IDENTIFICATION OF DEFECT IN THE AUTOMATED TAPE PLACEMENT PROCESS USING FIBER BRAGG GRATING SENSORS

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Abstract
There has been a tremendous growth of utilizing automated tape placement (ATP) method to manufacture highly precise components for high end applications in aircrafts and next generation of space crafts. ATP has been widely adapted by major aircraft manufacturers for producing large structure, such as one-piece barrels, fuselage panels, or wing spars but this has not attained greater acceptance for production of smaller parts with complex and compact geometries. Above all identification of potential defects within the laminates is critical to ensure the quality of the final product. The quality of composite laminates fabricated using ATP depends not only on the bonding conditions between the laminates, but also on the structural integrity of laminate. The mismatch between the tape paths can cause non-uniform laminate thickness or formation of gaps or overlaps. These defects are usually caused by machine tolerances or steering of the tape. Consequently identifying them at earlier stages of manufacturing help the manufacturers to ensure the quality of final product. In this paper a novel method based on optical fiber Bragg grating (FBG) sensor is implemented for structural health monitoring of composite structures fabricated via ATP method. The results obtained through this study reveal that the embedded FBG sensors can be utilized for on-line process monitoring of composite lay-up, formation of residual stresses after consolidation, identification of common misalignments and the formation of gap during the lay-up. Finally an experimental demonstration of using FBGs towards the identification of cracks through the detection of acoustic emissions is presented.

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1. Introduction

The capabilities of automated tape placement (ATP) machine for making bespoke components along with increasing productivity have provided wider range of application for the ATP in comparison with the other manufacturing methods [1]. Regardless of these advantages, producing defect free component using ATP is practically challenging. One of the common defect happening during the lay-up is misalignment between the successive courses which leads to formation of gap with in the laminate [2] . The negative effects of this defect on mechanical properties of fabricated laminate have been asserted by many researchers [2-4]. Sawicki and Minguet [2] have shown that, gaps with the width of less than 0.76 mm have resulted in reduction of strength by 5-27 %. While, the rate of this decrease for gaps greater 0.76 mm remains constant. Croft et al. [5] have studied the performance of composite laminates with gaps, under tension and compression loading conditions. The authors found that the ultimate strength of laminates is less affected by these defects. In the in-plane shear, tension and compression test, presence of gaps change the results by ±3%. Thus, to detect these failures/defects at early stages of manufacturing an appropriate selection of reliable on-line monitoring technique is vital.

There are several nondestructive methods available for defect identification in laminated composites after fabrication, like C-scan, ultrasonic and thermography [6], however few of the methods have been established for on-line defect monitoring which are laser and optical fibre based [7, 8] . Acoustic emission (AE) is also a well-known technique for continuous monitoring of structural integrity through detecting stress wave generated by propagation of defect in materials [9, 10]. The main advantage of AE over the traditional NDE techniques such as radiography, eddy-current is its ability to monitor micro crack propagation [11].

Shadmehri et al. [8] have utilized a laser system synchronized with a vision system to identify the misalignment, tow location and gap size. Regardless of the accuracy and reliability of this method, the authors have identified two limitations for that. First, the reflective properties of prepreg tape make it difficult to capture the image and the second, highly contoured parts make it difficult to project precisely. Optical fiber Bragg grating (FBG) sensors, on the other hand are considered as promising candidate for on-line structural health monitoring due to their localized and multiplexed sensing-capability [12] . These sensors, because of their small size and light weight [13] can be easily embedded within the laminates without affecting its integrity for continuous health monitoring [14]. Using them, parameters like stress, strain, temperature, natural frequencies [15] and cracks [16] could be monitored in real time. Several studies have been conducted on the application of FBG sensors in composite structure [15, 17-20]. Although FBG sensors are promising structural health monitoring technique, commercial FBG interrogation systems cannot operate at high frequencies (>100 kHz) and state-of-the art high acoustic emission interrogators capable of detecting nano/pico strain at high frequencies are required [21].

