave curing

For CFRP composites, microwave radiation may induce arcing at the tips of the carbon fiber bundles due to the strong microwave absorption, which would damage the materials and puncture the vacuum bag resulting in the loss of vacuum pressure [10,11,15,18,21]. This phenomenon is related to the conductivity of carbon fibers and conductor gaseous breakdown in electromagnetic fields [14,22]. Tentative efforts were made to avoid arcing via the microwave power regulation weakening the interaction between carbon fiber and microwave energy. The authors identified that using the WZD1S-03 system a microwave power below 200 W did not cause arcing and therefore enabled the possibility to microwave cure the composite laminates without arcing at a curing pressure of 0.1 MPa throughout the microwave processing cycle.

The temperature profiles of the laminates processed at different power levels, plotted versus microwave heating time, are shown in Fig. 3. The carbon fiber was firstly and rapidly heated by microwaves and then the thermal energy was transferred to resin matrix [22], leading to the quick increase in the temperature. The average heating rates in the initial stage at 67 W, 100 W, 133 W and 167 W were found to be 16 °C/min, 20 °C/min, 25 °C/min and 30 °C/min, respectively. Subsequently, a considerable amount of heat was lost to the cold surrounding and thermal equilibrium was achieved within the material. The equilibrium temperature values during microwave radiation with 67 W, 100 W, 133 W and 167 W reached about 130 °C, 165 °C, 195 °C and 220 °C, respectively. Hence, the heating rate and the ultimate temperature obtained during microwave curing enhanced with increasing microwave power.

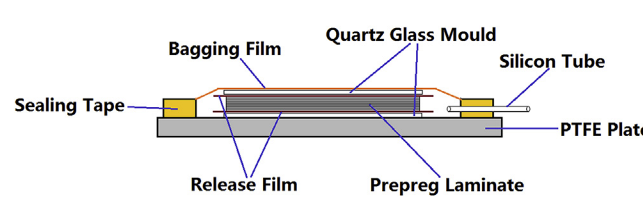

Fig. 1. Vacuum bagging arrangement used in this study.