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Non-destructive investigation of thermoplastic reinforced composites☆

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ABSTRACT

This paper studies various manufacturing defects in glass fiber/Polypropylene (PP) composite parts and their methods of detection. Foreign Object Inclusion (FOI) of different shapes, sizes, and materials were placed in a glass fiber/PP panel made by compression molding. The paper aims to characterize the fiber orientation and fiber related defects such as fiber waviness in the composite specimen. Comprehensive investigation for different Non Destructive Evaluation (NDE) techniques, namely X-ray radiography and Ultrasonic Testing (UT) techniques to trace and characterize the embedded defects and the composite texture are presented. Conventional X-ray radiography successfully identified the fiber orientation in two dimension (2-D) plane; however, information for the sample depth was not captured. The radiography techniques showed low relative errors for the defect size measurements (maximum error was below 9.5%) when compared to the ultrasonic techniques. Ultrasonic techniques were able to map all the embedded artificial defects. Phase Array (PA) ultrasonic technique was able to precisely locate the FOI in the glass fiber/PP specimen. Nerveless, the shape and size of the defects were not accurately determined due to the high signal attenuation and distortion characteristics of the E-glass fiber.

1. Introduction

Composite material applications have grown rapidly over the last few years as market studies showed that the US composite market grew by 6.3 percent to reach $8.2 billion in 2014 and the main economic indicators predicts a growth of 4.9 percent by the end of 2015 [1]. The market study shows that glass fiber is the most dominant material in the reinforcement segment [1]. This market expansion is due to the superior composite materials properties (i.e. high strength to weight ratio, corrosion resistance, high specific modulus and their improved damping capacity) [2,3]. Thermoplastic reinforced composite materials are widely used in the fabrication of various high-end products in many industrial applications such as marine and offshore, mass-transit and automotive industry [4,5]. They are being preferred over other composite materials as they have a shorter processing times and the ability to being recycled [6,7]. Different discontinuity mechanisms can occur during the manufacturing processes or at the service life of the component. Defects such as fiber wrinkling and waviness, porosity, FOI, and ply misalignment that can progress during the fabrication process could lead to other damages such as delamination, disband, and crack formation [8–10]. The characterization of these defects is extremely important and it is preferable to be evaluated nondestructively. With the increase of the composite share the efforts for Non Destructive Testing/Evaluation (NDT/E) are exploding and over the past few years various NDE techniques have gradually percolated into mainstream testing criteria on a global scale.

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Several NDT/E techniques such as X-ray, thermography, ultrasonic testing and techniques are widely used to characterize different defects in composite materials [11–13]. Thermography could be used to study near surface regions of composite structure [11]. This technique mainly detects near surface features. However, it can penetrate a shallow depth through the material (few millimeters) depends on the modulation frequency and the type of material tested. The technique suffers from depth limitation, as the attenuation of the modulated thermal diffusion process is high [14]. Radiography is widely used in defect and discontinuity detection in composite materials [15,16]. However, special considerations should be taken when scanning low atomic weight elements (such as polymers) with low X-ray attenuation coefficients. Low energy X-ray parameters (i.e. tube voltage of an average between 10 and 50 keV) with short exposure time are often used to test polymeric materials [17,18]. Conventional X-ray radiography suffers from structural superposition (i.e. lack of providing three dimension (3-D) information). On the other hand, X-ray CT technique provides 2-D density maps of the part cross sections that can be stacked together to provide accurate 3-D information of the entire part. Researchers used X-ray CT to detect several types of discontinuities and characterize different composite materials and structures, including honeycomb composites, fiberglass power poles, and carbon foams [19–21].

UT is a widely used technique for internal defects detection in composite materials, quality inspection, control and monitoring for different applications such as wind turbine blades, ship hulls, automotive components, aircraft structures piping and welds [18,22–24]. Using A-scan ultrasonic inspection technique for detecting defects in composite is quite challenging, however the interpretation of the scanned signals could provide indications for the location and the depth of the defects, accurate information about the shape and the size of the defect is difficult to be visualized [25]. C-scan mapping technology offer a standard, easy defect detection and more detailed evaluation compared to intensive manual scanning of conventional methods. Theodoros et al. characterized two different types of materials used for marine applications (i.e. carbon/epoxy and glass/polyester) using C-scan UT [26]. Both were fabricated using 14 laminates where several artificial defects were embedded into the test plates. Using a flat UT transducer, they were able to determine the location and the shape of the defects. However, in some cases the exact size was difficult to be obtained. Fiber waviness is a material defect that occurs at the fabrication stage and can be divided into out-of-plane and in-plane fiber waviness [27]. Fiber waviness could result in a substantial decrease in the mechanical properties as the fiber shear angle increased, hence it is curtail to identify and detect the areas of fiber waviness in the fabricated composite part. Research work done in the measurement of in-plane and out-of-plane fiber waviness using ultrasonic testing can be found in Refs. [10,27,28]. Dayal successfully developed a theoretical model of a longitudinal wave propagating through a composite laminate with a wavy sublamina [10]. The wavy lamina was buried inside the composite laminate and is not visible from the outside. He validated his model experimentally using a set of graphite/epoxy wavy laminates.