The authors of this paper in their earlier work [7, 22, 23] have shown that, real time process monitoring could be possible using optical fibre Bragg grating sensor. In their experimental work the combined effect of both consolidation pressure and curing temperature were measured and recorded for each lay-up, as a wavelength change, at the positions of FBG sensors. The effects of stacking plies, recovering time and residual strain/temperature on the measured wavelength also measured in real time were also considered in their previous study [22]. Whereas the capability of the FBG sensor for identifying misalignment defect (overlap) was studied separately by them [7]. Experiments were carried out by embedding an artificial overlap to introduce a defect between the plies and observe its influences on the reflected wavelengths. The obtained results indicate that the FBG sensors can be effectively utilized for on-line process monitoring parameters, residual stresses and identifying defects during the lay-up process. In this paper, optical FBG sensors are utilized for detecting misalignment defect (gap) during the ATP lay-up process. Also for the first time, the capability of FBG sensor towards the measurement of acoustic emissions in a composite laminates is demonstrated experimentally.

2. Background and Operating Principle

2.1. In-situ automated tape placement

The ATP layup is an advanced manufacturing method for making composite components in which several manufacturing stages are incorporated in the placement head. The machine includes compaction roller, heating system and a robotic arm, which is computer controlled [24, 25]. During the placement process, an incoming tape is delivered to compaction roller while temperature is being introduced through a heat source to the laminate. Hot gas troch is used as heat source which delivers high temperature nitrogen around the tape at the nip point. A number of parameters influence the quality of laminate manufacturing using the ATP machine include curing temperature, consolidation pressure, feed rate, ply orientation and lay-up speed.

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2.2. Operation principle of an FBG and Acoustic emission measurement system

An elementary fiber Bragg grating comprises of a short section of single-mode optical fiber in which the core refractive index is modulated periodically using an intense optical interference pattern [26], typically at UV wavelengths. This periodic index modulated structure enables the light to be coupled from the forward propagating core mode into backward propagating core mode generating a reflection response. The wavelength of light reflected by periodic variations of the refractive index of the Bragg grating (figure 1), having a central wavelength λ_B is given by;

$$\lambda_B = 2 n_{eff} \Lambda. \tag{1}$$

where Λ is the n_{eff} is effective refractive index of the core fibre.

The basic principle of operation of any FBG-based sensor system is to monitor the shift in the reflected wavelength due to changes in measurements such as strain and temperature.

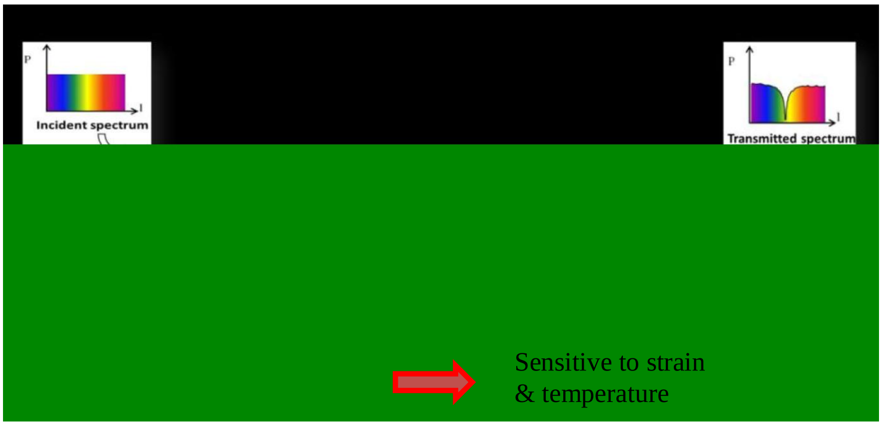

Figure 1. FBG working principle.

When an acoustic wave impinges on an optical fiber with an FBG the refractive index of the fiber and the FBG period are modulated due to acoustic wave induced mechanical strain in the fiber through the elasto-optic effect. The dynamic wavelength shift, corresponding to the acoustic signal induced strain $\Delta\varepsilon(z,t)$ can be written as,

$$\Delta\lambda_B(z,t) = \lambda_B(1-\rho_\alpha)\,\Delta\varepsilon(z,t). \tag{2}$$

where ρ_α is the photo elastic coefficient of the fiber.

Conventional FBG interrogation systems are relatively slow and the strain sensitivity is not sufficient to measure the AE induced events. An AE FBG interrogation system will typically need sub micro wavelength resolution and high frequency measurement capability.

3. Experimental program

3.1. Sample preparation

Two samples were fabricated using ten plies of unidirectional prepreg glass fiber/Nylon (TC910) supplied by Cytec. Both the samples were embedded with FBGs but first one is with an artificial defect whereas the second one is defect free. The first one will be used for defect identification

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