In previous research we attempted to study artificial defects embedded in a thick glass fiber/PP composite (i.e. 80 plies with overall thickness of ≈ 14.1 mm) with high fiber loading of 80% by weight using UT C-scan system [8]. Conventional flat transducer with two different frequencies (i.e. 5 MHz and 2.25 MHz) were used to scan the specimen and it was found that most of the defects were not detected due to the high signal attenuation characteristic of the E-glass fibers. This could be overcome using lower frequency (i.e. 1 MHz) through transmission ultrasonic or PA ultrasonic system. PA UT has the ability to inspect large structures quickly and can be customized for individual applications [29]. In contrast to conventional flat transducers, where a single-element probe is used, PA transducers uses multi-element probes in which each individual element can transmit and receive ultrasonic signals independently at different times. In this technique time delay is set for individual element to generate interference of the ultrasonic wave fronts that allows the energy to be focused and steered at any specified depth and angle in the test sample. Ber et al. were able to detect different size defects (ranging from less than 6.35 mm to inches to 19 mm) in a composite tube using a curved PA props. They only reported qualitatively that the defects were clearly visible in the time-of-flight and amplitude C-scans [30]. The work presented in this paper aims to study the capabilities and limitation of radiography method and ultrasonic techniques when used to detect fiber orientation, fiber waviness and FOI in thermoplastic composites. The effect of changing the inspection technique parameters and configurations on the ability of quantitatively characterizing the FOI defects shape and size is within the interest of this paper.

2. Materials and test specimens preparation

Thermoplastic composite, namely glass fiber/PP, was used to fabricate the specimen used in this work. The glass fiber/PP was provided by (Polystrand Inc.) in a tape form with density of 1.9 g/cm^3 and 80% as glass fiber weight fraction. The specimen were fabricated using a total of 80 plies with X-ply $[0/90]_{80}$ configuration and with dimensions of 152.4 mm (6 inch) × 152.4 mm (6 inch) and cross-sectional thickness of approximately 14.1 mm (0.55 inch) and total weight of 630 g. The plies were stacked and molded into squared shape plaque using 150 metric ton press (Pasadena Hydraulic Inc.). The tool was heated up to 170.5 °C (339 F) in a constant rate of 5 °C/min. As the temperature reached 65.5 °C (150 F), 10 tons of pressure was applied. The dwell time was 40 min and then allowed to cool in air.

Six artificial defects with different shapes and materials were embedded in the panel to help assess the capabilities of the inspection system and criteria limits, as shown Fig. 1. The dimensions and the locations for the defects are listed in Table 1 and Fig. 1. The selections of the distances between the defects were carefully designed to avoid interference between each defect and its neighbor during the inspection process. The A1, A2 and A4 FOI are made from Kapton and Teflon as shown in Table 1 that has densities comparable to the Glass Fiber Reinforced Plastic (GFRP) composite density (≈2.1 g/cm^3 and 1.4 g/cm^3 for Teflon and Kapton respectively). These types of FOI are presented to evaluate the NDT/E systems capabilities to distinguish these FOI from the background material. A3 and A5 are metallic FOI with relatively larger thickness, compared to the other FOI. The insert of A3 and A5 FOI into the composite laminates will create a separation between the adjacent plies at two different locations shown in Fig. 1. The A6 defect was created by oversize cut, relative to the compression-molding mold, of the last 12 plies that created fiber waviness defect during the compression molding process.

3. Experimental setup

Two different NDT techniques were used in this study, namely ultrasonic testing and radiography. The UT method is divided into two categories: Phase Array UT and Through Transmission UT (TT UT). In radiography, two different methods were used in this work: X-ray radiography and X-ray CT. Moreover, two different X-ray imaging procedures were used for imaging the samples that include convention focusing (i.e. macro focus) and micro focus, which are described in more detail in later sections.